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Spectral characterization of different indoor lighting systems and electronic devices with backlit screens and analysis of their potential to suppress melatonin levels in humans

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Article

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Abstract

Many humans carry out most of their work and leisure activities indoors under the artificial light emitted by luminaires as well as using light-emitting backlight screens as in smartphones, laptops, televisions, etc. The aim of this study is to characterise the spectral irradiance of several artificial light sources (both led and fluorescent) that may appears in the normal daily routine of professional or students in workplaces inside buildings and then calculate the effective biological irradiance for melatonin suppression and the time required to suppress melatonin significantly in humans under the effect of these two groups of sources of artificial lighting.

The spectral characterization of electronic devices with white light background at maximum brightness and luminaires in indoor lighting installation has been done by using a laboratory and portable spectroradiometers respectively. The irradiance measurements were weighted by the melatonin generation action spectrum and the time under each light source were calculated to obtain a minimum dose of 50% melatonin suppression. The weight of the blue light radiation compared to the total amount emitted of the different commercial lamp sources analysed varies between 20% and 32% depending on the type of lighting technology and its correlated colour temperature. This indicator along with the total energy radiated necessary to achieve the required illuminance values by regulatory standards to perform indoor working activities generate exposure times required to achieve a 50% suppression of melatonin varied, between 1 hour and 20 minutes in general classrooms (600 lx) and up to 10 hours in common areas (200 lx). On the other hand, electronic devices screens showed a 50% melatonin suppression capacity between 10 minutes for laptop screen and 15–30 minutes for smartphones. These times indicates that the light exposure suffered in regular working and educational buildings have a significant potential negative effect on the circadian rhythm of persons inside them due to the melatonin reduction that their light emitting equipment generates.

INTRODUCTION

Since the invention of the incandescent light bulb in 1879, humans have been changing the way they live, interact and work [1]. In less than 150 years, we have moved from the open air to the interior of offices, industries, hospitals, shopping centres and educational institutions installed with electric artificial lighting equipment [2]. In addition to general purpose luminaires, the 1930s started with the generalization of television systems [3] and, from this starting point, a process lead by the electronics that is digitalizing our world and placing light emitting screens almost everywhere [4]. More recently, in 1995, PC White LED lighting technology was introduced [5]; and nowadays, they are the unequivocal emitters within indoor and outdoor luminaires as well as in smartphones, tablets and laptops [6]. This reality means that a significant number of people spend most of their day exposed to artificial light and thus, to the Phosphor-converted white light-emitting diodes (PC-WLEDs) visible spectrum radiation of electronic screens and lighting equipment [7].

This exposure to artificial light sources produces various biological effects in humans, both positive and negative. Among the positive effects, this is the ability to see in spaces with little natural light available; and among the negative effects, this is the disruption of sleep patterns due to a deregulation of light-dark cycles [8], since artificial light allows us to work more flexibly at different times extending into the late afternoon or before the sunrise [9]. Artificial lighting enables jobs that involve night shifts in the industry or healthcare staff on duty in hospitals; and electronic screens provides us with a wide range of leisure activities via internet connection, such as video streaming or social media, which is often used excessively [10].

The circadian rhythm of humans is responsible for regulating the sleep and wakefulness status [11]. Its main synchronizer is the cycle of light and darkness, and the biological structure that acts as the central pacemaker is the suprachiasmatic nucleus (SCN), located in the anterior part of the hypothalamus behind the optic chiasm on both sides of the third ventricle, which regulates the synthesis and secretion of melatonin [12, 13]. This is an indole hormone synthesized in the pineal gland and other extrapineal organs such as the retina, bone marrow, serotonin-producing cells in the gastrointestinal tract, skin, cerebellum and immune system [14]. Starting with tryptophan, a process of hydroxylation and decarboxylation takes place,

converting it into serotonin, mainly in the gastrointestinal tract and the brain [15]. Serotonin, through the action of the enzyme N-acetyltransferase, is converted into N-acetyltryptophan, which subsequently undergoes a process of methylation by the enzyme hydroxylindole-O-methyltransferase to form melatonin [16].

Although there are several neural pathways that control the circadian rhythm, the most important, and the one related in this work, is regulated through the retinoid-hypothalamic tract [16]. Light is captured by a subpopulation of retinal ganglion cells that possess a pigment called melanopsin and are not involved in image formation. These cells send information about the perceived light intensity and wavelength to the SCN which, respectively, sends a signal to the paraventricular nucleus of the hypothalamus [17]. These signals then move through efferent fibers of the sympathetic nervous system to the spinal cord, passing through the superior cervical ganglion, which, via sympathetic nerve fibers, finally delivers the signal to the pineal gland [13]. Other functions of melatonin in humans have been described, apart from its role in regulating the circadian rhythm, such as the control of temperature, sexual development and the reproductive cycle, as well as its antioxidant action [18].

High plasma levels of melatonin signal the body that it is nighttime and promote the organization of homeostatic rhythms related to sleep. On the other hand, low plasma levels indicate to the organs that it is daytime, organising homeostatic rhythms related to wakefulness [19]. In this way, the presence of light captured by the ganglion cells of the retina informs the SCN that it is daytime and melatonin production is inhibited; while the absence of light capture during dusk is interpreted by the central pacemaker as a signal that it is nighttime and melatonin production is induced [20]. In detail, light suppresses melatonin through a specialized non-visual phototransduction pathway beginning in intrinsically photosensitive retinal ganglion cells (ipRGCs), which contain the photopigment melanopsin and exhibit peak sensitivity to blue light around 480 nm. When exposed to light at night, ipRGCs depolarize and send a signal to the suprachiasmatic nucleus (SCN), the brain's master circadian clock. Activation of the SCN triggers intracellular cascades involving NMDA receptors, calcium influx, and CREB phosphorylation, shifting clock-gene expression to a "daytime" state [21, 22].

The alteration of the circadian rhythm that has negative repercussions on rest, attention and performance is called chrono-disruption [23]. It has been reported that, in healthy individuals, melatonin production begins at dusk, between 8 and 10 p.m., reaching its peak between midnight and 2–3 a.m., regardless of the sleep phase [12, 13]. Exposure to artificial light in the evening caused a delay in the circadian cycle, delaying melatonin production and worsening night-time rest [24].

The degree of melatonin suppression depends on the specific wavelength of each amount of irradiation emitted by a light source, whether it comes from the sun or an artificial light source, and the radiation dose received by the subject, which is determined by the duration of exposure.

Brainard et al. [25] described the action spectrum of the melatonin suppression at each wavelength in humans. Results show how melatonin suppression corresponds mainly to the blue light region of the visible spectrum (380–500 nm), reaching its peak at 464 nm. On the contrary, melatonin suppression was imperceptible from 550 nm onwards. Based on this study, it is possible to estimate how harmful for the circadian rhythm is the light exposure of a specific spectrum and radiation intensity – or absolute physical irradiance- weighing these values by the action spectrum curve indicated to obtain an effective biological irradiance for melatonin suppression. In a previous work [26], it was described the amount of blue radiation found under the sun throughout the day was around 26% of the total visible spectrum. Regular LED lamps offer a range of correlated colour temperature (CCT) with percentage of blue light that goes from 3000K (11.99%) to 6000K (30.84%). In the case of LED screens such as laptops, smart phones or tablets, the percentage of blue light was 32.3% as the average value of the 13 devices analyzed (ranging from 19.1% to a maximum of 39.82%). The M/P ratio (melanopic lx/photopic lx) is an indicator defined as the ratio between the amount of light energy that promotes alertness (melatonin suppression) and the amount of light energy that produces the perception of light quantity (allows colours to be seen) [27]. Thus, a warm LED light source (2500–3500K) would have a lower M/P and is more appropriate for relaxation and the moments before sleep, while a cool light source (more than 5500K) would have a higher M/P ratio and is more suitable for increasing alertness and productivity at work.

Irradiance levels also play a fundamental role in the variation of melatonin levels. At a wavelength of 460 nm (close to the peak wavelength value for melatonin suppression), irradiance levels of 2.3 μW/cm^2 or lower do not significantly suppress melatonin levels [25]. However, when irradiance is increased to levels of 3.1 μW/ cm^2 or above, significant melatonin suppression is achieved. A similar behavior has been measured using other wavelengths in the blue region of the spectrum [21]. They analyzed the effect in melatonin suppression with several wavelengths (424 nm, 456 nm, 472 nm, 496 nm, 520 nm & 548 nm) emitting different irradiance values.

The combination of spectrum, irradiance and time exposure configures a dose of visible light radiation effective for melatonin suppression which is a significant indicator for the characterization of light exposure limits for circadian cycle disruption. West et al. [28], determined that using a blue LED light source (with an effective suppressed melatonin irradiance of 92%) at an irradiance of 24.5 μW/cm^2 for 90 min achieved a 50% suppression of melatonin levels in a group of volunteers. The biological effective dose under the exposure time in this experiment is 122.3 mJ/cm^2 and this value is considered the Minimum Biological Dose for 50% melatonin suppression (MMSD50). This experimental result allows to estimate the time of exposure necessary to reach a significant circadian cycle disruption calculating the effective or biological radiation dose that suppressed melatonin levels considering the spectral characteristics of the illumination source and the irradiance of the source using this previous value as limit of reference.

It is common for urban people that their natural sun radiation exposure is complemented or replaced by large exposure to different types of artificial lighting sources. In this sense, the design of lighting installations for homes, afternoon/evening working places, leisure venues, etc are aimed to optimize lumino-technical parameters to achieve optimal visual efficiency, without taking into account, in most cases, aspects related to circadian rhythm alterations. As example, higher education teaching takes place from morning until late afternoon/evening in university buildings, and their lighting systems commonly cannot regulate its intensity or CCT and, consequently, change the amount of blue light radiation emitted in the different moments of the day. Adding the exposure to different electronic screens, that also emit blue light radiation without time regulation, commonly used in this type of buildings elements, melatonin rhythms can potentially be significantly altered.

The aim of this study is to conduct a quantitative analysis with several LED indoor lighting systems and screen electronic devices, in order to measure their emission irradiance discriminated by wavelengths and address the effective irradiance in terms of melatonin suppression weighed using the action spectrum of the melatonin suppression in humans described by Brainard et al. [25]. With that information, the results of West et al. [28] are used to calculate the exposition time necessary to reach, using the previous equipment under real light exposition in several indoor working places with different illuminance requirements, the doses of light radiation required to produce a 50% melatonin suppression that the human body should be generating in the evenings beyond 8:00 pm and, thus, a significative disruption of the circadian cycle.

RESULTS

The values obtained in the present study for the different lighting systems and electronic devices analyzed are reported in Tables 3 and 4, together with their corresponding spectral distributions (Figures 2–4) and the estimated exposure times required to reach the Minimum Melatonin Suppression Dose ($MMSD_{50}$).

For indoor lighting installations, the spectral irradiance distributions of the analyzed light sources are presented in Figure 2A. These distributions show differences in spectral power across the visible range (380–780 nm), with variations in the relative contribution of the blue (400–500 nm), green (500–600 nm), and red (600–700 nm) bands depending on the lighting technology and correlated color temperature (CCT) of the luminaires installed in each space. Following the application of the biological weighting function for melatonin suppression, the effective spectral irradiance is shown in Figure 2B, highlighting the contribution of wavelengths within the 400–570 nm range.

The mean values of visible irradiance, spectral band distribution, and effective biological irradiance for the different indoor environments (classrooms, common areas, laboratories, library, and offices) are summarized in Table 3. Based on these

values, the exposure times required to reach $MMSD_{50}$ were calculated, yielding estimated times that vary according to the irradiance level and spectral characteristics of each lighting condition. Measurements performed using a spatial grid approach enabled the determination of representative average values describing the exposure conditions in each type of indoor environment.

For electronic light-emitting devices, the spectral irradiance distributions of smartphones, tablets, laptops, and the television are shown in Figure 3 (panels A–C). These results exhibit a characteristic spectral profile, with a dominant peak in the short-wavelength region and additional contributions across the visible spectrum. The biologically weighted spectral irradiance is presented in Figure 4 (panels A–C), representing the effective distribution for melatonin suppression within the 400–570 nm range.

The mean values of visible irradiance, spectral band distribution, and effective biological irradiance for each device are reported in Table 4. From these values, the exposure times required to reach $MMSD_{50}$ under standardized viewing conditions were estimated. The estimated exposure times vary across device types and measurement distances, reflecting differences in spectral emission and irradiance levels.

Irradiance values were expressed as means and standard deviation, which was less than 2% in all cases. In the case of electronic devices (smartphones, laptops, tablets and televisions), 5 measurements were made for each device. The mean values of the different lighting systems were compared using ANOVA to analyse the significance of the means with a significance level of $p<0.05$. The Excel spreadsheet statistics add-in was used to determine these comparisons

DISCUSSION

Sleep and rest disturbances associated with circadian rhythm disruption represent an increasing concern affecting the general population, as exposure to artificial blue light sources is widespread across social, educational, and occupational environments. This exposure has intensified in recent decades with the expansion of LED-based lighting systems, driven by their energy efficiency, durability, and lighting performance, although similar conditions are also present in environments dominated by fluorescent lighting. Common behavioral patterns, such as the use of electronic devices before sleep, have been associated with reduced sleep quality, increased sleep onset latency, and alterations in sleep architecture [31], as well as delayed melatonin secretion [24, 32]. In academic settings, prolonged exposure to smartphones, tablets, laptops, and televisions constitutes an additional factor that may contribute to circadian disruption [33, 34].

A key aspect addressed in this study is the estimation of the exposure time required to induce relevant levels of melatonin suppression. Previous studies have reported different temporal thresholds: West et al. [26] observed that 90 minutes of exposure to blue LED light could result in approximately 50% melatonin suppression, while Tähkämö et al. [32] reported significant effects after approximately 2 hours of LED exposure. Similarly, Nagare et al. [35] reported a suppression of 21% ±4% after one hour of exposure to white light and 41% ±4% after three hours. In the present study, the estimated exposure times, derived from effective biological irradiance values, fall within comparable ranges to those reported for indoor environments.

The analysis of different indoor spaces indicates that the estimated time required to reach 50% melatonin suppression varies as a function of lighting characteristics. Environments with lower irradiance levels, such as offices or low-intensity spaces, are associated with longer estimated exposure times, likely reflecting reduced effective irradiance. Although similar correlated color temperatures are observed across several spaces, variations in irradiance levels and spectral composition appear to influence the biological response [25]. In contrast, spaces characterized by higher correlated color temperatures tend to exhibit a greater proportion of short-wavelength content, which may be associated with shorter estimated exposure times [27].

Sensitivity to blue light exposure is also known to vary across population groups. Previous studies have shown that younger individuals exhibit a stronger biological response under comparable lighting conditions [36], suggesting that university

populations may be particularly sensitive to these effects. In this context, standardized viewing distances for electronic devices, as reported in experimental studies [37], provide a relevant framework for approximating real exposure conditions and were considered in the present estimations.

For electronic devices, previous research has demonstrated a progressive increase in melatonin suppression with exposure duration [36, 37]. In this study, the estimated exposure times, derived under controlled measurement conditions, suggest that these devices may reach relevant levels of melatonin suppression over shorter intervals compared to ambient lighting systems. However, these findings should be interpreted cautiously, as they are dependent on specific experimental conditions, including maximum brightness settings, uniform white display, and standardized viewing distances.

An additional aspect to consider is the potential combined effect of ambient lighting and electronic device exposure. Previous studies have indicated that simultaneous exposure to multiple light sources may enhance melatonin suppression [38–40]. This suggests that, under real-world conditions, where environmental lighting and device usage coexist, the overall circadian impact may exceed that estimated for each source independently. Nevertheless, further research is required to quantify and characterize this potential interaction.

Overall, the findings of this study, based on estimates derived from effective biological irradiance, indicate that the time required to reach relevant levels of melatonin suppression may vary substantially depending on the lighting environment and the type of light-emitting device. In particular, devices used at close viewing distances may be associated with shorter estimated exposure times compared to ambient lighting conditions. These observations underscore the importance of considering both spectral properties and usage conditions when evaluating the impact of artificial light on the human circadian system

MATERIAL AND METHOD

A cross-sectional observational study with environmental analysis was conducted to achieve the objectives proposed. Different indoor spaces and lighting installations and electronic light emitting equipment are analyzed and evaluated quantitatively regarding the alteration of the circadian cycle. The time to achieve the Minimum Biological Dose for 50% melatonin suppression (MMSD50) was calculated for the different activities and situations to be assessed.

First, absolute irradiance of the lighting system as well of the screen of different electronic devices was measured. Lighting installation was measured using a handheld CCD portable spectroradiometer Uprtek Nanotech MK350S(Uprtek, Zhunan, Taiwan). Each indoor common space (classrooms of faculty, laboratories, offices) was divided into 1.5 m x 1.5 m grids, and a tripod was used to take the measurements at a height of 1.20 m, which corresponded approximately to eye level when seated and measurements were taken with the sensor at a position perpendicular to the human eye. Previoustly, the CCD spectroradiomenter was calibrated with respect to a Macam SR-9910-V7 double monochromator spectroradiometer (by Irradian Co., UK) against 5 different lamps: 3 LED strips of 4000K, 6000K and 10,000K, 1 white fluorescent lamp (22 W) and 1 incandescent bulb (60 W) (see Table 1). Calibration were performed in terms of spectral irradiance (mW/cm2/nm). Macam spectroradiometer was previously calibrated against a certified calibration lamp at the Spanish Institute of Aerospace Technology (Huelva, Spain).

The spectral irradiance emitted by the screen of different electronic devices was measured by the Macam double monochromator spectroradiometer. Devices are turned on in a dark room for 10 minutes to reach stable radiation emission and spectroradiometer sensor was situated parallel to the device screen. Each device was set up to emit white light at maximum brightness. The sensor of the spectrometer sensor placed at 20 cm for smartphone and tablets (average distance of human interaction) and 60 cm for laptop screens and 230 cm for the smart TV following the European standard for safe exposure [29,30] (see Table 2).

An average of 40-50 measurements were taken in each classroom and for each backlit Led device, five measurements were taken from the predefined distances to calculate spectral irradiance under normal exposure conditions. Irradiance values

were expressed as means and standard deviation, which was less than 2% in all cases.

Absolute spectral irradiance values for illumination systems and screen providing electronic devices were weighted at each wavelength by their relative effective potential value obtained from the action spectrum of melatonin suppression as described by Brainard et al. [25]. (See Figure 1). So, the absolute physical irradiance of each illumination system and device could be relativized in terms of effective biological irradiance for melatonin suppression.

Following the effective biological spectral irradiance calculations, it was necessary to calculate the time under each light source to reach the 50% of melatonin suppression. For that, we were based on the study by [26] where the authors calculated the dose for 50% melatonin suppression by means of exposure different human volunteers under a blue LED device. Volunteers were exposed for 90 min under different irradiances of the lamp in order to be exposed to an increased dose of blue radiation. Physical irradiance of the lamps was expressed in terms of effective biological irradiance as previously described. So, the biological dose was calculated for each condition. Authors found that, in terms of physical irradiance, the minimal dose for 50% melatonin suppression was obtained. The ratio between the effective and absolute irradiance of the source (blue light led device) was calculated, and it was found that 92% of the blue LED effectively suppressed melatonin. Thus, an irradiance value of 24.5 mW/cm2 (in terms of physical irradiance) for 90 minutes achieved 50% suppression of melatonin levels. The biological effective dose under the exposure time was finally 122.3 mJ/cm2. This value was considered the Minimum Biological Dose for 50% melatonin suppression (MMSD50).

Finally, the amount of time a person had to be exposed to classroom lighting, a mobile device, computer or tablet in order to suppress 50% of their melatonin was calculated. This calculation was performed by dividing 122.3 mJ/cm2 by the effective irradiance of the source in mW/cm2, obtaining the time in seconds, which was then converted into minutes and hours.

Statistical analysis

The spectral measurement values for the different lighting systems were expressed in terms of mean standard deviation from a total of 50 measurements taken in each room. In the case of electronic devices (mobile phones, screens, tablets and televisions), 5 measurements were made for each device. The mean values of the different lighting systems were compared using ANOVA one way-test to analyse the significance of the means with a significance level of $p<0.05$. The Excel spreadsheet statistics add-in was used to determine these comparisons.

Declarations

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Authorship contribution

RGS and JA were responsible for the inception of this study and model creation. SP and RGR were responsible for data acquisition, execution of the validation and analysis. SP was responsible of writing the first version of the manuscript. ENDG, MVDG and RGS contributed to the interpretation of results and provided revisions to the final manuscript. All authors read and approved the final manuscript.

Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Competing interests

The author(s) declare no competing interests.

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Tables

Table 1. Mean average illuminance (Eavg) and correlated colour temperature (CCT) measured in the analysed indoor environments, classified according to area type and lighting technology.

ID	Category	Light Technology	Eavg [lx]	CCT [K]
1	Office	LED	222	3000
2	Laboratories	LED	209	3500
3	Office	LED	365	3500
4	Office	LED	760	3800
5	Office	LED	575	3800
6	Common Areas	LED	242	4000
7	Classroom	LED	370	4000
8	Classroom	LED	645	4000
9	Classroom	LED	600	4000
10	Laboratories	LED	1033	5000
11	Laboratories	LED	1256	5700
12	Office	LED	607	5700
13	Library	Fluorescent	550	4000
14	Common Areas	Fluorescent	218	5400
15	Classroom	Fluorescent	480	6000
16	Classroom	Fluorescent	653	6000
17	Classroom	Fluorescent	848	6000

Table 2. Electronic display devices included in the study, classified according to device category, model and lighting technology.

ID	Category	Model
1	Smartphones	Xiaomi Mi Max 3
2		BQ Aquaris X
3		Huawei P Smart
4		Motorola C Plus
5		iPhone 7
6	Tablets	BQ Kepler 2
7		Lenovo M10
8		Samsung Galaxy Tab A
9	Laptops	Huawei MateBook D
10		ASUS GA401IU-HE002
11		BenQ Z706PQ
12		HP 1943HR
13	Smart TV	LG 75UM7050

Table 3. Spectral distribution of visible irradiance, physical and biologically effective irradiance for melatonin suppression, and estimated $MMSD_{50}$ exposure time measured in the analysed indoor environments, classified according to area type.

		Visible irradiance					
ID	**Category**	**Visible irradiance (380-780 nm) [mW/cm²]**	**% Blue light (400-500nm)**	**% Green light (500-600nm)**	**% Red light (600-710nm)**	**Biological Irradiance (400-570 nm) [mW/cm²]**	***Time to $MMSD_{50}$ [min & s]***
1	Office	0.017	19.90	46.85	32.75	0.004	540 min 45 s
2	Laboratories	0.032	17.14	50.69	31.39	0.006	327 min 33 s
3	Office	0.056	14.64	50.97	33.76	0.009	220 min 41 s
4	Office	0.013	19.90	46.85	32.75	0.003	695 min 2 s
5	Office	0.024	20.05	46.57	32.78	0.006	370 min 20 s
6	Common Areas	0.040	20.84	46.46	32.24	0.009	218 min 47 s
7	Classroom	0.063	21.32	45.61	32.03	0.015	137 min 31 s
8	Classroom	0.110	21.29	45.10	33.10	0.026	78 min 57 s
9	Classroom	0.097	19.79	47.46	32.39	0.022	93 min 56 s
10	Laboratories	0.157	26.22	46.75	26.40	0.045	45 min 20 s
11	Laboratories	0.108	29.80	46.80	22.51	0.035	58 min 23 s
12	Office	0.052	29.80	46.80	22.51	0.017	120 min 43 s
13	Library	0.064	22.50	42.32	34.40	0.014	150 min 48 s
14	Common Areas	0.028	31.42	43.51	24.33	0.008	241 min 41 s
15	Classroom	0.074	33.94	41.85	23.46	0.023	88 min 38 s
16	Classroom	0.081	33.56	42.82	23.05	0.026	78 min 53 s
17	Classroom	0.107	31.24	42.44	25.53	0.031	64 min 44 s

Table 4. % of the different visible spectral bands corresponding to blue (400-500nm), green (500-600nm) and red (600-700nm) as well as the p*hysical, the biological irradiance effective for melatonin suppression in humans (mW/cm²) and the estimated $MMSD_{50}$ time (minutes: seconds) were measured for different electronic devices under standardized use conditions. Devices included monitors, smartphones, tablets, and smartTV.*

			Visible irradiance					
ID	**Category**	**Model**	**Visible irradiance (380-780 nm) [mW/cm²]**	***% Blue light (400-500nm)***	***% Green light (500-600nm)***	***% Red light (600-710nm)***	**Biological irradiance (400-570 nm) [mW/cm²]**	***Time to $MMSD_{50}$ [min & s]***
1	Smartphones	Xiaomi Mi Max 3	0.287	19.14	39.62	37.23	0.061	33 min 18 s
2		BQ Aquaris X	0.22	31.11	37.5	27.81	0.073	27 min 56 s
3		Huawei P Smart	0.188	30.02	36.94	26.74	0.059	34 min 47 s
4		Motorola C Plus	0.213	36.79	46.98	16.3	0.08	25 min 17 s
5		iPhone 7	0.100	39.97	52.81	8.69	0.044	46 min 41 s
6	Tablets	BQ Kepler 2	0.332	32.26	39.64	25.85	0.116	17 min 35 s
7		Lenovo M10	0.509	34.48	49.17	16.03	0.187	10 min 54 s
8		Samsung Galaxy Tab A	0.151	35.53	39.47	21.38	0.056	36 min 25 s
9	Laptops	Huawei MateBook D	0.199	28.47	42.68	22.11	0.058	35 min 11 s
10		ASUS GA401IU-HE002	0.103	33.29	47.36	16.7	0.037	55 min 37 s
11		BenQ Z706PQ	0.616	29.8	41.93	28.38	0.193	10 min 34 s
12		HP 1943HR	0.291	33.3	43.86	23.17	0.1	20 min 13 s
13	Smart TV	LG 75UM7050	0.14	27.77	33.29	30.17	0.036	56 min 00 s

Figures

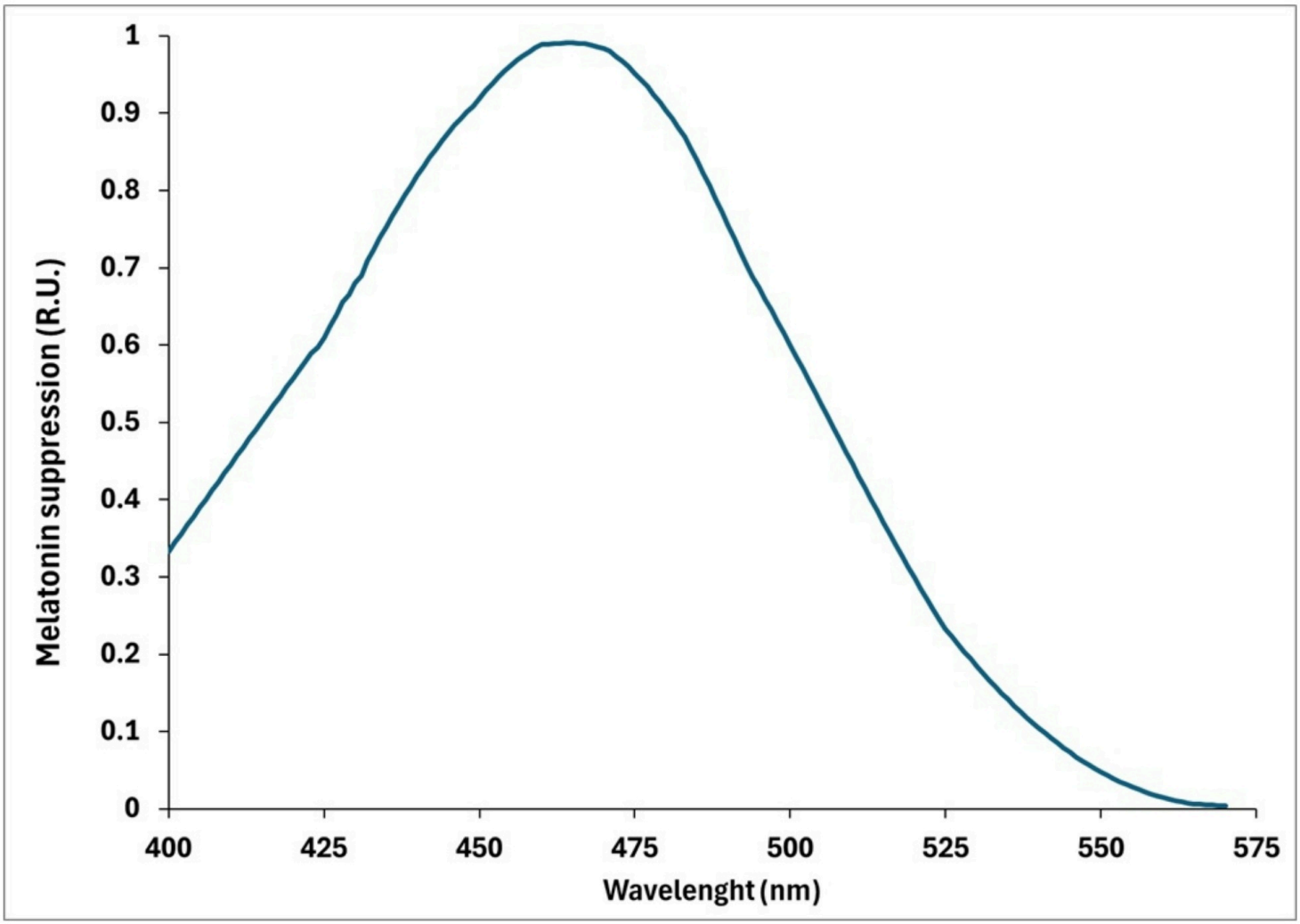


Figure 1

Action spectrum curve in terms of wavelength dependence of the human melatonin suppression (in relative units). Data were obtained from Brainard et al. [25].

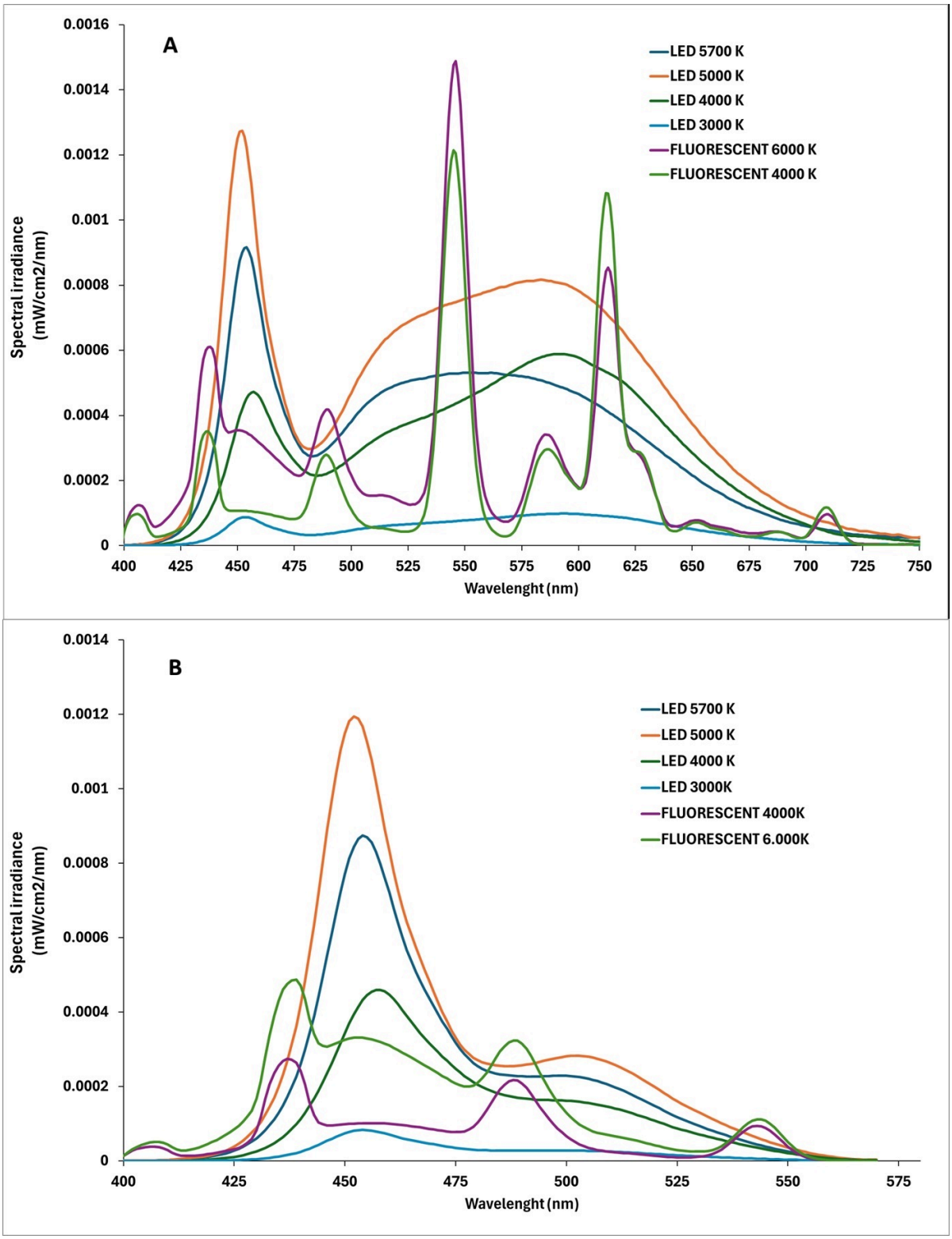


Figure 2

Spectral distribution of the light sources analyzed in indoor environments, expressed as: A) physical spectral irradiances and B) biologically weighted irradiances for human melatonin suppression.

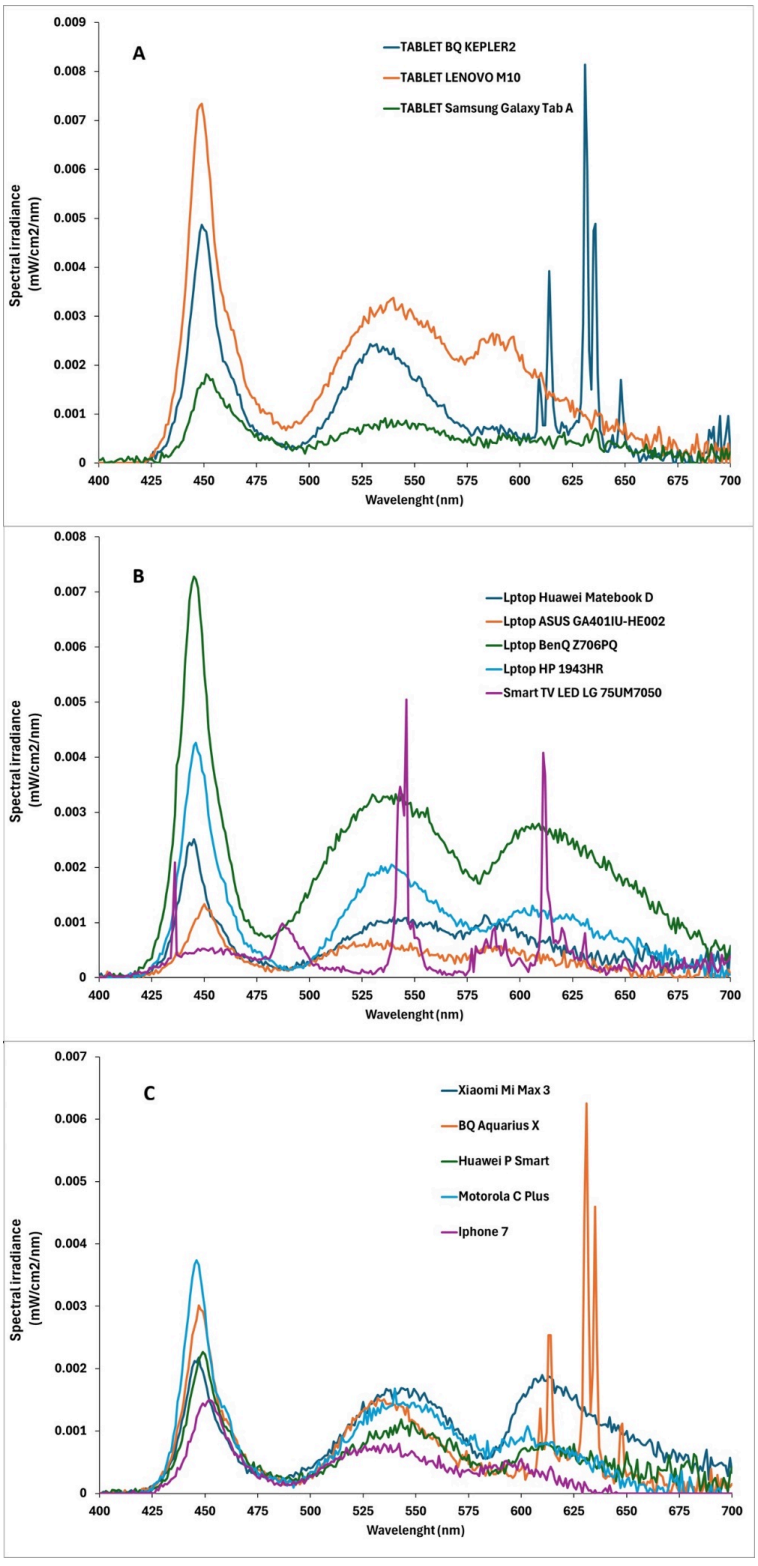


Figure 3

Spectral distribution of the physical irradiances emitted by mobile phone, tablets, computers and smartTV screens under white background and maximum brightness conditions, measured at standardized viewing distances in accordance with current regulations. A) tablet screens measured at 20 cm from the eyes. B) computer and smartTV screens measured at 60 cm from the eyes. C) Smartphones measured at 20 cm from the eyes.

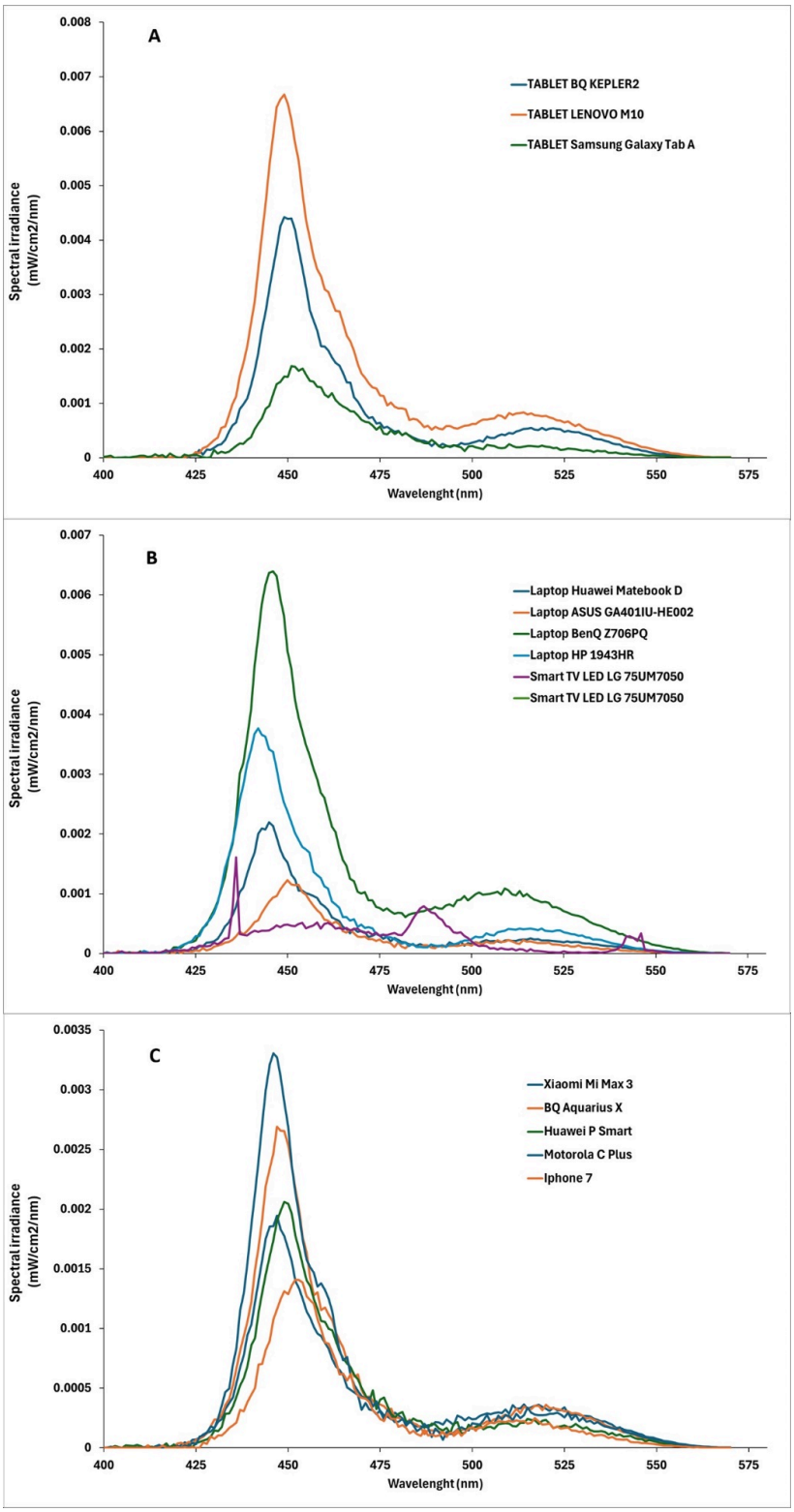


Figure 4

Spectral distribution of the biologically weighted spectral irradiances emitted by mobile phone, tablets, computers and smartTV screens under white background and maximum brightness conditions, measured at standardized viewing distances in accordance with current regulations. A) tablet screens measured at 20 cm from the eyes. B) computer and smartTV screens measured at 60 cm from the eyes. C) Smartphones measured at 20 cm from the eyes.