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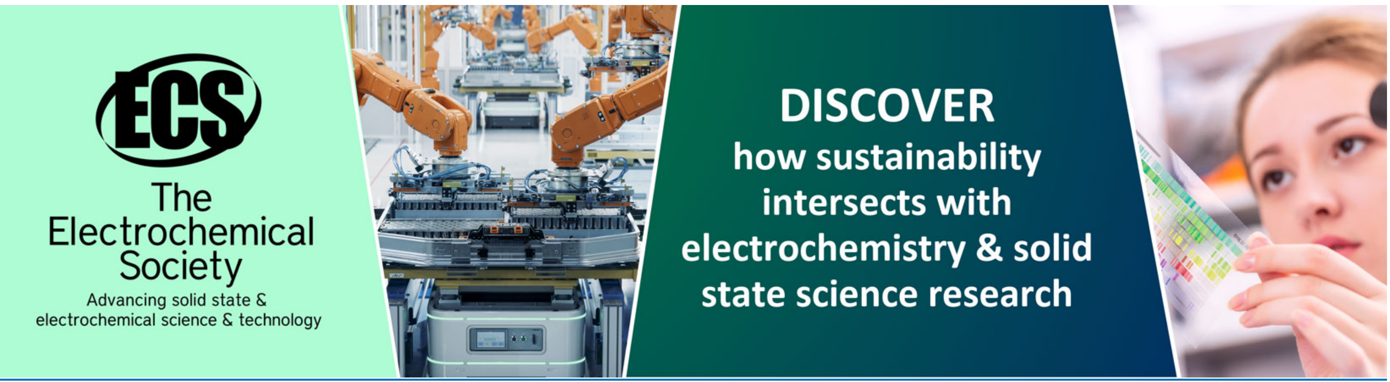

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The circadian impact of computer monitors with different color configurations

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Abstract. The objective of this study is to find out if it is possible to achieve the circadian levels recommended by different published lighting guidelines using different color configurations in a text editor. By measuring 25 monitors of different sizes, the circadian impact is evaluated at a standard distance using two different parameters: Circadian Stimulus and Melanopic Equivalent Daylight Illuminance. After analyzing the results, we see that during the night Circadian Stimulus is, in most cases, within the recommended range, but the same is not true for Melanopic Equivalent Daylight Illuminance. In addition, the circadian impact of the f.lux software has been analyzed and compared with two different cases of color configurations in a text editor.

1. Introduction

The human circadian system is related to numerous physiological, biochemical, and psychological variables, directly related to people's health. Without the presence of external elements, such as light, experiments show that the circadian rhythm has a duration of about 25 hours, as opposed to 24 hours a day. The impact of light helps to regulate and synchronize circadian rhythms with our environment, readjusting them to the daily 24-hour cycle [1].

At the same time, modern human beings live a large part of our time enclosed in spaces without access to natural light. Artificial light, in general, is static with no regulation according to external daylight conditions. This can lead to an imbalance in circadian rhythms, as we lose reference to the outside world.

Several studies have been published linking light exposure to the regulation of melatonin, a hormone related to circadian rhythms. Essentially, the sunlight that reaches our retina helps to synchronize our internal circadian rhythms with the outside world, telling our body what to do at any given moment. An imbalance in circadian rhythms can lead to health problems, increasing the predisposition to mood disorders, including impulsivity, mania, and depression [2]. If exposure to light is not correct, in the long term, a disruption of the light-dark cycle can lead to other problems, such as weight gain, obesity or diabetes [3], as well as certain forms of cancer [4], among others.

Institutions such as Lighting Research Center (LRC) have carried out studies in different environments and have published guidelines with a series of recommendations on how to correctly use light, from a circadian point of view [5]. In this case, a parameter developed by LRC itself is used: the circadian stimulus (CS). CS is a parameter related to the suppression of melatonin due to a light stimulus incident on the human eye [6]. LRC itself has published calendars that relate a time of day to a CS value. A case applied to office lighting is shown below:

Table 1. Recommended CS value based on the time of day in an office. EOB refers to End of Business Day.

Local time	CS
07:00 – 16:00	0.3
16:00 – 17:00	0.3 → 0.2
17:00 – 19:00	0.2
19:00 – 20:00	0.2 → 0.1
20:00 - EOB	0.1

On the other hand, other authors suggest the adoption of other parameters such as Melanopic Equivalent Daylight Illuminance (mEDI), which describes the light-sensitivity of human physiological response [7]. In a similar way, the circadian impact of light reaching the human eye is evaluated and a calendar that relates mEDI values to the time of the day has been defined:

Table 2. Recommended mEDI value depending on the time of day.

Local time	mEDI (lx)
Daytime	> 250
Evening	< 10
Nighttime (vision)	< 10
Nighttime	< 1

When assessing the circadian impact of light, it is important to take into account the spectral shape of the light source and the luminous flux incident on the eye, i.e., the illuminance. Both CS and mEDI take these two factors into account, although the equations defining them are different. Generalizing, at the spectral level, both cases are mainly related to the amount of blue contained in the incident light, although the effective circadian response is different in each case. Other longer wavelengths (green, yellow, red...) also affect the circadian system, although their impact is much more limited. To see the lack of direct relationship between CS and mEDI, we have analyzed and compared a set of 718 commercial white LEDs, as can be seen in figure 1:

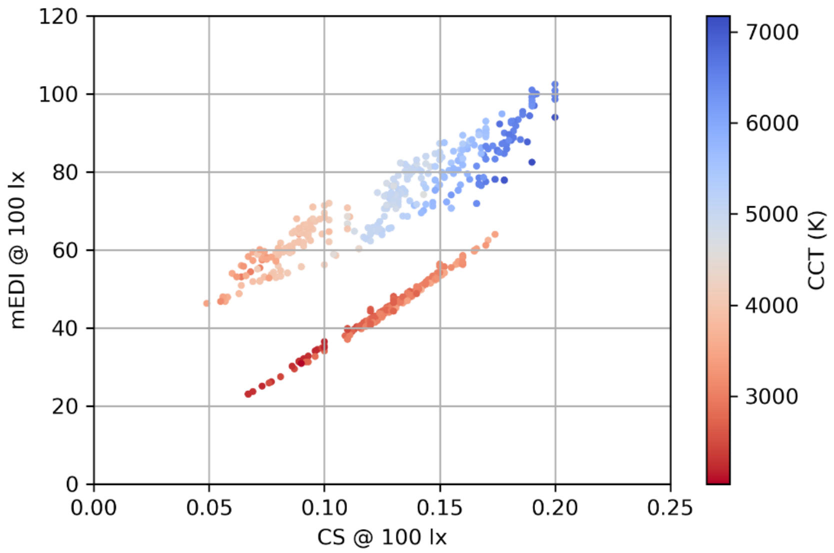

Figure 1. Relation between mEDI and CS at 100 lx for 718 commercial white LEDs.

The data for the 718 LEDs of the figure 1 have been collected through the information provided by different LED manufacturers and is available on the spectral design platform developed by Kumux. All the information has been standardized and numerous colorimetric and circadian parameters have been calculated, including mEDI and CS.

Often only the illumination coming from outdoors (natural light) or indoors (from luminaires) is taken into consideration. However, studies have shown that prolonged exposure to light from a computer monitor has an impact on melatonin secretion in adolescents and can suppress melatonin by a 30%, approximately [8].

To minimize this effect, some initiatives have arisen, such as f.lux, a computer program which varies the warmth of the colors of a computer screen depending on the time of day [9]. Thus, as night approaches, the computer screen on which this software is installed begins to redden, while during the day it retains its original colors.

This article presents a new approach to the problem. In this case, to find out the potential impact, a text editor called Visual Studio Code (VS Code) is used, which allows full customization of the colors of the graphical interface. VS Code has been chosen because it is one of the most widely used programs for software developers, although there are other very popular editors (VIM, Emacs...) that also allow the customization of colors, being a commonly used tool among programmers. In a similar way to f.lux, two different color configurations have been created and spectral and illuminance measurements have been taken for both, comparing the acquired values with the recommended CS and mEDI values shown in table 1 and table 2.

2. Method

A study on the impact of computer screens at the circadian level is conducted. For this purpose, two different color schemes of the VS Code text editor have been created, providing two different scenarios with potentially low (with a dominance of dark colors) and high (with a dominance of white colors) melanopic impact.

Twenty-five displays of different sizes, technologies and time of use (aging) have been analyzed to find general patterns that can be used for future studies. This analysis includes circadian calculations based on CS and mEDI parameters, as well as a comparison with f.lux software.

2.1. Location

The study was carried out at the Facultat de Física of the Universitat de Barcelona and at the Barcelona Science Park. In total, two offices with access to natural light and one laboratory without access to the outside were analyzed. However, the calculations did not take into account the contribution of illumination beyond the light from the monitors themselves.

2.2. Experimental equipment

In this case, we have used a UPRtek MK250S Premium spectrometer. It is a portable spectrometer with an integrated camera with a wavelength range of 380 to 780 nm, 1 nm resolution and an illuminance measurement range from 1 to 150,000 lx. In this case, the spectrometer provides the spectral power distribution (SPD) and the illuminance (in lx) of the measured screen, the two parameters needed to calculate CS and mEDI.

To perform the measurements, the spectrometer was mounted on a tripod with an adapter created with LEGO Technic, as shown in figure 2:

Figure 2. Spectrometer mounted on the tripod making measurements on a monitor.

2.3. Data acquisition

The acquired data comes from 25 different monitors. These monitors differ in manufacturer, size, technology (TFT, LCD and LED) and aging. To perform the measurements, two different images

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(scenarios) are displayed on the different screens: one with white colors dominance and one with dark colors dominance. In other words, the same image with a white background and the same image with a black background is displayed on all screens, and spectral measurements of both are then taken. In all cases, the monitors have been configured to provide the maximum possible brightness (100%). Other options such as blue dominance have been discarded, because although the circadian response of the eye depends on the amount of blue light impinging the eye, in a computer screen, the white color already includes the blue color at maximum power. For clarification, the white generated by the computer is composed of a vector of red, green and blue components, all at maximum. This fact implies that the maximum circadian effect that can be achieved coincides with the white color at maximum power.

Moreover, as mentioned above, the measurements were taken with a spectrometer mounted on a tripod. Since the spectrometer has a built-in camera, the measurements have been taken pointing to the center of the screen. The distance of the measurements to the screen has been set at 68 cm from the center, as this is the working distance recommended by some studies [10]. The height has been set at 1.20 m, which corresponds to the recommended height in the mEDI schedule of table 2.

For each of the 25 monitors, three different measurements were carried out: a dark measurement with the screen turned off but with the corresponding ambient light, a measurement with black color dominance, and a measurement with white color dominance on the screen. Thus, by subtracting the dark measurement from the two measurements with the screen on, it is possible to obtain the clean spectral and illuminance values of the monitors in each case, suppressing the contribution from ambient light. Figure 3 shows the two images displayed by the screens with black and white color dominance:

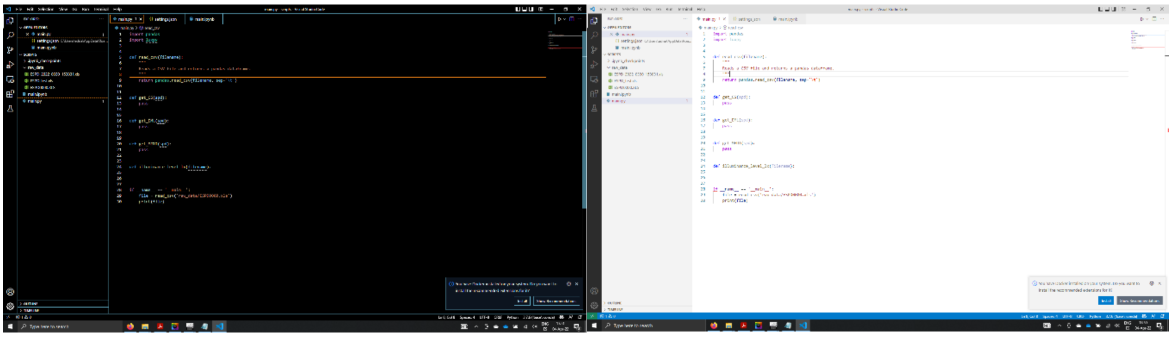

Figure 3. Screenshot of the VS Code Graphical User Interface with black color dominance (left) and with white color dominance (right).

2.4. Data analysis

For each measurement, the spectrometer generates a spreadsheet with spectral information that includes both SPD and measurements of basic colorimetry, horticulture and some other non-visual parameters, in addition to the illuminance value. CS and mEDI parameters have been evaluated from the acquired spectra using a simple script to perform the required calculation.

The script is developed in Python 3, and its main function is to read the set of spreadsheets derived from the spectrometer measurement and perform the calculations of the CS and mEDI parameters. To perform the calculations of these parameters, the Luxpy library has been used [11], which allows a fast implementation of the necessary equations. In these calculations, the dark values are subtracted from

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the values of the two-color configurations described. In this way, the values of the light coming from the monitors analyzed are obtained.

An analysis was performed in 3 parts. In addition to calculate CS and mEDI parameters, illuminance was also measured. Illuminance can be employed as a reference for checking the dependence on the diagonal of the monitor and its relation with the monitor area (i.e., quadratic dependence with the diagonal). Actually, as the diagonal of the monitor increases or decreases, the number of emitting points and the effective illumination area scales quadratically with the diagonal. The illuminance measurements of the 25 monitors with the white colors dominance configuration can be seen in figure 4:

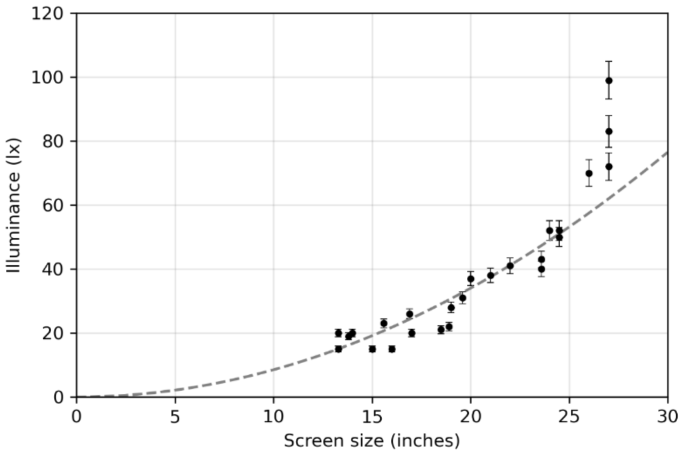

Figure 4. Illuminance (lx) vs screen size (inches) of the monitor in the white color dominance configuration. A quadratic function (dotted line) intersecting with the coordinate origin has been drawn as a reference.

In figure 4 an error of 2 cm has been estimated in the experimental measurement at 68 cm. This is approximately a 6% error in the illuminance value. This means that, to the human eye, such errors are only noticeable when the illuminance is high, as can be seen in the error bars of figure 4. On the other hand, the auxiliary quadratic function, of the type $f(x) = a \cdot x^2$, often does not fall within the error margins of the measurements, which means that there are other effects or other sources of error that were not considered. The discrepancies can be originated by the differential factors between monitors mentioned above, such as light emission technology, screen ratio, or aging, which can cause a decrease in the luminous flux of the screen.

In the case of the dark color-dominant configuration, no appreciable illuminance value could be measured. In other words: there is no perceptible light emission that circadianally impacts the human system. For the larger displays, the difference in illuminance measurements between the dark color dominance configuration and the screen off is much less than 1 lx, as can be seen in figure 5. Since CS and mEDI parameters depend on the illuminance value, if the illuminance has a zero value, CS and mEDI will also be zero. On a practical level, the dark color dominance setting is equivalent of having the screen turned off.

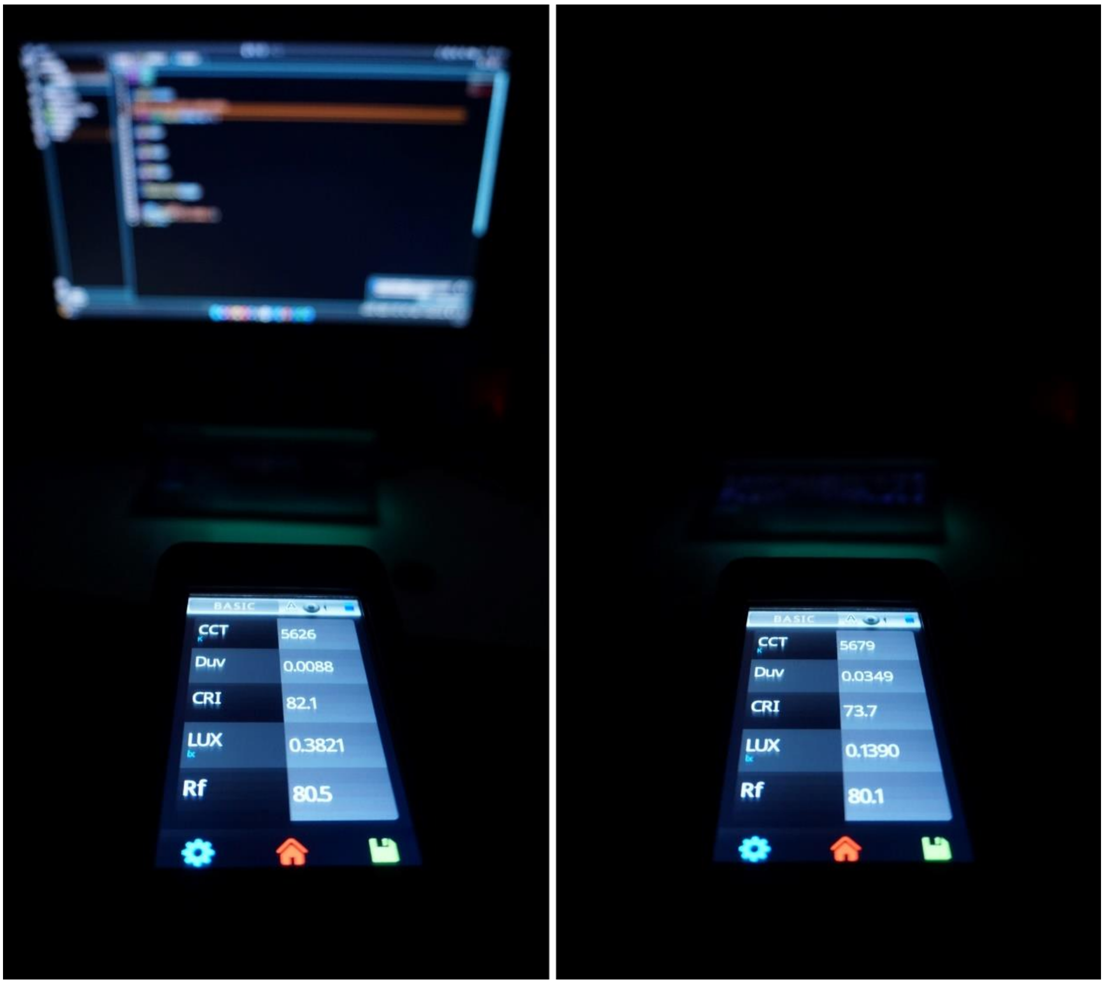

Figure 5. Photograph of the values measured by the spectrometer for a 27-inch screen in dark color dominance configuration (left) and with the screen turned off (right). It can be seen that the difference in illuminance is 0.24 lx.

3. Results

Similar to the case of illuminance, the dependence of CS and mEDI parameters on the screen size is visualized in figure 6. Due to the imperceptibility of the illuminance in the dark color configuration, only the net white color configuration, resulting from subtracting the ambient light (screen turned off measurement) has been taken into account.

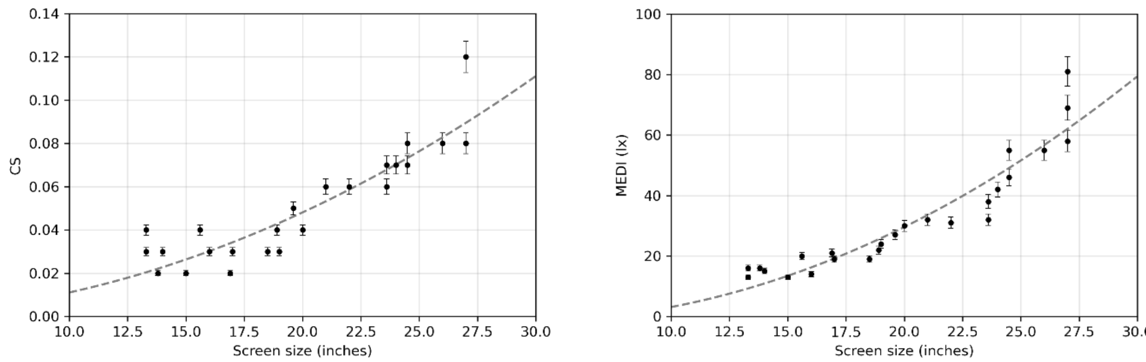

Figure 6. CS (left) and mEDI (lx) (right) *vs* screen size (inches) of the monitor in the net white color dominance configuration. A quadratic function (dotted line) intersecting with the coordinate origin has been drawn as a reference in both cases.

Similarly to the illuminance behavior with the screen size (figure 4), in the case of CS and mEDI we also find points that fall outside the expected values. The reasons for this are identical to those previously mentioned. Nevertheless, by comparing the values obtained with the values in table 1 and table 2, we can draw the following conclusions:

- To achieve the recommended circadian impact during daylight hours (CS > 0.3 or mEDI > 250 lx) a large screen is required. Following the reference trend lines in figure 6, the intersection between the recommended values and the screen size occurs at 50-inches for both CS and mEDI.

- To achieve the recommended circadian impact during nighttime hours (CS < 0.1 or mEDI < 1 lx) the conclusion is not clear for the net white color dominance configuration. On the one hand, if we stick to the LRC recommendations, we see that all but one of the screens analyzed meet the condition of CS < 0.1. Only large screens can have a circadian effect greater than necessary. However, if we look at the mEDI recommendations, none of the results fall below 1 lx. In fact, in the case of mEDI, none of the results meet the more restrictive conditions, related to evening values and nighttime activities requiring vision (mEDI < 10 lx).

We are going to analyze whether, in the case of mEDI, using software such as f.lux it is possible to fall below the recommended limits in the white color dominance scenario.

3.1. Comparison with other software
The f.lux software has been installed and spectral measurements of the mEDI parameter (the most restrictive during nighttime hours) have been performed at the same distance as in the previous cases. The results of the relative reduction of mEDI can be seen in figure 7:

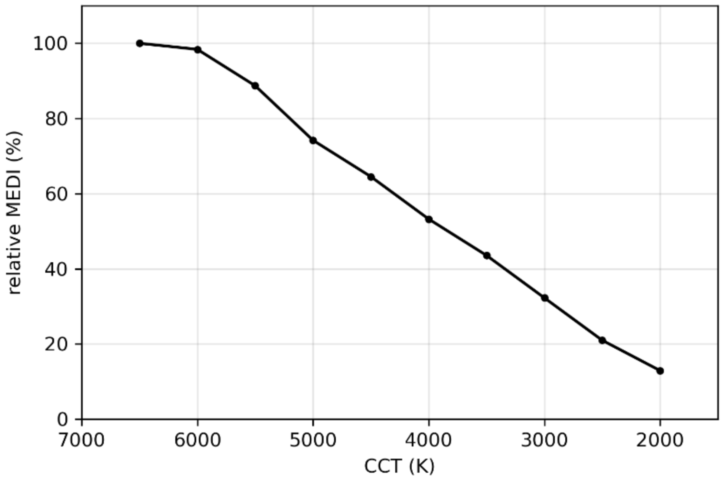

Figure 7. Relative mEDI values as a function of the CCT of the screen controlled by the f.lux software. Measurements were taken on a 27-inch screen.

The f.lux software allows automatic control of the display's CCT, which varies according to geolocation and time of day. In this way, the screen maintains its original colors during daylight hours and turns orange (with the absence of blues) as night approaches. With this control, as can be seen in figure 7, a progressive reduction of mEDI is achieved, reaching 92% at its most extreme point, when the CCT of the display is minimal.

Applying the 92% reduction of mEDI provided by the f.lux software to the set of displays analyzed in figure 6, we see that all of them would meet the evening condition (mEDI < 10 lx). However, although the smaller ones come close, there is no display that achieves the nighttime value of mEDI < 1 lx.

4. Discussion

Analyzing the results in depth, we have seen that a number of conclusions can be drawn about the circadian impact of the computer monitors considering that there is no ambient light:

- Having a black background in a text editor, at the circadian level, is practically equivalent to having the screen turned off. It was not possible to measure a relevant illuminance of screens with the dark color dominance setting, as it is too small, implying that the circadian impact is also null.

- To achieve a high circadian impact (CS > 0.3 or mEDI > 250 lx), a large screen (> 50-inches) or a combination of smaller screens is required. In addition, in a text editor such as VS Code, it is necessary to combine it with a white color-dominant background. However, a possible daytime scenario where there is only illumination due to screens is extremely rare.

- At night, according to the two guidelines analyzed, there is no consensus on the potential impact of the screens. On the one hand, if we follow the recommendations of the CS parameter, we see that in the vast majority of cases (small and medium-sized screens) there is no problem, even if a white-dominant background is used. However, if we follow the recommendations of the mEDI parameter, we see that no display meets the requirements in the white color dominance setting. For this reason, it is necessary to change the luminance of the display with some software resources that allow setting darker colors or with less blue content.

- As it can be seen in figure 1, there is no direct relationship between CS and mEDI. This can lead to problems such as the one described in this article: while according to the CS guideline, during the night, the requirements set out in table 1 are met, the same is not true for mEDI (table 2). This can lead to confusion, and it is necessary that scientifically there is a clear methodology to follow.

- A study of the f.lux software has been conducted, and while it is absolutely true that it can greatly reduce circadian impact, it is not as effective as other strategies, like changing the background color. Changing the background color to black results in zero circadian impact, while using the f.lux software results in a 92% reduction.

For this reason, as a general recommendation, it is proposed to use white-dominant backgrounds during the day and black-dominant backgrounds at night. The potential circadian impact of the screen, especially during the day, is not very high, although depending on conditions it may help to reach the limit of CS > 0.3 or mEDI > 250 lx. During the night, on the other hand, we should limit exposure to white colors as much as possible in computer screens. Specifically, in the case of CS, in most cases the CS > 0.1 value is not reached, but possible contributions from external illumination to the monitor must be taken into account. Thus, in the case of displays it is very important to control both the potential output spectrum and the luminance, since a low luminance value will hardly imply a high circadian impact.

In a similar way, the conclusions can be extrapolated to today's intelligent lighting systems. There are numerous systems that allow for CCT tuning or brightness variation, although in order to have a high circadian impact, both parameters must be controlled simultaneously. Moreover, these variations must take into account factors such as geolocation, type of activity or time of day and date of year, among others. All these parameters have a huge influence on the amount and type of illumination entering the retina of the eye, so automated solutions are needed to allow automatic control of the circadian impact due to artificial lighting systems.

Future studies are needed with a larger sample of monitors to differentiate technologies or aging, among other parameters. In this way, it will be possible to draw more appropriate conclusions about the correct use of monitors during the day and at night.

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