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Lighting in indoor environments: Visual and non-visual effects of light sources with different spectral power distributions

L. Bellia [a,*], F. Bisegna [b,1], G. Spada [a]

[a] Faculty of Engineering, Department of Energetics, Applied Thermofluidodynamics and Environmental Conditioning, University of Neaples, P.le Tecchio, 80-80125 Naples, Italy
[b] Faculty of Engineering, Department of Astronautical, Electrical and Energetic Engineering, Via Eudossiana 18-00184 Rome, Italy

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A B S T R A C T

Since the end of the 1990s, good quality lighting was that which balanced the needs of humans, economic and environmental issues, and architectural design. Recent studies aimed to find a correlation between environmental lighting and human performance and health, with positive results. What is known, is that insufficient or inappropriate light exposure can disrupt standard human rhythms which may result in adverse consequences for performance, safety, health. By studying the relationship between human physiology and light, research in photobiology has advanced to the point where some attempts to foresee what the lighting practice will be in future. The question is if lighting practice and lighting practitioners are ready for changes.

This paper has the aim of introducing the recent discoveries in photobiology to those interested in lighting design, starting from a critical overview of traditional parameters since now used in lighting applications and then presenting a new theoretical approach to introduce non-visual parameters for lighting applications.

1. Introduction

Light is a basic need for humans: it is generally known that it is able to affect physical, physiological and psychological behaviors.

Since the end of the 1990s, good quality lighting was that which balanced the needs of humans, economic and environmental issues, and architectural design. Good lighting should provide for the needed level of visual performance, but it also determines spatial appearance, it provides for safety, and it contributes to well-being [1–3]. With the first discussions on the role of light on human health, the lighting quality concept has become more complex, and a change in the way of thinking has occurred [4–8]. Recent studies aimed to find a correlation between environmental lighting and human performance and health, with positive results. What is known, is that insufficient or inappropriate light exposure can disrupt standard human rhythms which may result in adverse consequences for performance, safety, health [9–14].

A shift away from the dominance of visual performance as the chief goal for a lighting installation is now occurring, and the direction is pointed out by the recent discoveries in photobiology, that are creating a link between lighting and health and well being. Visibility still remains an essential part of any lighting installation. But good quality lighting is becoming a matter of other important features, like the quantity and quality of light required for well being and health, interpersonal relationships, aesthetic tastes [15–21].

By studying the relationship between human physiology and light, research in photobiology has advanced to the point where some attempts to foresee what the lighting practice will be and need in future are ongoing [22–24]. The idea of designing and using light as a health measure is obviously fascinating, but there are questions to be answered before considering the idea of changing lighting practice [17]. The question then is if the lighting practice, and lighting practitioners and designers as well, are ready for a change. And if not, what is missing to be ready.

At the best of our knowledge, very few considerations have been developed to consider the role of these recent discoveries within the lighting field [22] and none from a theoretical point of view, for future lighting applications.

Starting from the traditional lighting design approach, this paper has the aim of introducing in the lighting application field, and especially to those interested in lighting design, the recent discoveries in photobiology, which can in future have an impact on the way lighting in buildings is designed. Illuminating engineers

* Corresponding author. Tel.: +39 081 2538778; fax: +39 081 2390364.
E-mail addresses: bellia@unina.it, laura.bellia@teletu.it (L. Bellia), fabio.bisegna@uniroma1.it (F. Bisegna), spada@unina.it (G. Spada).
[1] Tel.: +39 06 4814332; fax: +39 06 4880120.

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Nomenclature

E	Illuminance
Φ	Flux
λ	Wavelength
K	Luminous efficacy
I	Luminous Intensity
L	Luminance
ω	Solid angle
A	Area
r	Reflectance
$C(\lambda)$	Circadian efficiency function
C	Circadian efficiency
$V(\lambda)$	Photopic function
V	Luminous efficiency
a	Circadian action factor

Subscripts

min	Minimum value
m	Average value
v	Visible
e	Radiant
r	Reflected
i	Incident
λ	Spectral
VF	Visible field
n	Normaliszed
max	Maximum value
cv	circadian vs visible

and lighting designers should be aware of new possibilities, even of new parameters, methods and approaches to lighting design that could be required to consider both visual and non visual aspects of light. The traditional parameters considered by designers generally include luminous flux and illuminance to satisfy general needs and specific tasks, luminous intensity to distribute light, luminous efficiency to consider energy related problems. The paper presents a critical overview of the traditional parameters used in lighting applications and introduces a new theoretical approach to non-visual parameters.

2. Traditional lighting design approach

Lighting design for interiors, with particular reference to work places, is fundamentally based on the application of the European Standard EN 12464-1 [25], which refers exclusively to electric lighting systems. The conformity to the Standard can be useful in order to choose, size and locate lighting systems to assure the required mean maintained illuminance values on the task areas and on the immediate surroundings for the different working activities. Besides, uniform illuminance distributions and sufficient uniformity ratios as $E_{\mathrm{min}}/E_{\mathrm{m}}$ on both task areas and immediate surroundings should be achieved. Glare phenomena are dealt with by means of the Unified Glare Rating (UGR) approach, which refers only to electric sources. Usually UGR values are provided by luminaires factories in form of tables as a function of room dimensions, position of luminaries with respect to work positions and symmetric conditions.

On the other side, daylighting, which is often present in offices during the work time, is usually considered separately, and in most cases it is still evaluated by means of a "daylight factor" approach, even if new parameters, such as the "Useful Daylight Illuminances" [26], have been proposed. Besides, daylight glare ratings are not well established, the Daylight Glare Index (DGI) has not been revealed reliable while other glare indexes have been proposed in the scientific literature [27,28]. Recent researches take into account daylighting for its energy saving potential. This is also highlighted by the European Code "Energy performance of buildings – energy requirements for lighting" [29], which specifies the metering and calculation methodologies to be used for the evaluation of the amount of energy used for lighting in buildings. However, no code or recommendation refers to conditions in which daylighting and electric lighting are contemporary present.

The reflectance of surfaces is a parameter used to obtain well balanced luminance distribution and to avoid glare or veiling reflections.

According to the Code [25], the colour quality of electrical light sources is described by two parameters: the colour appearance and the Colour Rendering Index, CRI. However, the choice of the colour appearance is a matter not only of the visual performance, but also of psychology, aesthetics and implies even climatic, social and cultural factors.

As regards the CRI, it assumes a maximum value equal to 100, corresponding to the colour rendering of an incandescent lamp. Light sources with poor spectral content are characterized by a low value of CRI. In interiors where people stay for long periods, CRI should not be lower than 80. Besides, nowadays the CRI is also under discussion inside the scientific community for the limits it has shown when new light sources (i.e. LEDs) are considered.

Last, but not least, nothing is said about the spectrum of light sources. From the above mentioned considerations, it can be inferred that up to now, in the common lighting design practice for indoor work places, particular importance is devoted to the effects of lighting on the interior environment, rather than to the visual and non-visual effects on human beings. Further research is needed in order to better establish the relationships between luminance patterns in the visual field and the corresponding brightness patterns. Besides, today it is confirmed that exposure to optical radiation affects human physiology and behavior, both directly and indirectly. Some of the uncertainties about the research in this area arise from the differences in terms of spectral sensitivity between the visual and non-visual responses to optical radiation. Owing to these differences, the existing metrics, based on the photopic luminous efficiency function, are not adequate to characterize non-visual responses. Consequently new spectral weighting functions are needed and research is moving towards this direction [5,6].

3. Non-visual effects of light

Many aspects of human physiology and behavior are dominated by 24 h rhythms that have a major impact on our health and well being: sleep/wake cycles, alertness, performance patterns, core body temperature, production of hormones. Recent advances in photobiological science have provided unexpected insights into fundamental processes, starting a "cultural" revolution in both medical and technical fields that will probably lead to future changes in lighting recommendations.

Light information is captured exclusively by the eyes using photoreceptors: rods and cones detect visual information, making the visual system working. The visual system, influenced by the quantity of light available at the retina, is the system that allows the human being to evaluate the surrounding environment, by the perception of the space and the details. In 2001 [5,6], the existence of one more kind of receptor located in the human retina and named "intrinsecally photosensitive Retinal Ganglion cell" (ipRGc) containing the melanopsin, the photopigment most sensitive to short wavelength radiation (λ_{max} approximately 480 nm, blue light), has been discovered. Studies on animals and humans showed that short wavelength radiations stimulate a wide range of physiological responses associated to the neuroendocrine and neurobiological systems, like resetting the timing of the circadian pacemaker, suppressing nocturnal melatonin production, improving alertness [9,30–33]. The task of these receptors is to capture the non-visual information of light and transmit it with a purpose, to activate the circadian system. As far as we know, the circadian system is sensible to very short wavelengths, has a slow response, needs a long lighting stimulus, and has a fundamental role in regulating and adapting the human biological clock situated in the SupraChiasmatic Nucleus (SCN). In this nucleus, the cells generate rhythms close to, but not exactly, 24 h, and are synchronized to environmental time by the daily light–dark cycle: when the harmony between our biologic clock and the night-day rhythm is altered (i.e. jet-lag), our eyes give information on the new day–night rhythm, with potentially negative, although temporary, consequences on physical functions (i.e. tiredness). To confirm this consideration, it has been shown that many blind people who do not receive daily light information are unable to synchronize their internal clocks and consequently suffer from “non-24 h sleep wake disorder”. But similar entrainment disorders (daytime sleepiness, night-time insomnia, gastro-intestinal distress, irritability, mild depression, confusion) are caused by possibly common living conditions (travel, shift work, sleep disorders), or when the light quantity is artificially or naturally reduced, as during the winter period (seasonal depression). Other consequences are an increased error rate, memory disruption, and cognitive confusion. For people working shifts that rotate rapidly, these can be chronic problems.

But the biologic clock, and so far the light, has an effect not only on circadian rhythms: it has been noted that melatonin shuts down certain metabolic activities, particularly in certain cell types. These cell types include some forms of cancer, like breast cancer. The epidemiologic evidence that night workers present higher cancer rates is increasing, and breast cancer rates are higher in the industrialized world than elsewhere. Many studies show a relationship between light exposure during night time for work and risk of breast cancer [34–37].

The human circadian rhythm needs to be reset each day, in order to maintain an appropriate phase relationship with the environment. Light seems to have a fundamental role for the circadian system and the biological clock. It operates as the synchronizer of the day-and-night cycle, as well as the synchronizer of the activity and rest phases. Depending on the timing of light exposure, light can both phase advance the clock to an earlier time or phase delay it to a later time: the magnitude of the phase shift depends on the intensity, duration and number of exposures.

On the other side, light exposure at night simultaneously suppresses melatonin production, the hormone that acts as the biochemical marker of night in both diurnal and nocturnal animals. In humans, melatonin onset is closely associated with the onset of the circadian rhythm of sleepiness and, if given synthetically, induces sleepiness. These findings suggest that the alerting effects of light at night may be due to the simultaneous suppression of melatonin production. This is not the case of the alerting effects of daytime light exposure, however, as no melatonin is produced during the day. It is possible that there are multiple mechanisms by which light can improve alertness and performance, and these mechanisms are the subject of on-going research.

The role of light is of particular interest for lighting design applications. The discoveries of Brainard and Thapan, and all the studies that followed, can lead to a revolution in the lighting field. Although the community of experts and researchers has contrasting opinions, the influence of light on health, physiology, mood will be in future considered and integrated in the design practice, as well as in standards and recommendations. But since circadian photoreception sensitivity, $C(\lambda)$, peaks presumably in the interval (480, 490) nm, traditional parameters calibrated on the human photopic system ($V(\lambda)$, λ_{max} up to 555 nm) do not appropriately express the circadian stimulus, and consequently it cannot be used to understand the effects of lighting on humans.

Before the field of light and lighting will be ready for such a revolutionary change, therefore, many steps should still be done, many questions should find an answer. And, above all, a new theoretical approach for lighting is required to understand the role lighting practice can play for improving the design of the luminous environment basing on these discoveries.

4. A new role for lighting applications into the environment

The standard approach to lighting is based on the definition of a visibility function as a fundamental element for defining photometric parameters. Photometric parameters, together with information on the environment, are the basic elements for each lighting design procedure (Table 1).

If this approach could be useful during the design stage in order to choose and size lamps, luminaires, windows and so on, it cannot be considered sufficient to guarantee visual comfort and performance, neither to understand and evaluate the “non visual” role of light. Two examples could make easier to understand this consideration:

- the selection of a specific colour temperature of the source should be associated to the spectral properties of the materials inside the environment;
- discomfort glare phenomena should be dealt with, analyzing and processing the luminance pattern in the visual field [38].

But in order to better understand the relationships between the luminous environment and the visual response, in terms of comfort and performance, as well as to let the biological effects of light on humans be considered in the lighting design practice, other luminous properties should be evaluated, like the illuminances at the eye, or the spectral distribution of the radiant power that strikes on the eye.

The circadian effects of light depend on the intensity, spectrum, and timing of the light exposure, as expressed in [7] with the principles for healthy lighting:

1. The daily light dose received by people in industrialized countries might be too low.
2. Healthy light is inextricably linked to healthy darkness.
3. Light for biological action should be rich in the regions of the spectrum to which the non-visual system is most sensitive.

Table 1
Main parameters in a standard lighting design approach.

Parameter	Formulation	Unit
Luminous flux, Φ_v	$\int_{380}^{780} \frac{d\Phi_e(\lambda)}{d\lambda} K(\lambda)\, d\lambda$	[lm]
Luminous intensity, I	$\frac{d\Phi_v}{d\omega}$	[cd]
Illuminance, E	$\frac{d\Phi_v}{dA}$	[lx]
Luminance, L	$\frac{dI}{dA\ \cos\alpha}$	[cd/m^2]
Reflectance, r	$\frac{\Phi_r}{\Phi_i}$	[–]

4. The important consideration in determining light dose is the light received at the eye, both directly from the light source and reflected off surrounding surfaces.
5. The timing of light exposure influences the effects of the dose.

The previously developed considerations, together with the five principles of healthy lighting, show that the future of lighting design for interiors (at least) should be based on a change of perspective, and on a new subject. What is clear from the five principles is that if we want to consider the biological effect of light, then we should consider what happens at the eye (#4), increasing the overall quantity of light inside the environments (#1), deepening the knowledge on mesopic and scotopic conditions (#2), considering an interval of the spectrum that nowadays is not considered (#3), and last introducing the time as a fundamental element for defining control parameters (#5).

The new approach should not forget or neglect the standard design approach: all the parameters considered in the design process should still be considered. But there is the need for new ones to assess the non-visual effects of light.

Especially considering statement #3, it seems evident the need to introduce international weighting functions and associated units. Researchers could then be able to compare their results without difficulties or interpretative misunderstandings, with the aim of giving useful contributes to the definition of new lighting design criteria.

Some units have recently been proposed [23,39]. With the same aim, in the following a characterization of the potential circadian effect of light sources has been carried out, and the results of a comparison based on spectral measures weighted with circadian and photopic sensitivity functions are presented.

5. A theoretical approach to introduce new properties for the characterization of the luminous environment

Up till now, the relative sensitivity of the human circadian sensor is not perfectly known, even if a few attempts to characterize the spectral response function are available [5,6,39]. In Fig. 1a, the circadian relative sensitivity values obtained merging Brainard's [5] and Thapan's [6] data are reported [40]. In Fig. 1b, two different circadian functions obtained by means of mathematical regression from the experimental data reported in [5,6] are presented. In the same figure the circadian function proposed by Kozakov [39] is also reported. From the analysis of the available data, the maximum value of circadian sensitivity is approximately at 450 nm.

According to the requirement of considering the circadian impact of light on humans, a circadian efficiency, that is the counterpart of the visibility curve in the standard approach, should be added to the properties of the lighting sources.

Starting from the definition of the spectral radiant power:

$$\Phi_{e\lambda} = \frac{d\Phi_e(\lambda)}{d\lambda}, \quad [\mathrm{W/nm}] \tag{1}$$

and considering the radiant power emitted by the source in the visible field (VF) for the wavelengths between 360 and 800 nm:

$$\Phi_{e\mathrm{VF}} = \int_{360}^{800} \Phi_{e\lambda}\, d\lambda, \quad [\mathrm{W}] \tag{2}$$

a normalized spectral radiant power is derived:

$$\Phi_{e\lambda\mathrm{VF}n} = \frac{\Phi_{e\lambda}}{\Phi_{e\mathrm{VF}}}, \quad \left[\mathrm{nm}^{-1}\right] \tag{3}$$

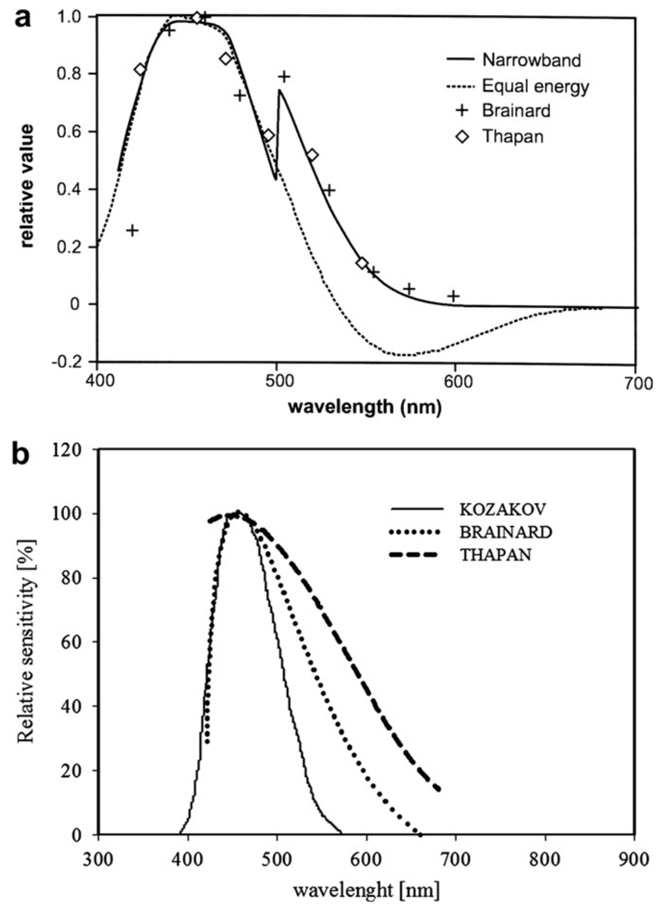

Fig. 1. (a) Relative values of $C(\lambda)$ [40]. (b) Circadian spectral sensitivity functions derived from Brainard, Thapan and Kozakov data [5,6,39].

being

$$\int_{360}^{800} \Phi_{e\lambda\mathrm{VF}n}\, d\lambda = 1, \quad [-] \tag{4}$$

Weighting the normalized spectral radiant power by the circadian sensitivity function or the circadian efficiency function $C(\lambda)$, a dimensionless circadian normalized power that can be introduced as the circadian efficiency in the visible field C_{VF} has been obtained:

$$C_{\mathrm{VF}} = \int_{360}^{800} \Phi_{e\lambda\mathrm{VF}n} C(\lambda)\, d\lambda, \quad [-] \tag{5}$$

The circadian efficiency in the visible field represents the potential circadian effect corresponding to a unitary radiant power emitted in the visible field. This definition is introduced in analogy with the definition of the luminous efficiency V given by the CIE. In fact, weighting the normalized spectral radiant power by the sensitivity photopic function $V(\lambda)$, a dimensionless photopic normalized power or luminous efficiency in the visible field V_{VF} is obtained:

$$V_{\mathrm{VF}} = \int_{360}^{800} \Phi_{e\lambda\mathrm{VF}n} V(\lambda)\, d\lambda = \frac{\int_{360}^{800} \Phi_{e\lambda} V(\lambda)\, d\lambda}{\int_{360}^{800} \Phi_{e\lambda}\, d\lambda}, \quad [-] \tag{6}$$

The expressions "circadian efficiency in the visible field" and "luminous efficiency in the visible field" have been chosen according to the CIE vocabulary, in which the luminous efficiency V is expressed as:

$$V = \frac{\int_0^{\infty} \Phi_{e\lambda} V(\lambda)\, \mathrm{d}\lambda}{\int_0^{\infty} \Phi_{e\lambda}\, \mathrm{d}\lambda} = \frac{\int_{360}^{800} \Phi_{e\lambda} V(\lambda)\, \mathrm{d}\lambda}{\int_0^{\infty} \Phi_{e\lambda}\, \mathrm{d}\lambda}, \quad [-] \tag{7}$$

The circadian and luminous efficiency values depend on the relative spectral power emitted by the source in the visible and by the spectral efficiency functions $C(\lambda)$ and $V(\lambda)$. Following this approach, a comparison among the spectral power distribution of several lighting sources to evaluate their visual and circadian potential, does not require to involve the concepts of "luminous flux", lumen, and spectral luminous efficacy function $K(\lambda) = K_{\max}V(\lambda)$. Likewise, it is not necessary to introduce a "circadian flux", which would require the concept of "circadian lumen", with a corresponding circadian efficacy.

The choice to restrict all the integrals to the visible field (360–800 nm) in Eqs. (2), (4), (5), (6), excluding the UV and IR ranges (Fig. 2), is due to the fact that in this way it is easier to compare results obtained by means of commercially available spectro-radiometers, each of which has different extensions of the operative range of wavelengths in the UV and IR fields. At the same time, this choice allows to detect and compare the spectral characteristics of light sources as regards to both visual and circadian effects.

Besides, the circadian action factor, a_{cv}, according to [39] or the "relative ratio of circadian to photopic lumens" introduced in [23], takes the form:

$$a_{cv} = \frac{C_{VF}}{V_{VF}}, \quad [-] \tag{8}$$

6. An experimental characterization of the visual and non-visual effects of several lighting sources

The proposed quantities have been evaluated for several lighting sources, considering both daylighting and electric lighting. Measures of the spectral radiance have been carried out by means of a spectro-radiometer and then weighted by means of the luminous and circadian efficiency functions, following the theoretical approach previously described. The mean features of the instrument are:

- wavelength range (360–1000) nm;
- wavelength accuracy ±0.25 nm;
- resolution 1.5 nm;
- integration range 1–4000 ms;
- field of view with radiance head 14.4°.

Measures for eight kinds of light sources (six electric lamps, sky vault and direct radiation) have been carried out. The examined lamps are: incandescent, white LED, metal halide, low pressure sodium, compact fluorescent warm appearance and compact fluorescent cool appearance.

Sky vault measures were collected at 11:00 a.m. on a day of September with a clear sky, pointing the instrument towards the North, with an elevation of 40°. In the same place, at about the same time, measures of direct radiation were collected, aiming at the solar disk.

For each lighting source, the values of spectral radiance, expressed in [μWcm^{-2} sr nm] have been normalized dividing each measure by the whole radiance in the range 360–800 nm, expressed in [μWcm^{-2} sr], obtaining the normalized spectral radiant power in nm^{-1}. Such values, taken with a step of 1 nm have then been multiplied for the corresponding $V(\lambda)$ and $C(\lambda)$ functions.

The main characteristics of each considered source as peak wavelength, dominant wavelength, Colour Rendering Index and Colour Temperature, are shown in Table 2. The diagrams of the spectral relative radiance are reported in Fig. 3a–h.

The values of the luminous and circadian efficiencies, expressed respectively by V and C, and the circadian action factor are reported in Table 3. Since it has not yet been established a standard spectral circadian efficiency, and some functions deriving from different experimental researches are available in the literature, the circadian efficiency in the visible field has been calculated for the three different curves, in accordance to the sensitivity values obtained by Brainard [5] and Thapan [6], and to the function proposed by Kozakov [39].

Basing on the definition of circadian efficiency, and on the developed measures, it seems evident that the sky vault, as well as all the sources with a dominant wavelength in the interval (480, 500) nm, present the higher values of circadian efficiency, C.

From the data reported in Table 3, it results that the choice of the sensitivity function $C(\lambda)$ leads to different values of the circadian action factor. For all the sources, the circadian efficiencies obtained by means of Thapan's data are always the greatest ones, while the results obtained by means of Kozakov' function are always the smallest ones. In Fig. 4, the percentage deviations between the data derived from Brainard and Thapan respect to those derived from Kozakov are shown. As it can be seen, such deviations depend on

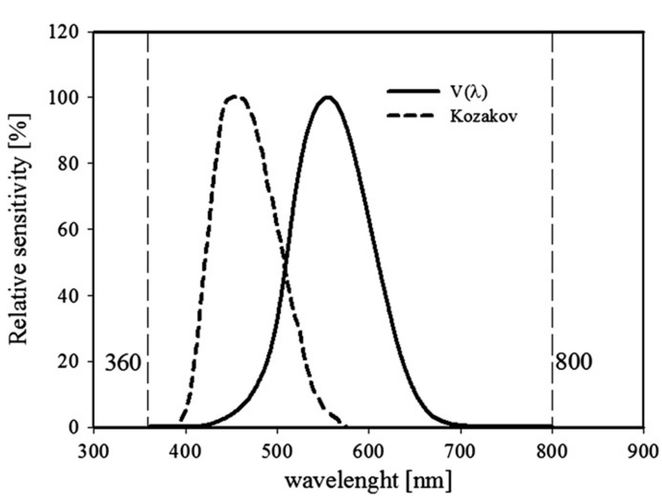

Fig. 2. Wavelength range of interest for both photopic and circadian spectral sensitivities.

Table 2
Characteristics of the sources.

Source	Peak wavelength [nm]	Dominant wavelength [nm]	CRI [–]	Colour temperature [K]
Sunlight	–	–	–	–
Sky vault	–	–	–	–
Incandescent	866	574	87	4100
White LED	446	482	73	14,000
Metal halide	507	490	76	7000
LP sodium	568	585	24	2300
Fluorescent warm	435	575	81	4300
Fluorescent cold	435	481	81	8500

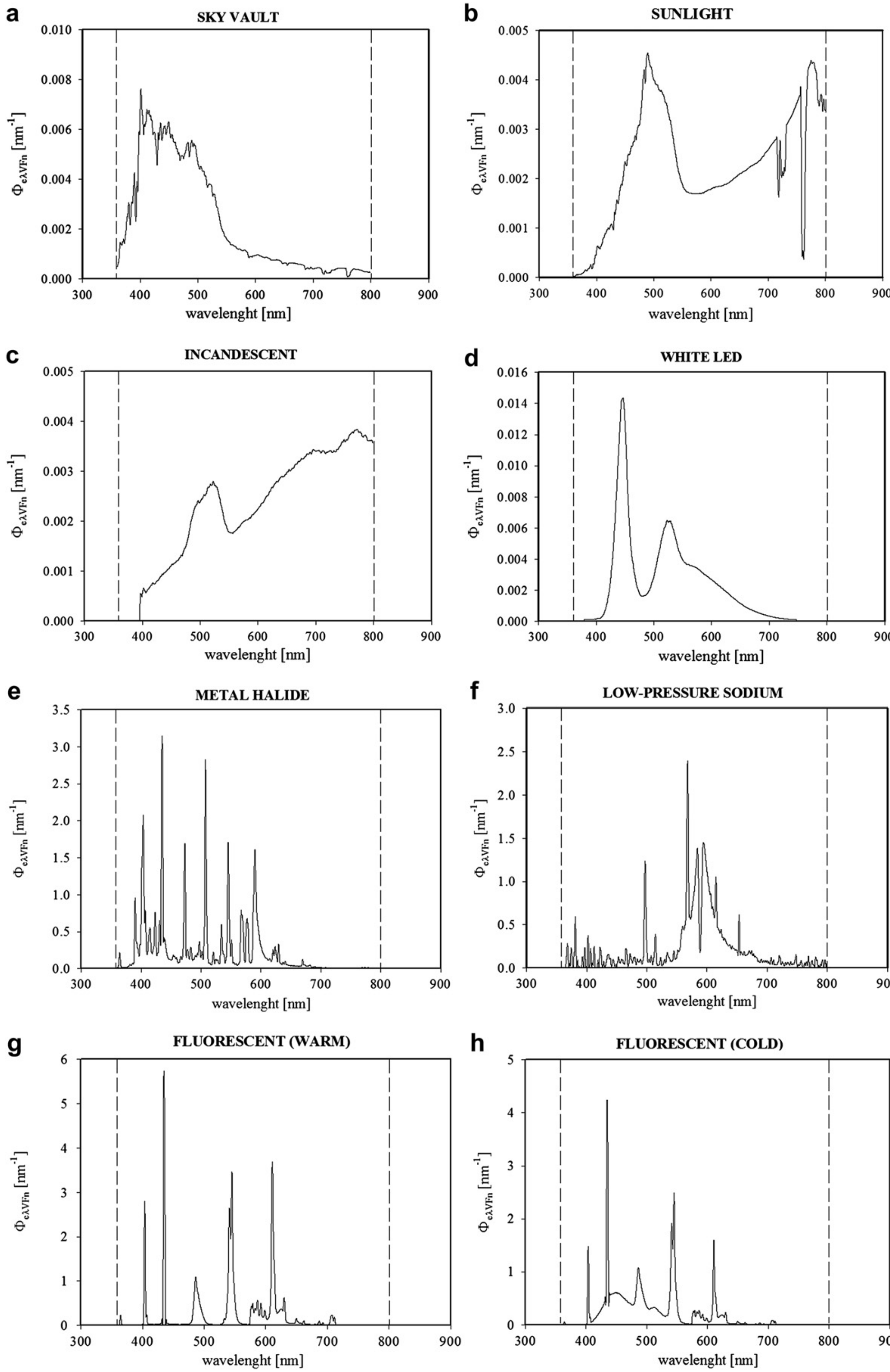

Fig. 3. (a–h) Measured spectral relative radiance of the sources considered in this study.

Table 3
Visual and circadian efficiencies for different light sources in the range 360-800 nm.

Range 360–800 nm							
Source	V_{VF}	C_{VF} (Bra)	C_{VF} (Bra)/V_{VF}	C_{VF} (Tha)	C_{VF} (Tha)/V_{VF}	C_{VF} (Koz)	C_{VF} (Koz)/V_{VF}
Sunlight	0.25	0.33	1.33	0.42	1.71	0.24	0.96
Sky vault	0.22	0.52	2.34	0.59	2.66	0.46	2.08
Incandescent	0.24	0.22	0.92	0.32	1.35	0.13	0.56
White LED	0.40	0.61	1.52	0.75	1.86	0.47	1.15
Metal halide	0.36	0.45	1.25	0.57	1.59	0.33	0.94
LP sodium	0.51	0.27	0.53	0.46	0.91	0.10	0.20
Fluorescent warm	0.47	0.43	0.93	0.61	1.30	0.26	0.56
Fluorescent cold	0.36	0.64	1.78	0.76	2.12	0.50	1.40

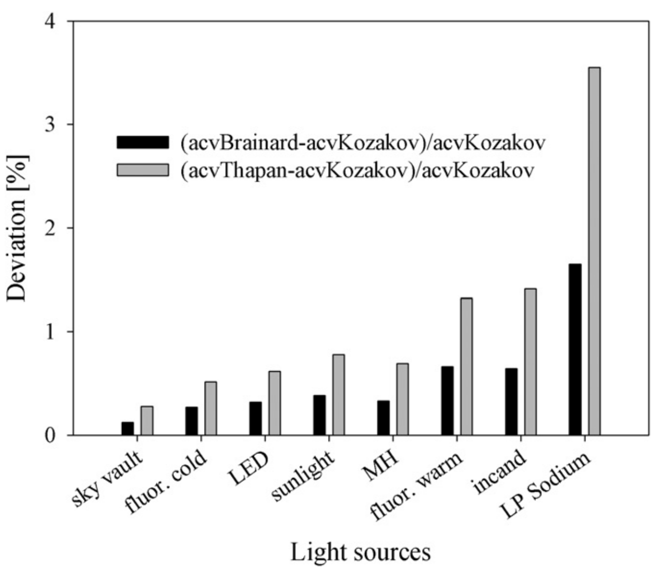

Fig. 4. Deviation between results obtained with different circadian sensitivity functions.

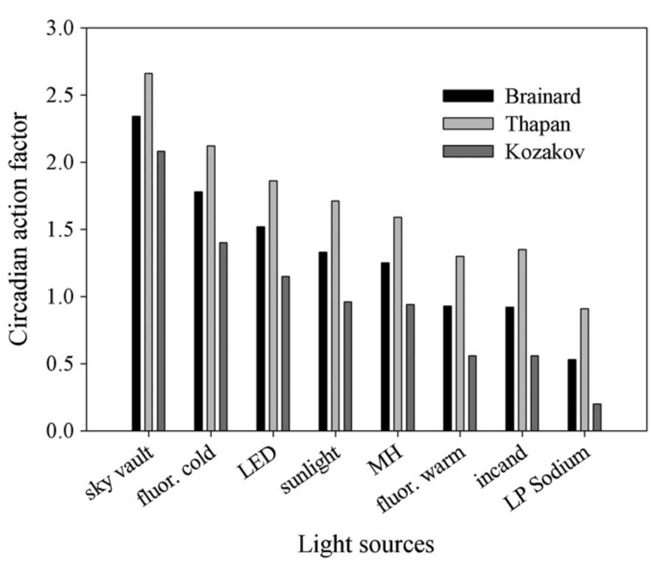

Fig. 5. Circadian action factors for several lighting sources.

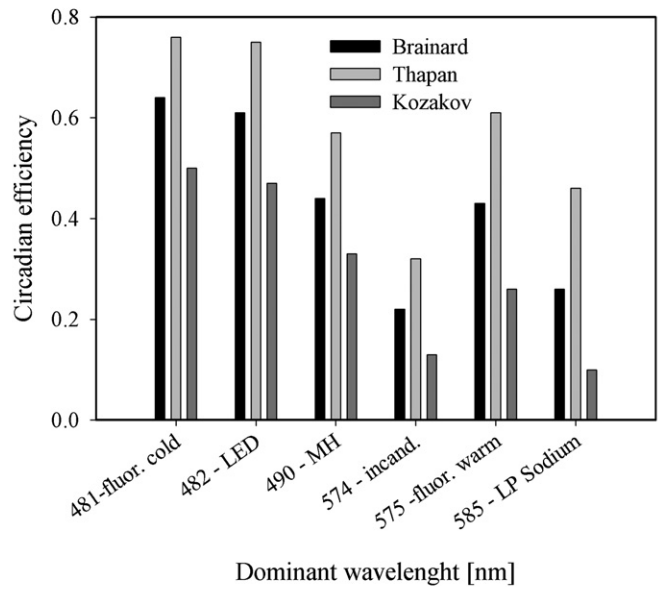

Fig. 6. Circadian efficiency in the visible field as a function of the dominant wavelength.

the light source, confirming that more research is required to define a standardized circadian sensitivity function.

In Fig. 5, the circadian action factors for the examined sources are reported. Although the data from the three circadian sensitivity functions are different, the trend of a_{cv} is the same, showing the greatest values for sky vault and fluorescent (cold), while the smallest values belong to LP sodium, incandescent, and fluorescent (warm). It can be noticed that incandescent and fluorescent (warm) present nearly the same circadian action factors.

In Fig. 6, the circadian efficiency in the visible field is reported as a function of the dominant wavelength. It can be observed that the circadian efficiency generally decreases with the increase of the dominant wavelength, with the exceptions of the fluorescent (warm) and LP sodium lighting sources. It is interesting to note that the fluorescent (warm) and incandescent lighting sources have different circadian efficiencies, while the circadian action factor is quite the same for both.

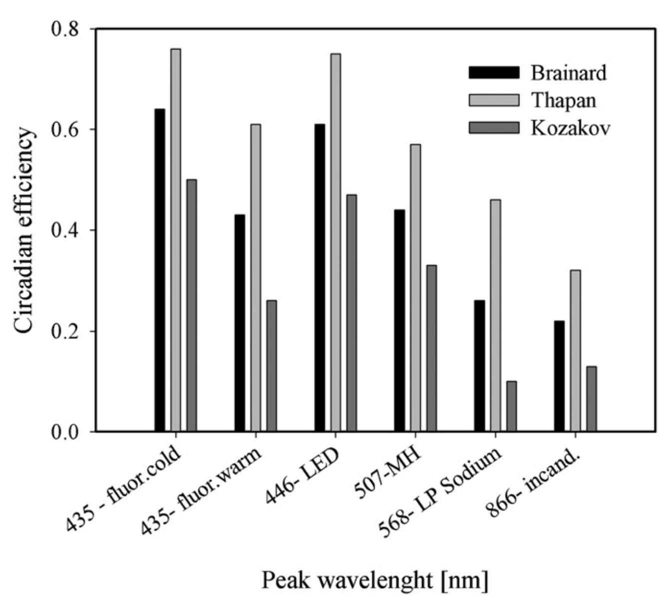

Fig. 7. Circadian efficiency in the visible field as a function of peak wavelength.

Table 4
Visual and circadian efficiencies for different light sources in the range 360–1000 nm.

Range 360–1000 nm							
Source	V_{VF}	C_{VF} (Bra)	C_{VF} (Bra)/V_{VF}	C_{VF} (Tha)	C_{VF} (Tha)/V_{VF}	C_{VF} (Koz)	C_{VF} (Koz)/V_{VF}
Sunlight	0.17	0.23	1.33	0.29	1.71	0.16	0.96
Sky vault	0.22	0.51	2.34	0.58	2.66	0.45	2.08
Incandescent	0.13	0.12	0.92	0.18	1.35	0.08	0.56
White LED	0.40	0.61	1.52	0.74	1.86	0.46	1.15
Metal halide	0.35	0.43	1.25	0.55	1.59	0.32	0.94
LP sodium	0.39	0.20	0.53	0.35	0.91	0.08	0.20
Fluorescent warm	0.47	0.43	0.93	0.61	1.30	0.26	0.56
Fluorescent cold	0.36	0.64	1.78	0.76	2.12	0.50	1.40

In Fig. 7, the circadian efficiency is expressed as a function of the peak wavelength. In this case too, the circadian efficiencies decrease increasing the wavelength, with the exception of the fluorescent (warm).

In Table 4, results obtained extending the field of measure to the range 360–1000 nm are reported. As it can be seen, the extension of the range of interest produces little variations in the evaluation of visual and circadian efficiencies, while the circadian action factor remains the same.

7. Discussion and conclusions

Recent discoveries in photobiology established a link between human physiology and light, and put in evidence the need to understand what the future of lighting practice will be if the "non-visual" effects of light will be considered in the future recommendations. New principles of healthy lighting have been already produced, and what seems for sure is that a new approach is required, an approach that should be based on a change of perspective, considering as a main element the light received at the eye. The aim of this paper is to propose a theoretical basis to this new approach, introducing from a theoretical point of view the circadian efficiency, and the circadian action factor as well.

The circadian effect is here presented only in terms of efficiency and not in terms of efficacy. While the relationship between watts and photopic lumens has in fact a historical origin deriving from the need to be in accordance to the fundamental unit of the International System, the candela, this is not necessary for the circadian quantities, if we accept to use normalized radiances.

The proposed quantities are normalized respect to the radiant power in the visible wavelength.

Basing on this theoretical approach, experimental measures on several lighting sources have been developed, and circadian efficiencies and circadian action factors have been calculated, using all the hypotheses of circadian efficiency functions available in literature (Fig. 1b). In particular, the maximum value of all the three sensitivity functions is at about 450 nm. For longer wavelengths, the function proposed by Kozakov decreases more rapidly, while the function obtained by Thapan's data decreases less rapidly. This is why the circadian action factor presents always the smallest values with Kozakov's data, while the greatest values are always obtained with Thapan's data (Fig. 5). This consideration is verified also for the circadian efficiency results (Figs. 6, 7).

Notwithstanding that the lack of a standard circadian function highlights the need for further researches, the percentage deviations among the results, as regards the action factor, are very small, as it can be inferred from Fig. 4, where they do not exceed a value up to 4%. The maximum deviation corresponds to the LP sodium source, because such source is characterized by a spectral power distribution poor of radiations in the whole visible field, with the exception of a few peaks at wavelengths greater than 500 nm, where the circadian sensitivity functions differ noticeably. For all the other sources characterized by spectral powers spread more uniformly in the entire visible field and consequently characterized by a higher CRI, the deviations always assume values below 2%.

For each source the relationship between circadian efficiency and circadian action factor depends on the spectral power distribution.

Although the circadian efficiency trend generally shows a decrease with the increasing of both the corresponding peak wavelength and the dominant wavelength, this is not always true, as it has been noted for the warm fluorescent lighting source, owing to its spectral distribution.

Diagrams reported in Figs. 6, 7 reveal the attempt to correlate the circadian efficiency to other parameters characterizing the lighting sources, like the dominant wavelength or the peak wavelength. This attempt clearly shows the need and the difficulties as well in finding affordable relationships between these parameters. In general, the circadian efficiency decreases on increasing the dominant wavelength, or increasing the colour temperature, with some exceptions. For this reason further investigation is needed, taking into account the spectral power distribution of many more sources. As far as the action factor is concerned, this parameter is a candidate to represent a useful link between circadian and visual measures. The sources with the highest values of action factor are those which are more efficient from the circadian point of view, under the same conditions of light emission, that is same luminous flux. From the data reported in Tables 3 or 4 and from Fig. 5, it can be inferred that the sources which have a greater circadian effect respect to the photopic effect are sky vault, fluorescent cold and LED.

More investigation is needed to understand how much circadian light is needed at the eye in the different hours of the day. In the future, the results from these studies could be used and could lead to a link between illuminance values on task areas and illuminances at the eye, that is between current standards and ongoing research.

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