Reducing the circadian input from self-luminous devices using hardware filters and software applications

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Abstract

The widespread use of self-luminous devices at nighttime (cell-phones, computers, and tablets) raises some reasonable concerns regarding their effects on human physiology. Light-at-night is a known circadian disruptor, particularly at short visible wavelengths, and it seems advisable to have practical tools for tailoring the spectral radiance of these displays. We analyze two possible strategies to achieve this goal, using hardware filters or software applications. Overall, software applications seem to offer at present time the best trade-offs for controlling the light spectra emitted by existing devices. We submit that such kind of tools should be included as a standard feature on any self-luminous device and that their default settings should be established according to the best available knowledge on the circadian effects of light.

Keywords

Circadian system, self-luminous devices, displays, melatonin suppression.

1. Introduction

Portable electronic devices with self-luminous displays are increasingly present in our lives. Beyond their leisure applications, they provide effective and practical tools for social and professional networking, voice and video communication, document editing and sharing, and many other activities that were traditionally carried out using specific mid-sized desktop equipment. Smartphones, tablets and small personal computers are part of our everyday environment and significantly contribute to shaping our lighting landscape, especially indoors and at nightime. It can be foreseen that their use will increase in the near future, given the fast pace of the technological development in the fields of photonics and microelectronics, the existence of a growing world market for this kind of consumer electronics and the initiation into their use at ever younger ages.

The spectral composition of the light emitted by these devices has some remarkable differences with the one emitted by classical thermal or gas-discharge sources. The self-luminous screens used in many consumer electronic products are made up of a white light-emitting diode backlight source (LED) illuminating a liquid-crystal display panel (LCD) which provides the required spectral modulation to obtain the red, green, and blue subpixels. Organic light-emitting diodes (OLED) [1] are used as well, specially in small-size screens. In all cases the light spectrum is appreciably concentrated in three broad spectral bands, corresponding to the R, G, and B channels.

The frequent and prolonged use of these devices shortly before bedtime is becoming a matter of concern. The combination of relatively high radiance levels with a strong contribution from the blue region of the spectrum is a typical feature of these displays. Light at night is a significant input for the circadian regulation system, [2,3] and an increasing body of research is unveiling its unintended side-effects in shifting the circadian phase and suppressing pineal melatonin production.[4-6] Recent results indicate that adolescents, one of the main user segments of these devices in industrial societies, may be more sensitive to these non-visual light effects than older populations.[7]

Although a great deal of additional work will still be needed to build a comprehensive quantitative model of the non-visual interactions between light and the human circadian system, several broad recommendations are gaining consensus within the scientific community. Reducing unnecessary high levels of light at night and attenuating the blue components of the spectrum is one of them. [8-11] It seems then advisable to have at hand practical tools that allow to modify in a controlled way the spectral radiance of the self-luminous displays, in order to reduce the unwanted circadian input received by the users at nightime.

In this paper we explore two possible ways of achieving this goal, based on the use of transmission filters and of software applications. In section 2 we briefly outline these approaches. In section 3 we describe the parameters we used to quantify the circadian inputs produced by the displays. Section 4 presents two examples based on some of the displays, filters, and applications currently available. Discussion and some additional remarks are included in section 5. Conclusions are summarized in section 6.

2. Tailoring the spectral radiance of self-luminous devices

The spectral distribution of the light emitted by self-luminous displays can be controlled in several ways. A possible one, although technologically demanding, is to modify the radiant elements themselves by developing new solid-state sources whose unwanted photobiological effects can be minimized in origin, as proposed by several authors for smartphone displays[12,13] and general lighting applications.[14] Existing devices, however, require short-term solutions compatible with the kind of light sources they are already equipped with. Two main approaches can be used to that end: (i) using classical transmission filters that selectively attenuate certain regions of the spectrum or (ii) using software applications to control the relative weight of the signal emitted by each color subpixel, attenuating that way some of the spectral bands and, if required, reinforcing others.

Conventional transmission filters are always a feasible option for modifying the spectral radiance received from a self-luminous device, in the form of protective goggles worn by the user or filters directly fitted to the displays. Relatively inexpensive broadband polymer filters can be used for a coarse tuning of the emitted spectra, and more sophisticated operations (e.g. narrow -band transmission or rejection) can be made by using appropriately stacked dielectric multilayers. Transmission filters, however, have some basic disadvantages: they have to be physically attached to each self-luminous device (or worn by the users), and since their transmittance function cannot be modified they have to be replaced each time a different filtering effect is desired. This lack of tunability is a serious drawback for their use in screens if an adaptive filtering control is required, as e.g. for periodically dimming some wavelength bands depending on the timing of the circadian phase.

Software applications that control the spectral radiance of the screens by modifying the chromatic composition of the images sent to the display can be used as effective "software filters". That way the radiances of the R, G and B subpixels can be adaptively adjusted to produce the minimum circadian effects compatible with keeping some basic standards for visual quality. Software filters are intangible, do not require materials consumption and may be adjusted by the user to accomodate their effective transmittance to the requirements of the task to be performed, the spectral composition of the images, and the circadian phase. As a relevant drawback, since they ultimately act on the signal driving the color subpixels, they are not expected to be capable of performing very fine narrow-band spectral tunning operations. However, their adaptability allows for a wide control in real time of the circadian load associated to the nocturnal use of these devices.

3. Parameters for quantifying the circadian inputs

In order to describe the performance of the different methods for controlling the spectral radiance of self-luminous displays it is necessary to quantify the photic input to the human circadian system. Several approaches, widely different in scope and predictive power, have been proposed to that end. Their final aim is to relate a physically measurable magnitude, usually the spectral irradiance $E(\lambda)$ at the eye cornea, to the response elicited in the circadian system (e.g. the percentage of melatonin suppression produced under definite experimental conditions). Following the tradition of visual photometry most of the proposed models are linear, quantifying the circadian input J as a weighted integral of the spectral irradiance:

$$J = K \int w(\lambda) E(\lambda) \mathrm{d}\lambda \qquad (1)$$

where the weighting function $w(\lambda)$ and the scaling constant K are chosen according to some predefined criterium. An early example of this kind of models is the one proposed by Gall,[15,16] whose weighting function $w(\lambda) = c(\lambda)$ tries to fit in an approximate way the Brainard[17,18] and Thapan's[19] action spectra for acute pineal melatonin suppression in healthy subjects under quasi-monochromatic illumination. Based on Gall's $c(\lambda)$ weighting curve several magnitudes like the circadian illuminance (CIL), the circadian efficacy of radiation (CER) and the circadian action factor (CAF) can be defined, for the photopic, mesopic and scotopic ranges.[12-15]

However, a linear model with a single weighting function seems clearly insufficient for capturing all features of the interaction between the light and the human circadian system. Besides the intrinsically photosensitive retinal ganglion cells (ipRGC)[20], the rods and the S, L and M cones play a relevant role in the circadian photic regulation,[21] through a network of complex interactions whose quantitative details are beginning to be understood but have not yet been fully characterized. In order to allow successful intercomparisons of results it has therefore been suggested that the spectral power distributions used in any experiment should be recorded and that, at least, the individual inputs to these individual photoreceptors should be reported.[10] These inputs are determined by the spectral irradiance at the eye cornea weighted by the appropriate α-opic functions $N_\alpha(\lambda)$ defined in Ref[10], normalized to unit area, and multiplied by a suitable constant in order to be expressed in cyanopic, chloropic, erythropic, melanopic and rhodopic lux. A recent CIE Technical Note[22] advocates for normalizing the $N_\alpha(\lambda)$ functions to 1 at their maximum and expressing the photoreceptor inputs as weighted corneal irradiances, in units W/m^2, according to the standard practice of the International System of Units (SI).

A comprehensive model of the photic input to the circardian system, based on the known neuroanatomy and physiology of the human visual and circadian systems, was proposed by Rea et al[23] in 2005 and refined in subsequent years.[24-26] In addition to the linear contribution from the ipRGC this model also takes into account several kind of nonlinear interactions, by including a cone-based spectral opponency term with an associated rod shunting factor. The model allows to compute the input to the circadian system in terms of *circadian light* (CL_A),[24,25] a magnitude from which the expected percentage of acute melatonin suppression under particular experimental conditions (CS) can be computed with the help of a sigmoid function.[26]

In this work we characterized each combination of display and filter, at a given viewing distance, by their Gall's parameters, the multi-receptor α-opic inputs, and their circadian light stimuli (CL_A) and outputs (CS). In addition to the physiologically based Rea's model results, which provide quantitative information on the effects of a given exposure to a light source, the remaining magnitudes offer some complementary insights that may be useful for a more complete assessment of the different approaches.

4. Examples

With the aim of providing some practical insights about the possibilities of controlling the circadian input produced by self-luminous devices we analyzed a few hardware and software configurations. The results reported here are intended to be illustrative, and should not be taken as an overall evaluation of any product, device, code or application, nor do they imply any kind of endorsement, recommendation or assessment of suitability for any definite purpose. Models and trademarks are mentioned for the sake of information and for allowing any interested reader to reproduce and critically assess these results.

4.1. Displays and filters

Two self-luminous displays were used for these measurements, corresponding to a portable computer MacBook Pro (Retina, 15-inch, Mid 2014), equipped with a 332 mm x 208 mm , 15.4-inch diagonal LED-backlit display with 2880 x 1800 in-plane switching (IPS) LCD pixels; and a Samsung GT-I8190 cell phone, featuring an active matrix OLED display of 480x800 pixels.

To the best of our knowledge no specific hardware filters for reducing the circadian input by fitting them to the self-luminous devices were widely available in the market at the time of writing these lines. There is however, an extense offer of filters that claim to reduce the amount of blue light reaching the eyes, with the declared main goal of avoiding potential photobiological damage to the retina. Although these claims remain controversial for want of sufficient proof we included in this study several filters of this kind, with the only purpose of assessing up to what point could they be useful for reducing the blue-light exposure at spectral bands known to elicit strong circadian responses. The models chosen were the Reticare M (Medium), H (High) and I (Intensive) filters for smartphone and tablets.[27]

Among the free software applications exisiting for different kind of devices and operating systems at the time of performing these measurements we selected two: f.lux (v 3.10), available for Windows, Mac, Linux , and iPhone/iPad devices[28] and Softworx's Bluelight Color Filter (v 2.8.2), for Android.[29]

4.2. Measurement procedure

The spectral irradiance measurements were made at the Light Pollution Lab of the Universidade de Santiago de Compostela using a radiometrically callibrated BlueWave spectrometer (STE-BW-VIS-25, StellarNet, Inc, FL), operating in the range 350-1150 nm with cosine correction.

4.2.1. Portable computer

The MacBook Pro computer was configured to display a white full screen with the maximum available brightness. Its irradiance was measured with the detector parallel to the display, centered in the middle of the screen, and at an axial distance of 40 cm from it. The detector integration time was set to 2000 ms.

(a) Software filters (f.lux): We measured the spectral irradiance at the detector plane with the f.lux set to CCTs of 1200 K, 1900 K, 2700 K, 3400 K, 4200 K, 5500 K, 6000 K, 6500K, and with no filter (f.lux closed). Additional measurements at these CCT settings were also made at 30 and 50 cm from the screen, and in all cases a complementary reading with 750 ms integration time was taken to assess the consistency of the measured spectra.

(b) Hardware filters (Reticare): The measurements were made at 40 cm from the screen with the I, H and M Reticare filters, and with no filter. We used filters of size 158 mm x 195 mm, centered on the display, that did not cover its full extent. The remaining area was blocked with a black screen, and the readings were corrected for the different size and viewing angle by scaling the 'No filter' irradiance obtained with this setup to that obtained with 'No filter' in the f.lux case (see above). We consistently obtained a scaling factor of 1.7008. This factor is smaller than the one that would be obtained from the proportion between the respective solid angles (2.0622) if the soruce were Lambertian, revealing that the computer display deviates in some degree from this ideal behaviour.

4.2.2. Smartphone

The irradiance was measured at 25 cm from the cell phone display, with the detector surface centered and parallel to it. The device displayed a full screen white field and its brightness was set at the maximum allowed value. The detector integration time was set to 3000 ms, to ensure a good signal-to-noise ratio even for the maximum attenuation values recorded in this measurement run.

(a) Software filters (BlueLight app): The display was set at the maximum brightness provided by this app and the red colour was chosen for the filter. With these parameters the strength of the filtering effect is determined by the 'opacity' control, which ranges from 0% (no filtering) to 90% (maximum filtering). The irradiance was recorded with the opacity parameter set to 0%, 15%, 30%, 45%, 60%, 75% and 90%. The baseline spectrum was measured with the app deactivated.

(b) Hardware filters (Reticare): the measurements were made using the I, H, and M filters, and with no filter, in all cases with the BlueLight app deactivated and at the same distance and integration times as quoted above.

4.3. Circadian parameters

From the measured spectral irradiances in $W \cdot m^{-2} \cdot nm^{-1}$ we computed the following parameters relative to the visual and circadian inputs for the different combinatios of displays and filters:

- The photopic illuminance (*PIL*), photopic efficacy of radiation (*LER*), circadian efficacy of radiation (*CER*), circadian action factor (*CAF*) and circadian illuminance (*CIL*).[12,13,15]
- The cyanopic, chloropic, erythropic, melanopic and rhodopic illuminances, according to the different normalizations proposed in Refs [10] and [22].

- The circadian light CL_A,[25] computed using the best-fitting model coefficients corresponding to a lens-corrected melanopsin function peaking at 484 nm, and the expected control-adjusted melatonin suppression percentage for a standard experimental condition using *CS* from Ref [26].
- The overall irradiance, and the chromatic (x,y) coordinates in the CIE 1931 color space.

4.4. Results

The spectral irradiance measured at 40 cm from the computer display is shown in Figures 1 (with the f.lux software filter) and 2 (with the Reticare hardware filters). In both cases the dots correspond to the unfiltered display. The corresponding circadian magnitudes are listed in Tables 1 and 2, respectively. The results with the smartphone display are shown in a analogous way in Figures 3 (with the BlueLight software filter) and 4 (with the Reticare ones), and the circadian magnitudes listed in Tables 3 and 4. Figure 5 shows the values of CL_A for these combinations of displays and filters.

The positions in the CIE 1931 chromaticity space of the light arising in each configuration are shown in Figure 6. They correspond to the computer screen (filled symbols) and the smartphone display (open symbols), using software filters (squares) and hardware filters (circles). Triangles correspond to unfiltered light.

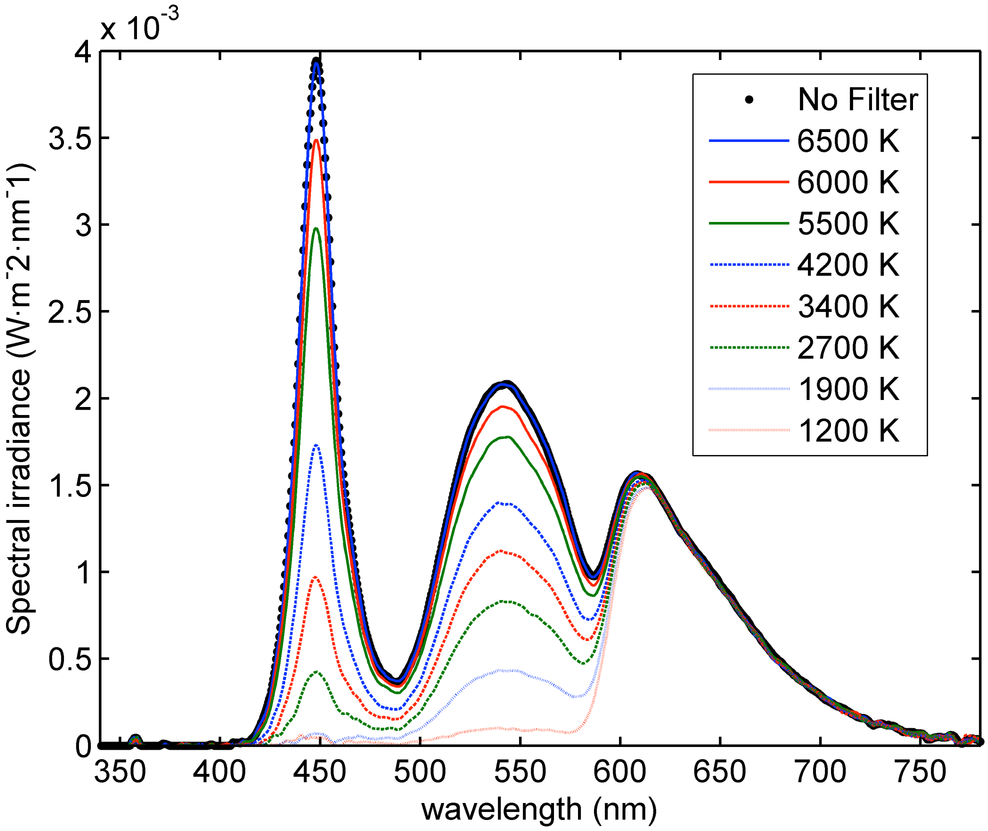

Figure 1. Computer display with f.lux software filters: Spectral irradiance (W·m^{-2}·nm^{-1}) measured at 40 cm from the device. The dotted line corresponds to the unfiltered display, and the remaining curves correspond to the use of a software filter with different CCT settings.

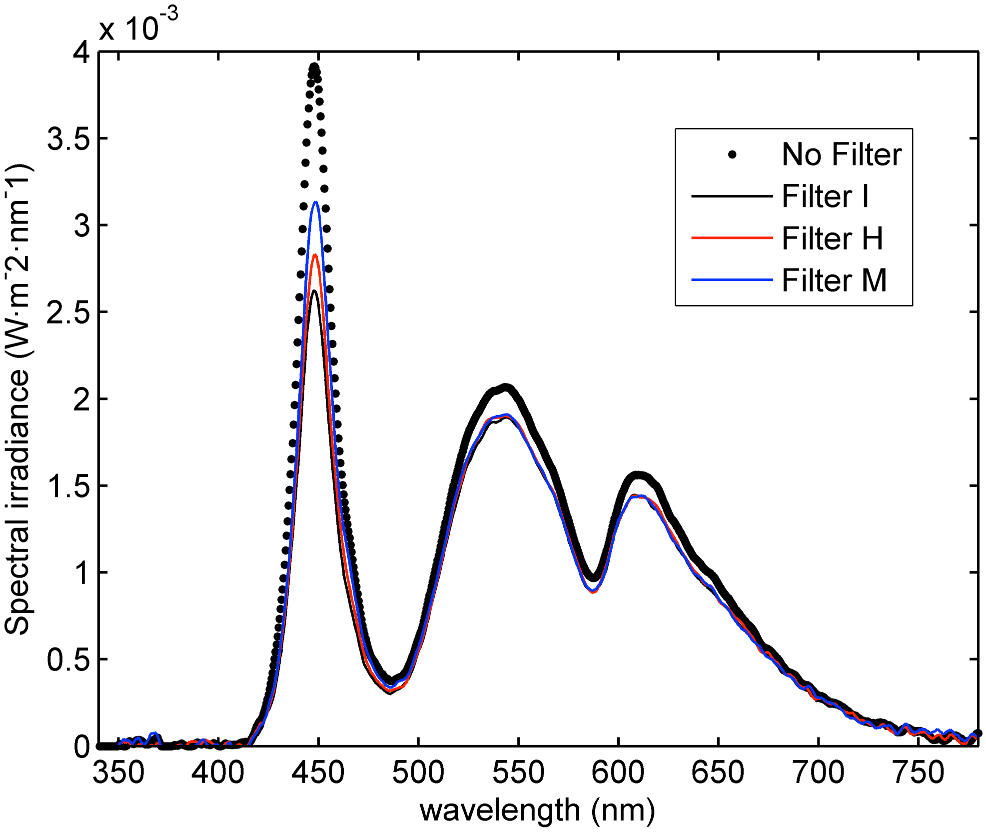

Figure 2. Computer display with Reticare hardware filters: Spectral irradiance (W·m^{-2}·nm^{-1}) measured at 40 cm from the device. The dotted line corresponds to the unfiltered display, and the remaining curves correspond to the use of a hardware filter with different filtering effects (M: Medium, H: High, I: Intensive).

Table 1. Circadian magnitudes corresponding to the spectral irradiance measured at 40 cm from the computer display with software filters (Fig1).

Filter (CCT)	**1200**	**1900**	**2700**	**3400**	**4200**	**5500**	**6000**	**6500**	**No Filter**
CL_A	5.45	18.33	43.45	69.97	49.27	101.60	120.89	139.20	138.98
CS (%)	0.69	2.56	6.27	9.99	7.11	14.05	16.33	18.36	18.33
Cya-lux	1.62	2.45	13.41	29.02	50.84	88.22	102.38	115.56	115.46
Mel-lux	2.87	10.21	23.16	36.24	51.48	75.68	85.52	93.84	93.71
Rod-lux	4.49	15.18	30.78	44.76	59.99	83.06	92.86	100.81	100.70
Chl-lux	13.55	26.53	43.19	56.59	70.18	89.64	98.33	105.03	104.94
Ery-lux	28.18	39.59	53.88	64.91	75.91	91.30	98.31	103.60	103.54
Cya (mW/m^2)	1.2	1.8	10.1	21.9	38.4	66.6	77.2	87.2	87.1
Mel (mW/m^2)	3.5	12.3	27.8	43.5	61.8	90.9	102.7	112.7	112.6
Rod (mW/m^2)	6.4	21.5	43.6	63.4	85.0	117.8	131.6	142.9	142.8
Chl (mW/m^2)	21.8	42.8	69.7	91.3	113.2	144.6	158.6	169.4	169.2
Ery (mW/m^2)	48.7	68.4	93.1	112.1	131.1	157.7	169.8	179.0	178.9
Irrad (mW/m^2)	117.5	141.0	179.6	214.0	254.0	315.5	340.8	361.9	362.1
LER	209.69	270.82	304.02	312.89	310.90	302.60	302.59	300.63	300.29
CER	15.29	36.75	83.59	125.33	165.42	213.33	226.34	237.47	237.03
CAF	0.07	0.14	0.27	0.40	0.53	0.70	0.75	0.79	0.79
PIL (lx)	24.64	38.17	54.60	66.97	78.98	95.47	103.13	108.80	108.74
CIL	1.80	5.18	15.01	26.82	42.02	67.30	77.14	85.95	85.84
x	0.6225	0.5491	0.4663	0.4148	0.3745	0.3342	0.3237	0.3154	0.3155
y	0.3521	0.4154	0.4197	0.4006	0.3747	0.3420	0.3356	0.3287	0.3287

Table 2. Circadian magnitudes corresponding to the spectral irradiance measured at 40 cm from the computer display fitted with hardware filters (Fig2).

Filter model	**I**	**H**	**M**	**No Filter**
CL_A	86.26	95.77	109.97	139.04
CS (%)	12.13	13.33	15.06	18.34
Cya-lux	78.63	84.84	93.40	115.49
Mel-lux	74.07	77.42	81.96	93.42
Rod-lux	83.83	86.51	89.69	100.30
Chl-lux	92.07	93.81	95.18	104.54
Ery-lux	92.57	93.88	94.44	103.30
Cya (mW/m^2)	59.3	64.0	70.5	87.1
Mel (mW/m^2)	89.0	93.0	98.5	112.2
Rod (mW/m^2)	118.8	122.6	127.1	142.2
Chl (mW/m^2)	148.5	151.3	153.5	168.6
Ery (mW/m^2)	159.9	162.2	163.2	178.5
Irrad (mW/m^2)	307.3	316.0	324.1	363.2
LER	319.33	314.29	307.17	298.42
CER	204.22	211.10	222.73	236.02
CAF	0.64	0.67	0.72	0.79
PIL (lx)	98.13	99.32	99.56	108.40
CIL	62.76	66.71	72.19	85.73
x	0.3355	0.3308	0.3233	0.3159
y	0.3636	0.3559	0.3441	0.3280

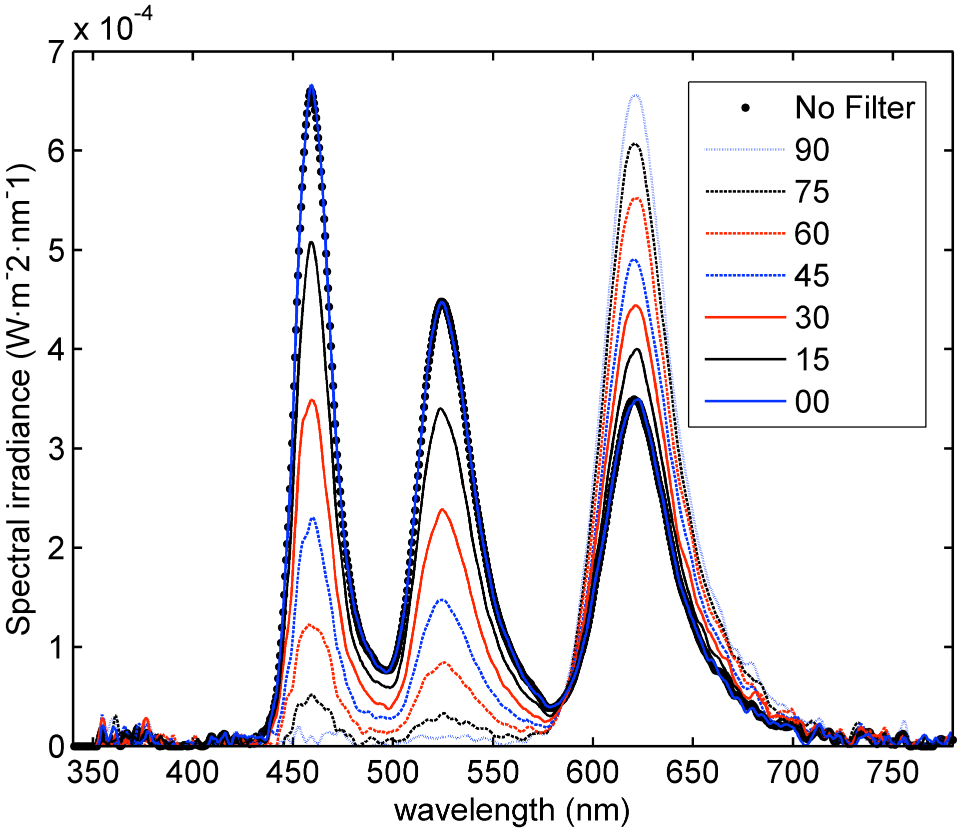

Figure 3. Smartphone display with BlueLight software filters: Spectral irradiance ($W \cdot m^{-2} \cdot nm^{-1}$) measured at 25 cm from the device. The dotted line corresponds to the unfiltered display, and the remaining curves correspond to the use of a software filter with different 'opacity' settings.

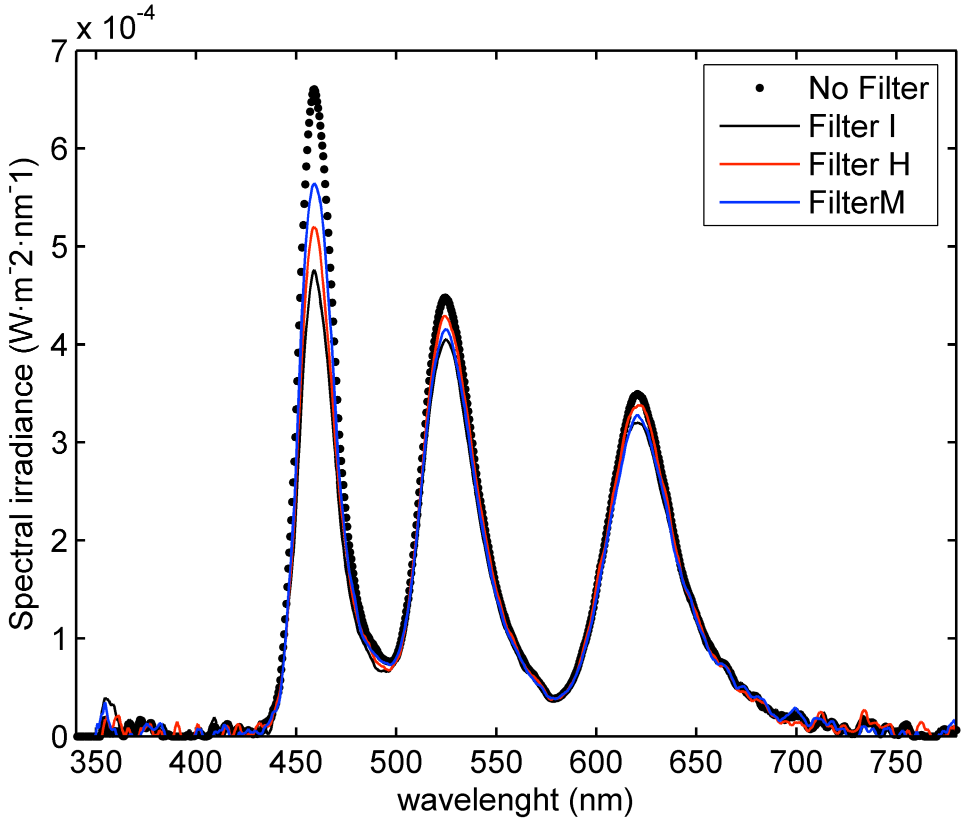

Figure 4. Smartphone display with Reticare hardware filters: Spectral irradiance (W·m^{-2}·nm^{-1}) measured at 25 cm from the device. The dotted line corresponds to the unfiltered display, and the remaining curves correspond to the use of a hardware filter with different filtering effects (M: Medium, H: High, I: Intensive).

Table 3. Circadian magnitudes corresponding to the spectral irradiance measured at 25 cm from the smartphone display using software filters (Fig3).

Filter (opacity)	**90%**	**75%**	**60%**	**45%'**	**30%**	**15%**	**0%**	**No Filter**
CL_A	0.99	2.50	6.72	6.76	11.94	18.30	24.75	24.38
CS (%)	0.11	0.29	0.87	0.87	1.62	2.56	3.52	3.46
Cya-lux	0.45	1.07	2.90	5.16	7.98	11.44	14.95	14.68
Mel-lux	0.49	1.25	3.38	6.04	9.46	13.60	17.80	17.59
Rod-lux	0.73	1.46	3.47	5.97	9.27	13.24	17.27	17.07
Chl-lux	3.46	3.81	5.10	6.72	9.08	11.92	14.80	14.62
Ery-lux	8.71	8.49	8.89	9.41	10.65	12.20	13.77	13.59
Cya (mW/m^2)	0.3	0.8	2.2	3.9	6.0	8.6	11.3	11.1
Mel (mW/m^2)	0.6	1.5	4.1	7.3	11.4	16.3	21.4	21.1
Rod (mW/m^2)	1.0	2.1	4.9	8.5	13.1	18.8	24.5	24.2
Chl (mW/m^2)	5.6	6.1	8.2	10.8	14.6	19.2	23.9	23.6
Ery (mW/m^2)	15.0	14.7	15.4	16.3	18.4	21.1	23.8	23.5
Irrad (mW/m^2)	32.9	31.8	33.6	35.5	39.8	45.4	51.1	50.5
LER	220.55	226.61	233.54	243.29	255.86	266.23	274.26	274.17
CER	11.66	30.84	80.70	136.53	189.72	239.20	278.18	277.85
CAF	0.05	0.14	0.35	0.56	0.74	0.90	1.01	1.01
PIL (lx)	7.26	7.21	7.84	8.64	10.20	12.09	14.019	13.84
CIL	0.38	0.98	2.71	4.85	7.56	10.86	14.22	14.02
x	0.6521	0.6189	0.5410	0.4627	0.3942	0.3370	0.295	0.2948
y	0.3263	0.3261	0.3221	0.3181	0.3179	0.3166	0.3157	0.3164

Table 4. Circadian magnitudes corresponding to the spectral irradiance (W·m^{-2}·nm^{-1}) produced with hardware filters by the smartphone display at 25 cm from the observer's eye (Fig4).

Filter	**I**	**H**	**M**	**No Filter**
CL_A	17.35	19.07	21.05	24.38
CS (%)	2.42	2.67	2.97	3.46
Cya-lux	10.87	11.88	12.81	14.68
Mel-lux	14.37	15.47	15.90	17.59
Rod-lux	14.44	15.48	15.61	17.07
Chl-lux	12.91	13.76	13.58	14.62
Ery-lux	12.33	13.06	12.74	13.59
Cya (mW/m^2)	8.2	9.0	9.7	11.1
Mel (mW/m^2)	17.3	18.6	19.1	21.1
Rod (mW/m^2)	20.5	21.9	22.1	24.2
Chl (mW/m^2)	20.8	22.2	21.9	23.6
Ery (mW/m^2)	21.3	22.6	22.0	23.5
Irrad (mW/m^2)	44.2	46.9	46.8	50.5
LER	286.64	286.41	278.35	274.17
CER	248.04	253.50	266.77	277.85
CAF	0.86	0.88	0.96	1.01
PIL (lx)	12.67	13.42	13.02	13.84
CIL	10.96	11.88	12.48	14.02
x	0.3133	0.3099	0.3013	0.2948
y	0.3429	0.3394	0.3257	0.3164

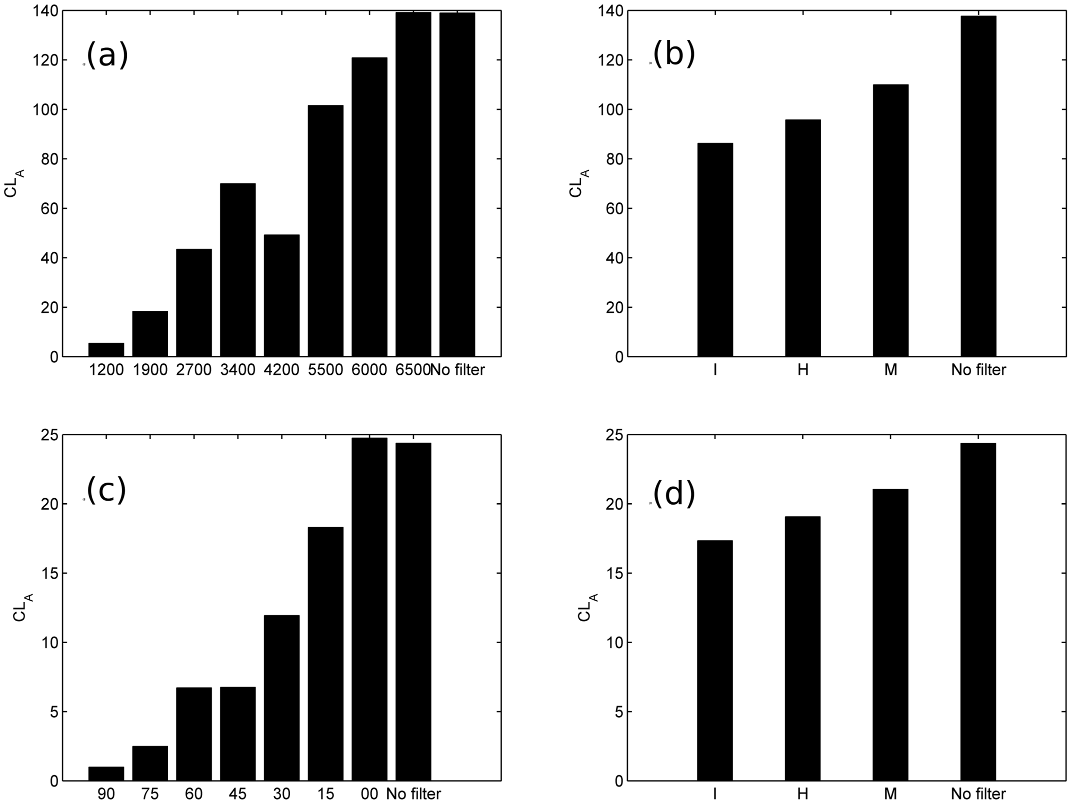

Figure 5. CL_A values for (a) computer display with f.lux filters. The X axis labels correspond to the CCT parameter in kelvin; (b) computer display with Reticare filters (I:intense, H:high, M:medium); (c) smartphone display with BlueLight filters. The X axis labels correspond to the opacity (equal to 1–Transmittance) expressed in percentage; (d) smartphone display with Reticare filters.

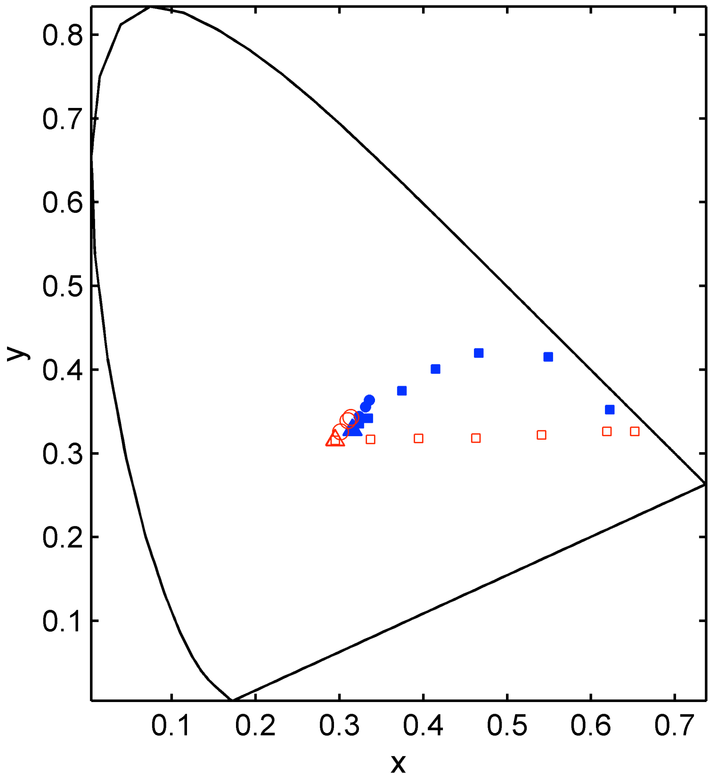

Figure 6. Chromatic coordinates in the CIE 1931 chromaticity space of the light emitted by the computer screen (filled symbols) and the smartphone display (open symbols), using software filters (squares) and hardware filters (circles). Triangles correspond to unfiltered light. Lower CCT or high opacity values in software filters displace the chromaticity point towards the monochromatic border of the diagram, in our case towards the red region.

5. Discussion and recommendations

The results here obtained show that software filtering is able to reduce significantly the circadian light (CL_A) and expected melatonin suppression (CS) values in comparison with unfiltered light, specially if low CCT settings (F.lux) or high opacity values (BlueLight) are used. The same can be said about other parameters directly related to the ipRGC sensitivity band, as the melanopic irradiance or the Circadian Action Factor (CAF). As a trade off, when the settings used in these software filters approach their strongest values (lowest CCTs or highest opacities, respectively), the chromatic coordinates of the light emitted by the displays displace themselves towards the monochromatic border of the CIE diagram, in our case towards the red region of the spectrum. The hardware filters analyzed in this study, in turn, keep the chromaticity point in the high CCT white region of the chromaticity space, but at the expense of a relatively weak filtering effect, as can be seen in the rather modest reduction achieved in the CL_A , CS or CAF values.

As stated above, the experimental results presented in this work are only meant to illustrate the performance of some available software and hardware filters when it comes to modifying the spectral content of the light emitted by self-luminous displays. As such, this is not an overall assessment of the performance of these particular products and, of course, no claim is made for completeness. Besides the reduced sample of displays and filtering methods, this study has other relevant limitations. We restricted ourselves to analyze the light that reaches the observer only from the devices, without including the effects of other ambient light sources that may be present in his or her environment. In case of using the devices within illuminated rooms the additional irradiance has to be taken into account.[12] Note that although the circadian magnitudes derived from Gall's curve or α-opic illuminances are linear on the spectral irradiances, and hence the values produced by the ambient lights just add to the ones produced by the displays, this is not the case for the outcomes of the physiologically based Rea's model: neither CL_A nor CS are strictly linear on the irradiances, altough the first one becomes linear in the limits of very low or very high irradiances (once the sign of the spectral opponency factor is settled), and the second behaves in an approximately linear way in the vicinity of the inflection point of the sigmoid curve.

No direct quantitative comparison between software and hardware filters should be made from these data, since the filters used in this study were not designed by their manufacturers for producing comparable effects. It can be anticipated that appropriately designed hardware filters could achieve a performance similar to that obtained with the software applications at low CCTs or high opacities. Hardware filters also offer the possibilty of performing narrow-band filtering operations, which can be of interest for efficiently blocking some well defined wavelength regions without affecting others. However, software filters have an exclusive feature, shown in Figure 3: whereas hardware filters are unavoidably passive ones, so that their transmittance is always less than unity for all spectral wavelengths, software filters can act as active ones, enhancing the light emission in some spectral regions while at the same time attenuating it in others. This offers additional degrees of freedom for implementing appropriate colour compositions and for tailoring the light emission to minimize the unwanted circadian effects produced by the use of these devices.

Overall, both approaches can be useful for the intended task of keeping the circadian load of the users within predefined limits. However, the intrinsic features of software filters make them in principle advantageous: they do not require the consumption of raw materials, can be easily adjusted for different lighting needs, can be distributed to the end users through habitual download channels and can be continuosly updated to adjust their performance to the best available knowledge on the circadian effects of the different spectral compositions and intensities of light. We consider that such kind of tools should be a standard feature of any off-the-shelf electronic device equiped with self-luminous displays.

6. Conclusions

Both hardware filters fitted onto the displays and software applications that allow modifying the spectral content of the displayed images are efficacious means to reduce the circadian load suffered by the users of self-luminous devices at nighttime. Overall, software applications seem to offer the best trade-offs for a flexible and tailored control of the spectral irradiance of the light emitted by existing devices. We submit that such kind of tools should be included as a standard feature in any off-the-shelf consumer product equiped with self-luminous displays, much in the same way as the traditional brightness and contrast controls are, and that their default settings should be established and updated according to the best available knowledge about the circadian effects of the different spectral compositions and intensities of light.

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