



OPEN Home lighting, blue-light filtering, and their effects on melatonin suppression

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Evening residential illumination possesses the capacity to impair sleep quality via the suppression of endogenous melatonin production, a process largely driven by short-wavelength (blue) light. In this investigation, we characterized the light emissions from 52 distinct examples across three common lamp technologies: light-emitting diodes (LED), incandescent, and compact fluorescent (CFL) lamps. To estimate the differential circadian impact of these sources, we determined the Melatonin Suppression Value (MSV), melanopic illuminance, and photopic illuminance for each. Our findings reveal that “cool” white LED (median 12.3% MSV) and “cool” white CFL (12.1% MSV) lamps induce considerably greater melatonin suppression than “warm” white LED (3.6%), “warm” white CFL (2.6%), or traditional incandescent (1.5%) lamps. As potential countermeasures, we examined the efficacy of tunable Correlated Color Temperature (CCT) lamps and “blue-light-filtering” (BLF) lenses. The four tunable LED lamps demonstrated a profound ability to mitigate circadian disruption, reducing estimated melatonin suppression from 10% at a 5700 K (cool white) setting to 0.1% at 2100 K (warm white). An analysis of eight BLF lenses identified variable performance; while six had moderate impacts compared to uncorrected vision, their benefit was limited relative to standard clear lenses. Only two BLF lenses, distinguished by a “brown” tint, proved highly effective, reducing estimated suppression to below 0.3%. These results suggest that cool white CFL and LED lamps may exert a greater disruptive influence on sleep physiology than other lamp types. Conversely, tunable lamps adjusted to warm settings and “brown”-tinted BLF lenses represent beneficial strategies for ameliorating this effect. (Detailed measurement methodologies are available in a previously published study, with supplementary calculations provided separately).

The past three decades have witnessed a significant transition in residential lighting, from incandescent to compact fluorescent (CFL) and, subsequently, light-emitting diode (LED) technologies. While this transition varies globally, many homes now employ a mixture of these lamp types¹. Incandescent sources are characterized by “warm” correlated color temperatures (CCT) (2700–3000 K). In contrast, CFLs and LEDs are available in both “warm” (~3000 K) and “cool” white (~5000 K) options.

These lamp types possess distinct spectral profiles. Notably, “cool” white sources have higher irradiance in the short-wavelength (blue) spectrum. This raises a significant physiological concern: the potential for “cool” white lamps used in the evening to suppress endogenous melatonin production more profoundly than traditional incandescent sources^{2–7}. Even “warm” CFL and LED lamps may exert a greater effect than incandescent bulbs due to their inherent spectral power distributions.

Physiological mechanism and health implications

Melatonin secretion is endogenously absent during daylight, with synthesis initiating in the evening as light diminishes. Artificial light at night (ALAN) can suppress this crucial secretion^{2,4,7}, an effect quantifiable as the Melatonin Suppression Value (MSV). The human circadian system is highly sensitive; even low irradiances of blue-wavelength light can disrupt numerous physiologic functions^{8,9}.

This circadian interference, commonly associated with jet lag or evening screen use, is a considerable health risk. Chronic circadian disruption is linked to impaired sleep¹⁰, mood disorders¹¹, metabolic dysregulation¹², obesity, diabetes, cardiovascular disease, and certain cancers^{13–15}. While appropriate blue-enriched lighting

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during the day can enhance alertness and mood¹⁵, conflicting findings exist¹⁶, underscoring the need for further research on its precise circadian effects.

The research gap and potential countermeasures

Recent studies indicate that typical home lighting can induce significant MSV, with some homes reaching 50% suppression^{1,3}. However, a key limitation in the literature¹ is the difficulty in isolating the impact of specific lamp types due to mixed-exposure spectral profiles in real-world settings. This leaves the relative circadian impact of LED, CFL, and incandescent sources equivocal and motivates the present study.

Two primary strategies have emerged to mitigate this risk:

1. Tunable CCT lamps: These “circadian” lamps allow users to shift from cool, alerting CCTs during the day to warm CCTs in the evening, theoretically aligning with the natural circadian rhythm^{17–19}.
2. Blue-Light Filtering (BLF) lenses: This approach aims to reduce the specific blue-green or “cyan” wavelengths (~460–530 nm) that maximally stimulate the intrinsically photosensitive retinal ganglion cells (ipRGCs) responsible for melatonin suppression. This is distinct from lenses designed merely to mitigate the “blue light hazard” (~400–460 nm). While the efficacy of BLF lenses is debated²⁰, often due to studies using inappropriate lens types, targeted “cyan-blocking” lenses show promise^{21,22}.

Study aims

This study sought to systematically evaluate these lamp types and countermeasures, which were not assessed in previous foundational studies^{1,3}. Our objectives were:

- (1) To compare the calculated MSV, melanopic EDI, and photopic illuminance of 52 incandescent, CFL, and LED lamps.
- (2) To determine the efficacy of eight different BLF spectacle lenses in reducing calculated MSVs.
- (3) To quantify the potential of four tunable LED lamps to reduce MSVs compared to fixed-CCT lamps.

Materials and methods

Lamp spectral irradiance characterization

A total of 52 fixed Correlated Color Temperature (CCT) lamps, representing 14 manufacturers, were procured from retail outlets in the USA and Mexico (see Table S1, Figure S1). These were categorized into five groups ($n = 10–12$ each): “cool” white LED, “warm” white LED, “cool” white CFL, “warm” CFL, and incandescent.

Spectral irradiance was measured using a system described previously²¹, employing an AvaSpec-2048 spectrometer with an integrating sphere. The system was calibrated from 324 to 1100 nm using a Newport monochromator with a 1000 W Xenon lamp.

Due to the wide variance in lamp wattage (Supplementary Figure S2, Table S2), all spectra were normalized to facilitate direct comparison. Normalization was achieved by equalizing the total radiant energy within the 400–700 nm range, which approximates the human photopic sensitivity region (see Section “[Normalization of spectral energy across lamps and MSV](#)” for methodology). Additionally, 34 spectral irradiances were measured from four CCT-tunable LED lamps, capturing their spectral output from 2100 to 5700 K. These spectra were also normalized for comparison.

Blue-light filtering (BLF) lens transmittance

The spectral transmittance of eight BLF lenses was measured from 350 to 800 nm. The lenses were grouped into four categories:

1. Coated (“Clear”): Crizal Previncia, Zeiss BlueProtect.
2. Tinted (“Yellow”): Seto Anti Blu-Ray, Vaccutek 1.60 UV Blue Light.
3. Tinted (“Light Brown”): CGID Blue Light Blocking, Spektrum Arctic Propek-50.
4. Tinted (“Medium Brown”): THL Sleep, Swanwick Night Swannies.

The first two categories, previously measured in²¹, were ophthalmic lenses purported to protect from the “blue light hazard.” The latter two categories were purchased online and marketed for sleep assistance. As described in²¹, transmittance was measured using an Oriel Xenon lamp (model 66924) and a Newport monochromator as the source, with a silicon detector (ThorLabs PDA100A). Transmittance (T) was calculated as the quotient of the transmitted power (PT) and the incident power (PI) from 350 to 800 nm.

Calculation of the melatonin suppression value (MSV)

To quantify the potential circadian impact of the radiation, we centered our analysis on the suppression of melatonin. We calculated the Melatonin Suppression Value (MSV) by first determining the circadian illuminance (CIL) for each lamp from its spectral irradiance. The intrinsic MSV for each lamp was then derived from this CIL.

Furthermore, we modeled the mitigating effect of the BLF glasses by recalculating MSVs, combining the transmittance spectra of the eight lenses with the median irradiances of the five standard lamp groups and the tunable lamps.

This approach was chosen because the circadian response, for our purposes, must be linked to melatonin secretion. We therefore employed the previously established relationship between MSV and circadian illuminance (CIL)²¹, which is formulated as:

$$MSV_{i,j} = \frac{1}{1 + \exp[-k(\log(CIL_{i,j}) - \log(CIL_0))]} \quad (1)$$

Here, $k = 1.782$ and $CIL_0 = 103.5$ were the fit parameters ($R_{adj}^2 = 99.9\%$)²¹ and CIL was defined as

$$CIL_{i,j} = 683 \int_{380}^{780} I_{c,i}(\lambda) T_j(\lambda) C(\lambda) d\lambda, [\text{blm/W}] \quad (2)$$

where, $I_{c,i}(\lambda) = \Phi_{c,i}(\lambda) / A_p$, $\Phi_{c,i}(\lambda)$ is the flux or power at the cornea of lamp i , A_p the pupil area, and $T_j(\lambda)$ the transmittance of filter j , and $C(\lambda)$ is the human circadian luminous efficiency function. For calculations of lamps alone (no filter), $T_j(\lambda) = 1$. The constant 683 came from the definition of a lumen. A lumen is equal to 1/683 Watts at 540 THz (approximately a wavelength of 555 nm, the peak of the luminous efficiency function).

The Melatonin Suppression Values (MSVs) presented in this manuscript are predicated on an exposure duration of 30–90 min prior to sleep. This timeframe is selected to model typical daily life exposure. This assumption is grounded in established research demonstrating that melatonin suppression magnitudes are contingent on both the duration and intensity of light exposure^{4,5}.

Furthermore, the circadian response is known to be complex, non-linear, and involves varying photoreceptor contributions over time²³. Acknowledging this dose-dependent relationship, where shorter exposures can still exert pronounced phase-delaying effects, is crucial for accurate MSV predictions. Integrating these findings ensures our calculations are empirically based, thereby enhancing the study's applicability. We note, however, that these estimates represent an average person, as the specific effects of widely varying exposures have not been rigorously studied and individual light sensitivity varies.

Normalization of spectral energy across lamps and MSV

The non-systematic procurement of our lamp sample yielded a collection that was highly heterogeneous in spectral profile, power, and “equivalent wattage” (Supplementary Table S2, Figure S2). To permit a valid direct comparison between these disparate sources, it was necessary to apply a normalization procedure. This normalization is predicated on the practical assumption that a consumer, when replacing a lamp, selects a new one based on comparable apparent brightness. This very assumption underlies the “equivalent watts” labeling used to market CFL and LED lamps, providing a sound basis for our method to ensure fair comparisons. We normalized the irradiance (I_c) of each (fixed CCT) lamp by the area under the curve integrated from 400 to 700 nm, and multiplied by the factor γ (W/m^2), thus retaining the units of the illuminance

$$I_{c,i}^{(N)} = \frac{\gamma}{I^{(vis)}} I_{c,i} [\text{W/m}^2], \quad (3)$$

where $I^{(vis)} = \int_{400}^{700} I_{c,i}(\lambda) d\lambda$ is the irradiance integrated in the main visible range. The factor γ can be calculated in terms of an arbitrary source. We chose a source of a 75 W incandescent lamp at 2 m, with an illuminance of $PIL_{75W} = 40 \text{ lx}$ ²⁴. It can be shown that the factor γ was equal to 0.16 W/m^2 (equations S8, and S9). The relationship between $MSV^{(N)}$ and $CIL_{i,j}^{(N)}$ can be written as

$$MSV_{i,j}^{(N)} = \frac{1}{1 + \exp[-k(\log(CIL_{i,j}^{(N)}) - \log(CIL_0))]} \quad (4)$$

See the supplement for the normalisation equations for the figures of merit used in the calculation of $MSV^{(N)}$ (equations S6, S7, S10).

Calculation of equivalent α -opic illuminance

Lucas et al.²⁵ noted that there are limitations to the use of $V(\lambda)$ (photopic spectral luminous efficiency function) when examining the effects on the circadian rhythm. They proposed the use of the equivalent α -opic illuminance, E_α , which is defined as:

$$E_\alpha = K_m \int_{380}^{780} \phi_c(\lambda) T(\lambda) N_\alpha(\lambda) d\lambda \cdot \int_{380}^{780} V(\lambda) d\lambda / \int_{380}^{780} N_\alpha(\lambda) d\lambda, [\text{lm/m}^2], \quad (5)$$

where $N_\alpha(\lambda)$ is the α -opic sensitivity curve with arbitrary normalisation²⁵. To calculate the equivalent α -opic illuminance for melanopsin ($N_s(\lambda)$), we used the melanopic data (available in a supplement to Lucas et al.²⁵). We used the normalised median measured spectra of the lamps and measured BLF lens transmissions as input data to calculate E_α for each standard lamp category and when in combination with BLF lenses.

Calculation of blue hazard

Blue-light hazard efficiency of radiation (η_B) and blue-light weighted radiance (L_B) were calculated by weighting the spectral power distribution of each source with the blue-light hazard function $B(\lambda)$ as defined by the CIE. Blue-light hazard efficiency of radiation was then expressed as

$$\eta_B = \frac{\int E(\lambda) T_j(\lambda) B(\lambda) d\lambda}{\int E(\lambda) d\lambda}, \quad (6)$$

where $E(\lambda)$ is the spectral irradiance of the source, $T_j(\lambda)$ is the spectral transmittance of the optical filter j , and $B(\lambda)$ is the blue-light hazard weighting function. This dimensionless efficiency quantifies the proportion of emitted optical radiation that contributes to the blue-light hazard after filtering, allowing direct comparison of different light sources and optical filters under the same illumination conditions. Similarly, the blue-hazard weighted radiance was obtained as

$$L_B = \int E(\lambda) T_j(\lambda) B(\lambda) d\lambda. \quad (7)$$

Statistical analyses

As the distributions of MSV, photopic illuminance and melanopic illuminance were highly skewed, to facilitate parametric analyses, we employed logarithmic base-10 transformations. To compare the $MSV^{(n)}$, MSV, photopic illuminance and melanopic illuminance of lamp categories without any filter, we used linear regression models, and post-estimation tests. To examine the effects of BLF lenses, we used mixed-effects models with filter as a factor, lamp category as a co-variate, and lens as a random effect, and post-estimation tests. Analyses were conducted using Stata/IC 14 (StataCorp, College Station, TX, USA) and R software (Version 3.3.3, R Foundation, Vienna, Austria), utilizing packages such as dplyr, readxl, corplot, and MASS.

Results

Irradiance of standard lamps (with a fixed correlated color temperature)

Figure 1A–E illustrates the measured irradiance spectra for the standard (fixed-CCT) lamps, grouped by technology (LED, CFL, incandescent) and CCT (cool/warm white).

The cool-LED spectra (Fig. 1A) exhibited low inter-model variability. All displayed a well-defined spectral profile with a primary peak centered at ~ 450 nm and a secondary, flatter local maximum spanning ~ 500 – 650 nm. The power at the 450 nm peak was typically 30% greater than this flatter region. This primary peak power ranged from 0.5 to 2.1 mW/m², while the power within the secondary band (~ 580 nm) ranged from 0.4 to 1.6 mW/m².

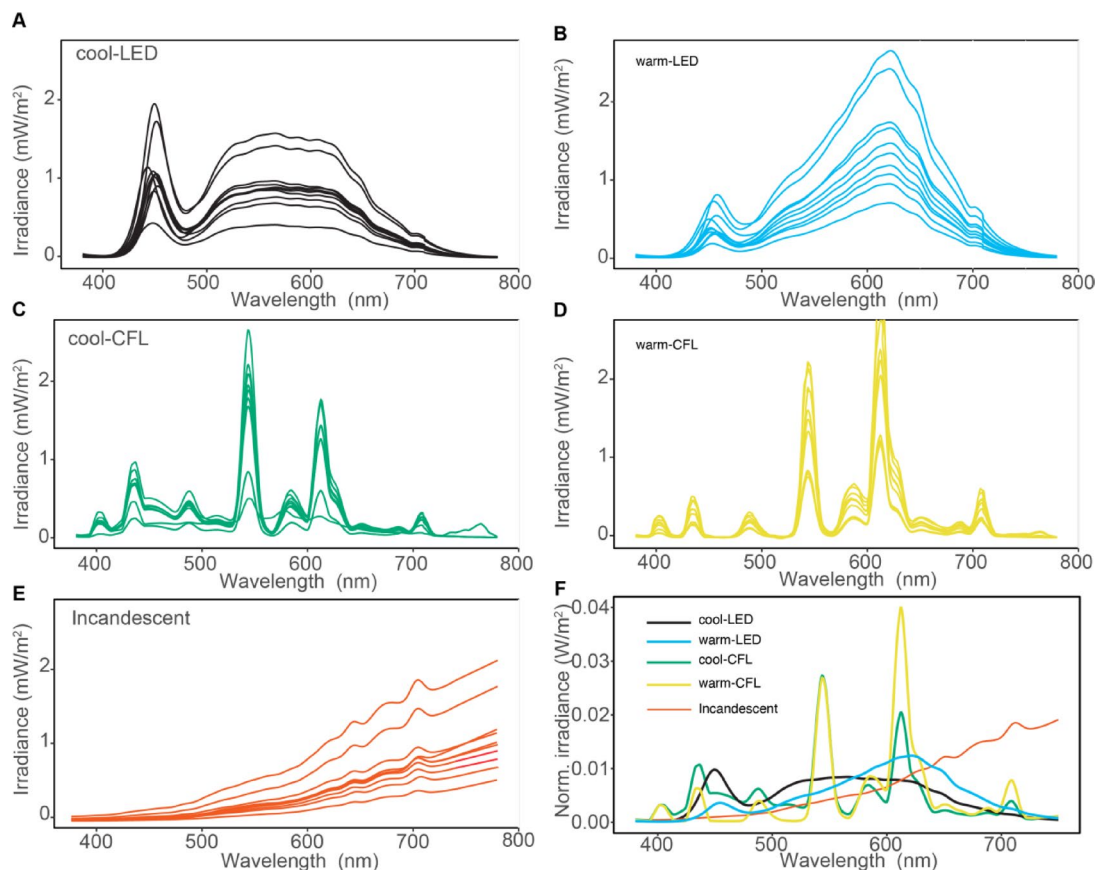


Fig. 1. Spectral irradiance at the corneal plane (not corrected for ocular media transmittance) for five lamp types: (A) cool LED, (B) warm LED, (C) cool CFL, (D) warm CFL, and E incandescent. Panel F shows the normalized median spectra of each lamp group. Note that the y-axis scale differs among panels.

Warm-LED spectra (Fig. 1B) exhibited low inter-model variability, all characterized by two well-defined peaks at approximately 450 nm and 620 nm, corroborating previous reports²⁶. The power of the 450 nm peak was typically less than 50% of the 620 nm peak's power. Quantitatively, the 450 nm peak power ranged from 0.2 to 0.8 mW/m², while the 620 nm peak ranged from 0.7 to 2.7 mW/m². Thus, the primary distinction between cool- and warm-LEDs was the magnitude of the 450 nm peak, which possessed roughly double the power in the cool-LEDs. Notably, both LED types exhibited a local minimum near 480 nm, the peak sensitivity wavelength for melanopsin^{25,27}.

In contrast, CFL lamps displayed more complex irradiance spectra (Fig. 1C, D) with multiple local maxima, consistent with Dain²⁶. Major peaks were observed at ~545 nm and ~610 nm, with lesser peaks at ~400, 435, 485, 580, and 710 nm. The principal difference between the CCTs was the greater power in the shorter-wavelength peaks for cool-CFLs. For cool-CFLs (Fig. 1C), median irradiances were 0.55 mW/m² (435 nm), 1.61 mW/m² (545 nm), and 1.11 mW/m² (610 nm). Warm-CFLs (Fig. 1D) had median irradiances of 1.42 mW/m² (545 nm) and 1.92 mW/m² (610 nm).

The incandescent lamp spectra (Fig. 1E) were distinct, exhibiting an approximately monotonic increase in power across the measured range (380–780 nm). Inter-lamp variability was manifested primarily as differences in the “slope” or total power. The median irradiance in our sample was 0.15 mW/m² in the short-wavelength region (380–500 nm) compared to 1.35 mW/m² in the long-wavelength region (650–780 nm), a ninefold disparity.

These differences in spectral power distribution across lamp technologies were expected to result in substantial differences in their impact on melatonin suppression. The negligible short-wavelength irradiance of incandescent lamps is hypothesized to cause minimal suppression. Conversely, the high-energy, short-wavelength peak in cool-LED lamps is expected to produce a much more significant suppressive effect.

Irradiance of the tunable LED lamp (variable correlated color temperature)

Examples of the measured irradiance spectra of the tunable LED lamps (Estevez, Philips-hue-color, Philips-scene-switching, and Wiz A19) at different CCTs are shown in Fig. 2. The Estevez (Fig. 2A) and Philips-scene-switching (Fig. 2C) lamps had similar spectra, although with different irradiances. For instance, the irradiance in the short-wavelength peak at 455 nm for Estevez varied from 0.23 to 0.87 mW/m² as the CCT increased, meanwhile for Philips-scene-switching varied from 0.01 to 0.24 mW/m². They appear to be composed of a diode emitting at a short wavelength with a phosphor emitting at a longer wavelength. The Philips-hue-color lamp (Fig. 2B) appeared to employ three diodes emitted at about 450, 525, and 620 nm wavelengths. As the CCT increased, the irradiance at 450 nm increased from 0.02 to 0.55 mW/m². The Wiz lamp spectra (Fig. 2D) had some similarity to the cool-LED spectra (Fig. 1B), except for the addition of two local maxima at about 614 and 633 nm. As the CCT increased, the irradiance at the 455-nm peak increased from 0.4 mW/m² at 2700 K

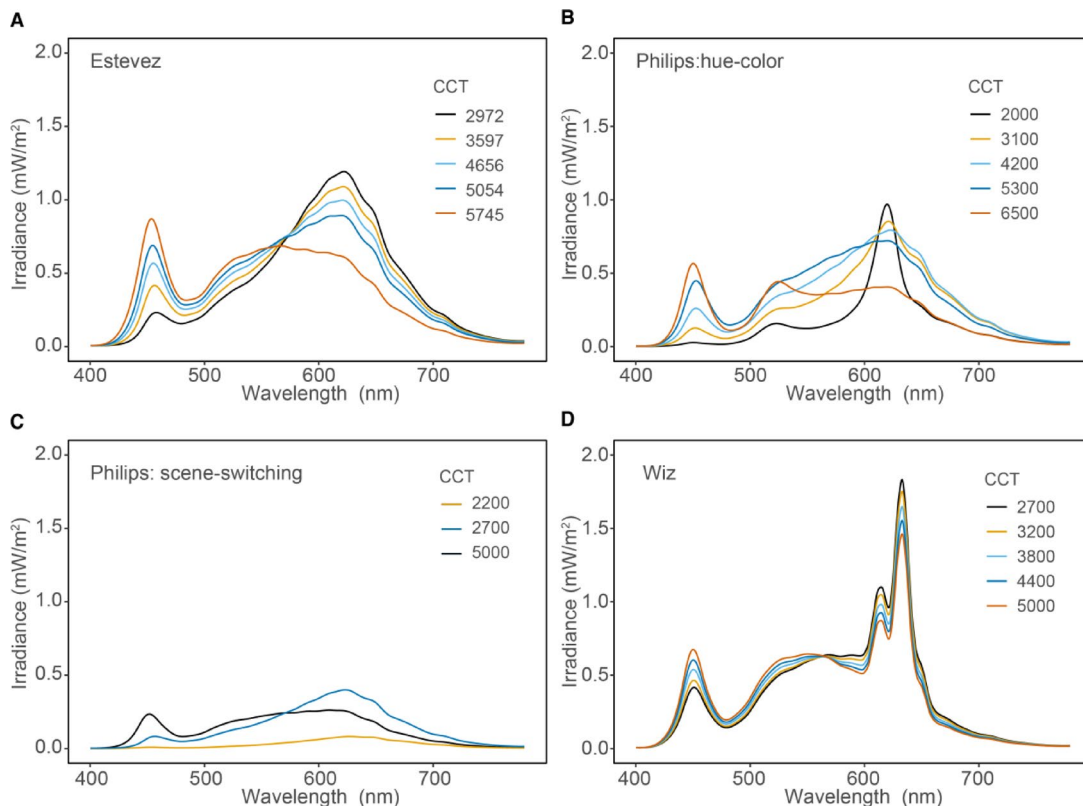


Fig. 2. Spectral irradiance of tunable LED lamps measured at up to five correlated color temperatures (CCTs): (A) Estevez; (B) Philips: hue-color; (C) Philips: scene switching; and (D) Wiz.

to 0.67 mW/m² at 5000 K. Conversely, as the CCT increased, the irradiance at the 613-nm peak decreased from 1.1 mW/m² at 2700 K to 0.86 mW/m² at 5000 K, and the irradiance at the 633-nm peak decreased from 1.85 mW/m² at 2700 K to 1.60 mW/m² at 5000 K.

Transmittance of the blue-light-filtering lenses

The measured transmittance spectra of the eight BLF lenses and a control clear lens (black line) are illustrated in Fig. 3. These lenses were categorized into two groups: four ophthalmic lenses from clinical practices, previously reported in²¹ (Fig. 3A, and four lenses procured from an online retailer (Fig. 3B). As described in²¹ the control clear lens exhibited minimal transmission below 360 nm, rising sharply in the 360–400 nm UV region before stabilizing at ~92% transmittance.

Within the ophthalmic category, all of which were marketed for “blue light hazard” protection, the two surface-coated lenses (Crizal, Blue-Protect) had similar transmittance profiles. However, Crizal allowed higher UV transmittance (36% avg.) compared to Blue-Protect (14% avg.). In the “blue-violet” wavelengths (400–460 nm), the range essential for blue light hazard protection, both showed transmittance increasing with wavelength. The two tinted ophthalmic lenses (Anti Blu-Ray, 1.6 UV Blue light) had nearly identical spectra, blocking all light from 350 to 405 nm, followed by a very steep rise to a constant transmittance.

Critically, all four ophthalmic lenses showed high transmission in the blue-green wavelengths (460–520 nm). This region corresponds to the maximal sensitivity of melanopsin (peak at 480 nm). Therefore, these lenses were not expected to substantially alter the degree of melatonin suppression produced by the lighting conditions.

The online-acquired BLF lenses, which were marketed as beneficial for sleep, showed two distinct spectral profiles (Fig. 3B). The “lightly-tinted” lenses (CGID, Spektrum) attenuated wavelengths below ~405 nm, but their transmittance rose rapidly between 405 and 500 nm. Consequently, these lenses permitted high transmission in the blue-green wavelengths, the very range associated with melatonin suppression.

In contrast, the “brown” BLF lenses (THL Sleep, Swanwick) were significantly more prohibitive, removing almost all light below the ~480 nm to 500 nm range. This strong reduction in transmission across the 400–500 nm band suggested that these “brown” lenses would be expected to have a substantial impact on melatonin suppression.

Melatonin suppression values of the standard and tunable lamps

The normalized melatonin suppression values, $MSV^{(n)}$, obtained for each of the five standard lamp categories are depicted in Fig. 4A, and summarized in Table 1 (summaries of the figures of merit used in the calculation of MSV are provided in Supplementary Table S3). The $MSV^{(n)}$ of the Cool-CFL and cool-LEDs were similar ($F(1, 47) = 0.06$, $p = 0.80$), and our hypothesis that those two cool white light lamp groups would have a higher $MSV^{(n)}$ than all other lamp groups was confirmed ($F(1, 47) = 1.665$, $p < 0.001$). Our hypothesis that incandescent lamps would have the lowest $MSV^{(n)}$ among the lamps was also confirmed ($t \geq 3.31$, $p \leq 0.002$). Non-normalised MSVs and other figures of merit are reported in Table S4. When not normalised, cool white light LEDs had much higher MSV than cool white light CFL, and warm LEDs had higher MSV than warm CFL, even though the luminous flux was similar (Supplementary Table S4), due to the differences in the spectral profiles (Fig. 1A–D).

The four tunable LED lamps tested possessed comparable power ratings: 9.5W (Philips-scene-switching, Philips-hue-color), 9W (Estevez), and 8.5W (Wiz A19). The normalized MSVs for these lamps are plotted as a function of CCT in Fig. 4B (see Table S5 for figures of merit).

As hypothesized, the MSVs of all tunable lamps increased proportionally with an increase in CCT. Performance varied by model: the Wiz lamp consistently exhibited the lowest MSVs, while the Estevez lamp showed the largest dynamic range, shifting from its warmest CCT (2972 K) to its highest (5745 K). The Estevez lamp also registered the highest MSVs overall.

This pronounced change in MSV, as observed in the Estevez and Philips Hue lamps, may create an optimal scenario for aligning with the circadian rhythm. Such lamps can be programmed (via applications for the Wiz,

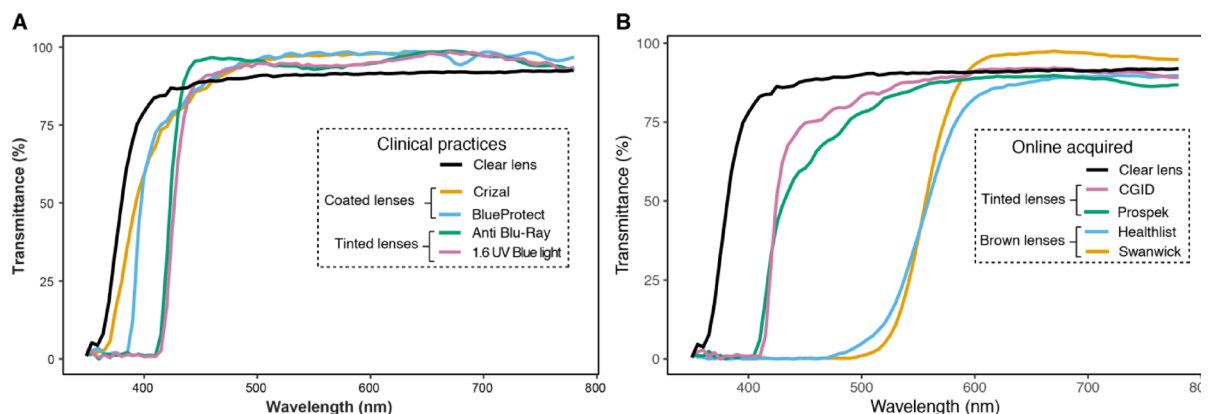


Fig. 3. Transmittance spectra of the eight blue-light-filtering (BLF) lenses examined in this study: four commonly used in clinical practice A and four acquired online B. The black line represents the transmittance spectrum of a clear lens used as a control reference. Coated and tinted lens types are indicated in the legends.

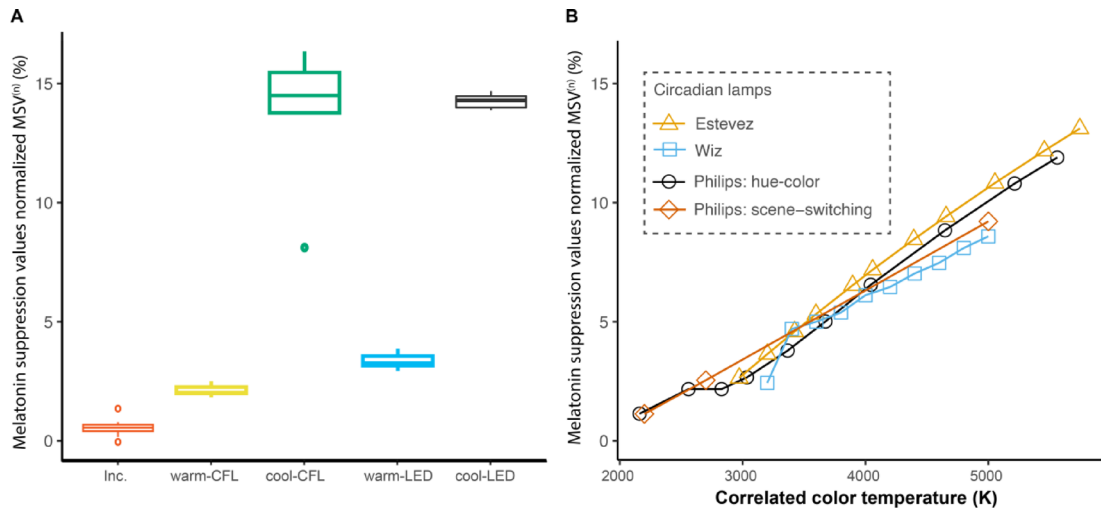


Fig. 4. Melatonin suppression values normalized ($MSV^{(n)}$, %) for **(A)** the five standard lamp categories and **(B)** the tunable LED lamps. Panel **(A)** shows median and range values for incandescent, warm-CFL, warm-LED, cool-LED, and cool-CFL lamps, while panel **(B)** illustrates the relationship between $MSV^{(n)}$ and correlated color temperature (CCT) for the four tunable LED models (Estevez, Wiz, Philips: hue-color, and Philips: scene-switching).

| Lamp group | $MSV^{(n)}$ (%) |
|--------------|------------------|
| cool-LED | 12.1 (11.8/12.4) |
| warm-LED | 3.6 (3.3/4.0) |
| cool-CFL | 12.3 (7.3/13.7) |
| warm-CFL | 2.6 (2.5/3.0) |
| Incandescent | 1.5 (1.0/2.1) |

Table 1. Median normalized melatonin suppression values ($MSV^{(n)}$, %) for the five standard lamp categories. Values in parentheses indicate minimum and maximum values. CFL, compact fluorescent lamp; LED, light-emitting diode; MSV, melatonin suppression value.

Estevez, and Philips-hue-color) to utilize a high CCT during the day and a low CCT in the evening to facilitate appropriate circadian cues. This confirms our hypothesis that tunable LED lamps have the potential to produce significant reductions in melatonin suppression from room illumination.

The relationship between effect of both the power and CAF (circadian action factor, Equation S3) on the normalized MSV is shown in Figure S3 in Supplementary information. CAF is the ratio of the circadian efficiency of radiation (Equation S5) and the luminance efficiency radiation (Equation S4). Power of the lamps was calculated from the photopic illuminance (blm; Equation S2) and efficiency values from the lamps ($k_{LED} = 102$, $k_{CFL} = 60$ and $k_{Incandescent} = 15$ lm/W) because they are related as $k_x = PIL_x / \text{Power}$, where $x = \text{LED, CFL or Incandescent}$.

Equivalent melanopic and photopic illuminance of the standard and tunable lamps

The melanopic equivalent daylight illuminance (mEDI) was calculated for all five lamp categories (Eq. 5), with results summarized in Table 2. (Data for all five α -opic illuminances are available in Supplementary Table S7 and Figure S4).

Statistical analysis of mEDI revealed significant differences ($F(4, 45) = 20.64$, $p < 0.001$). The incandescent and warm-CFL categories were statistically indistinguishable ($t = 0.20$, $p = 0.99$) and, as a group, produced lower melanopic illuminance than the other categories. Similarly, the mEDI of cool-CFL lamps was not statistically different from that of warm-LEDs ($F(4, 45) = 0.62$, $p = 0.85$). Cool-LED lamps produced a significantly higher mEDI than all other groups ($F(1, 48) = 46.76$, $p < 0.001$).

A different pattern emerged for photopic illuminance. Here, the incandescent, warm-CFL, and cool-CFL categories were statistically similar ($F(2, 27) = 0.26$, $p = 0.77$). The warm-LED and cool-LED categories were also not different from each other ($t = 1.40$, $p = 0.99$). However, the LED categories (warm and cool) combined had a significantly higher photopic illuminance than the other three categories ($F(1, 48) = 9.53$, $p < 0.001$).

The ratio of melanopic to photopic illuminance (M:P ratio) serves as a critical metric, describing the relative stimulation of the non-visual (circadian) versus the visual (photopic) system. To contextualize our data with previous in-home measurements¹, we plotted the M:P ratio as a function of melanopic illuminance (Supplementary Figure S5). This visualization is salient, as Cain et al.¹ associated improved sleep patterns

| Lamp group | <i>mEDI</i> (lx) | Photopic (lx) |
|--------------|------------------|-------------------|
| cool-LED | 41.6 (19.9/74.0) | 60.5 (28.7/107.6) |
| warm-LED | 22.4 (11.2/44.2) | 60.1 (30.2/113.5) |
| cool-CFL | 23.1 (10.6/32.4) | 35.2 (16.4/49.3) |
| warm-CFL | 9.3 (5.02/14.1) | 31.9 (17.8/51.2) |
| Incandescent | 8.2 (3.5/26.4) | 24.0 (10.6/64.6) |

Table 2. Melanopic equivalent daylight illuminance (*mEDI*) and photopic illuminance (lux) obtained from the standard lamp spectra (Fig. 1A–E) using Eq. (14) (implementation of the Irradiance Toolbox supplement to Lucas et al.¹⁸). Values in parentheses are minimum and maximum. CFL, compact fluorescent; LED, Light-emitting diode.

| BLF Lenses | | Standard Lamps | | | | |
|-----------------|------------|------------------|------------------|------------------|------------------|------------------|
| | | cool-LED | warm-LED | cool-CFL | warm-CFL | Incandescent |
| | No lens | 12.1 (11.8/12.4) | 3.6 (3.3/4.) | 12.3 (7.3/13.7) | 2.6 (2.5/3.) | 1.5 (1/2.1) |
| | Clear lens | 11.8 (11.5/12.1) | 3.5 (3.2/3.9) | 12.0 (7.1/13.5) | 2.5 (2.4/2.9) | 1.4 (1.0/2.0) |
| Ophthalmic | Seto | 12.0 (11.7/12.2) | 3.5 (3.2/4.0) | 12.2 (7.1/13.8) | 2.4 (2.3/2.8) | 1.4 (0.9/2.0) |
| | Vaccutek | 11.3 (11.1/11.6) | 3.3 (3.1/3.8) | 11.4 (6.6/13.0) | 2.2 (2.1/2.5) | 1.3 (0.9/1.9) |
| | Essilor | 11.1 (10.8/11.3) | 3.2 (3.0/3.7) | 11.3 (6.6/12.8) | 2.4 (2.2/2.7) | 1.3 (0.9/1.9) |
| | Zeiss | 11.2 (10.9/11.4) | 3.3 (3.0/3.7) | 11.4 (6.7/12.9) | 2.4 (2.2/2.7) | 1.4 (1.0/1.9) |
| Acquired online | CGID | 10.3 (10.1/10.5) | 2.9 (2.7/3.3) | 10.6 (6.1/12.1) | 2.1 (2.0/2.3) | 1.2 (0.8/1.7) |
| | Spektrum | 9.2 (9.0/9.4) | 2.6 (2.4/2.9) | 9.5 (5.4/10.9) | 1.9 (1.8/2.1) | 1.0 (0.8/1.5) |
| | Swanwick | 0.08 (0.08/0.08) | 0.02 (0.02/0.02) | 0.14 (0.08/0.15) | 0.05 (0.04/0.05) | 0.01 (0.01/0.01) |
| | THL Sleep | 0.21 (0.21/0.23) | 0.06 (0.06/0.06) | 0.33 (0.19/0.35) | 0.10 (0.08/0.11) | 0.02 (0.02/0.03) |

Table 3. Median $MSV^{(n)}$ (normalized melatonin suppression values, %) for a reference condition (no lens), a clear lens (without tint or coating), and the eight blue-light-filtering (BLF) lenses whose transmittance spectra are shown in Fig. 3. Values were calculated using the measured spectral irradiances of the 52 lamps (Figs. 1A–E). Parentheses indicate minimum and maximum values.

with conditions in the lower-left quadrant of this plot, representing both a low M:P ratio and low melanopic illuminance.

Our analysis revealed that the standard lamps formed distinct clusters corresponding to their lamp category. In contrast, the tunable LED lamps exhibited a clear monotonic increase in their M:P ratios as melanopic illuminance increased, with the only exception being the Philips-hue-color lamp at its highest CCTs.

Efficacy of blue-light-filtering glasses on melatonin suppression

To assess the efficacy of the eight BLF lenses in mitigating melatonin suppression, we computed the $MSV^{(n)}$ by combining the spectral transmission of each lens (Fig. 3) with the spectral radiance of all 52 standard lamps (Fig. 1A–E). The results are presented in Table 3 and Fig. 5A (see also Table S6).

Relative to the no-lens condition, no statistically significant reduction in $MSV^{(n)}$ was observed for either the clear control lens ($z = 0.45$, $p = 0.65$) or any of the four ophthalmic lenses obtained from clinical practices (e.g., Crizal, $z = 1.47$, $p = 0.14$; Zeiss, $z = 1.32$, $p = 0.19$).

In stark contrast, all four of the BLF lenses acquired online yielded statistically significant reductions in $MSV^{(n)}$ ($p \leq 0.006$ for all). Most notably, the two “brown-tinted” lenses (Swanwick and THL Sleep) demonstrated a profound effect, reducing $MSV^{(n)}$ by an average of 99% (range 96–100%) compared to the no-lens condition ($p < 0.001$ for both). This intervention effectively lowered $MSV^{(n)}$ to negligible levels (0.08–0.33%). This confirms our hypothesis that some, but not all, BLF lenses have the potential to produce significant and important reductions in melatonin suppression from room illumination.

Effect of blue-light-filtering glasses on melanopic illuminance

To determine whether the eight BLF lenses reduced equivalent melanopic illuminance, we computed this metric (Eq. 5) by combining the spectral transmission of each lens (Fig. 3) with the spectral irradiance of the 52 standard lamps (Fig. 1A–E).

The results, shown in Table 4 and Fig. 5B (see also Table S7), closely mirrored the $MSV^{(n)}$ findings. No statistically significant reduction in melanopic illuminance was observed for the clear lens ($z = 1.25$, $p = 0.20$) or any of the four ophthalmic lenses (e.g., Crizal, $z = 0.84$, $p = 0.40$; Zeiss, $z = 0.75$, $p = 0.46$) when compared to the no-lens condition.

Conversely, all BLF lenses acquired online (e.g., CGID, $z = 2.53$, $p = 0.01$; Spektrum, $z = 3.47$, $p = 0.001$) did provide a significant reduction. This effect was most dramatic for the two “brown-tinted” lenses (Swanwick,

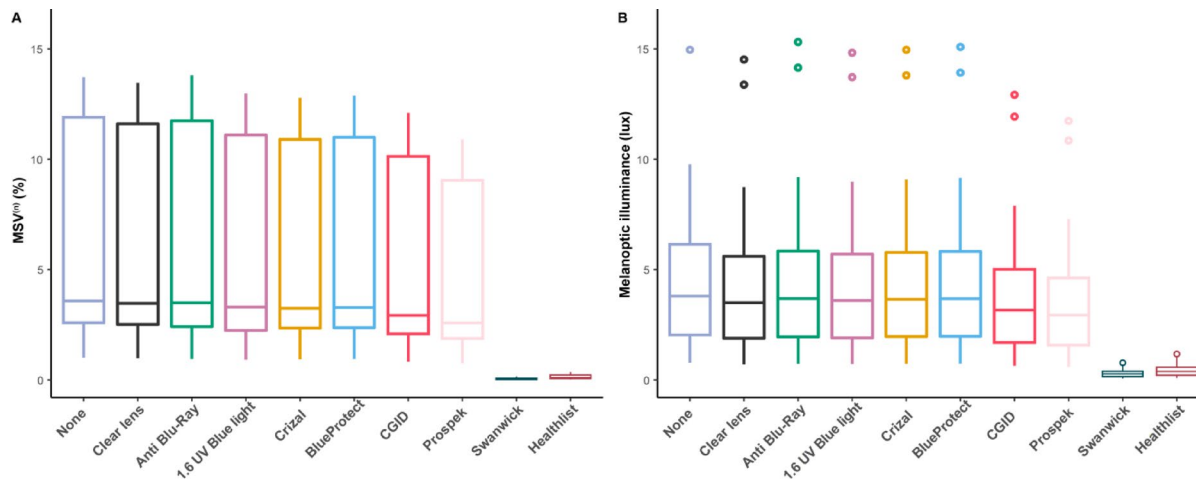


Fig. 5. Effects of blue-light-filtering (BLF) lenses compared with control conditions (no lens and clear lens) across all 52 fixed correlated color temperature (CCT) lamp spectra. Figure 5A shows the normalized melatonin suppression values ($MSV^{(n)}$, %) and Fig. 5B the melanopic illuminance (lux). The wide interquartile ranges highlight inter-lamp variability and substantial differences in photobiological response among the five standard lamp categories (see Fig. 4).

| BLF Lenses | | Standard Lamps ($lm\ m^{-2}$) | | | | |
|--------------------|------------|---------------------------------|---------------|---------------|---------------|---------------|
| | | cool-LED | warm-LED | cool-CFL | warm-CFL | Incandescent |
| | No lens | 9.1 (4.4/16.2) | 4.9 (2.5/9.7) | 5.2 (1.9/7.1) | 2.2 (1.1/3.1) | 1.8 (0.8/5.8) |
| | Clear lens | 8.2 (3.9/14.5) | 4.4 (2.2/8.7) | 4.7 (1.7/6.3) | 2.0 (1.0/2.8) | 1.6 (0.7/5.2) |
| Clinical practices | Seto | 8.6 (4.1/15.3) | 4.6 (2.3/9.2) | 4.9 (1.8/6.6) | 2.0 (1.0/2.9) | 1.7 (0.7/5.5) |
| | Vacutec | 8.3 (4.0/14.8) | 4.5 (2.3/9.0) | 4.7 (1.7/6.3) | 2.0 (1.0/2.8) | 1.7 (0.7/5.3) |
| | Essilor | 8.4 (4.0/15.0) | 4.6 (2.3/9.1) | 4.8 (1.8/6.5) | 2.0 (1.0/2.9) | 1.7 (0.7/5.4) |
| | Zeiss | 8.5 (4.1/15.1) | 4.6 (2.3/9.2) | 4.8 (1.8/6.6) | 2.1 (1.0/2.9) | 1.7 (0.7/5.5) |
| Online acquire | CGID | 7.2 (3.4/12.9) | 4.0 (2.0/7.9) | 4.1 (1.5/5.6) | 1.8 (0.9/2.5) | 1.5 (0.6/4.7) |
| | Spektrum | 6.6 (3.2/11.7) | 3.7 (1.9/7.3) | 3.8 (1.4/5.1) | 1.6 (0.8/2.3) | 1.4 (0.6/4.4) |
| | Swanwick | 0.4 (0.2/0.8) | 0.4 (0.2/0.7) | 0.3 (0.1/0.5) | 0.2 (0.1/0.3) | 0.1 (0.1/0.4) |
| | THL Sleep | 0.7 (0.3/1.2) | 0.5 (0.2/1.0) | 0.4 (0.2/0.6) | 0.3 (0.2/0.4) | 0.2 (0.1/0.6) |

Table 4. Melanopic illuminance ($lm\ m^{-2}$) for a reference condition (no lens), a clear lens (without tint or coating), and eight blue-light-filtering (BLF) lenses whose transmittance spectra are shown in Fig. 3. Values were calculated from the spectral irradiances of the standard lamps (Figs. 1A–E). Parentheses indicate minimum and maximum values.

$z = 31.3$, $p < 0.001$; THL Sleep, $z = 27.2$, $p < 0.001$). As seen in Fig. 5B, these lenses reduced the average melanopic illuminance from $4.8\ lm/m^2$ (range $0.8\text{--}16.1$) with no lens to just $0.3\ lm/m^2$ (range $0.13\text{--}0.65$).

Blue hazard

The analysis revealed substantial differences in both the blue-light hazard efficiency of radiation (η_B) and the blue-light weighted radiance (L_B) across conventional and tunable lamp types (Tables S8 and S9, see supplementary material). Incandescent lamps exhibited the lowest efficiency ($\eta_B = 0.038$) and radiance ($L_B = 189.2\ W\ m^{-2}\ sr^{-1}\ nm^{-1}$), consistent with their spectral distribution characterized by low short-wavelength emission. In contrast, compact fluorescent lamps with a cool spectrum (CFL-cool) reached the highest efficiency ($\eta_B = 0.199$), followed by cool white LEDs ($\eta_B = 0.171$). In terms of weighted radiance, cool white LEDs were the most hazardous ($L_B = 1283.5\ W\ m^{-2}\ sr^{-1}\ nm^{-1}$), nearly twice that of CFL-cool ($L_B = 734.2\ W\ m^{-2}\ sr^{-1}\ nm^{-1}$). Warm variants of both CFL and LED showed intermediate values, with efficiencies of $\eta_B \approx 0.07$ and 0.066 , respectively. These findings demonstrate that light sources with higher correlated color temperatures (CCTs) are associated with greater blue-light hazard.

Blue-light filtering lenses strongly attenuated the hazard values (Tables S10 and S11). Across all lamp types, filters from clinical practices (e.g., Swanwick, Healthlist) produced a markedly greater reduction compared with most commercial online filters (e.g., BlueProtect, Anti Blu-Ray). For example, under cool LED illumination, Swanwick lenses reduced η_B from 0.171 to 0.0029 and L_B from 1283.5 to $11.0\ W\ m^{-2}\ sr^{-1}\ nm^{-1}$, representing a reduction of nearly three orders of magnitude. Similarly, Healthlist filters achieved comparable attenuation ($\eta_B = 0.0040$; $L_B = 14.0\ W\ m^{-2}\ sr^{-1}\ nm^{-1}$). By contrast, lenses marketed clinical practices such as BlueProtect or

Anti Blu-Ray only reduced η_B to values between 0.16 and 0.18, and L_B to $\sim 1100 \text{ W m}^{-2} \text{ sr}^{-1} \text{ nm}^{-1}$, indicating a limited protective effect.

Discussion

It is well-established that white light sources from electrical and electronic devices can induce circadian disruption^{9,10,28}. Building upon this, the present study evaluated the potential for residential lighting to suppress melatonin (MSV). We systematically compared the impact of three common lamp technologies (LED, CFL, and incandescent), analyzing the effect of their correlated color temperatures (CCTs), “warm” versus “cool.” Furthermore, we investigated the efficacy of two potential mitigation strategies for reducing MSV: the use of blue-light-filtering (BLF) lenses and the implementation of tunable (variable CCT) LED lamps.

Our findings confirm a clear hierarchy of risk: the oldest technology, incandescent lamps, exerted the least circadian impact due to their low short-wavelength (380–500 nm) irradiance. Conversely, modern “cool” CCT technologies (cool-LED, cool-CFL) produced substantially higher MSV⁽ⁿ⁾ (Table 1), driven by their high spectral power near the melanopsin sensitivity peak ($\sim 480 \text{ nm}$)^{25,27}. This suggests the technological shift from incandescent to LED lighting, while energy-efficient, has introduced a potential circadian health risk, particularly during pre-sleep hours. The MSV⁽ⁿ⁾ of cool-LEDs was comparable to that of smartphone displays²¹.

Given that LEDs are the emerging standard, our results provide a clear recommendation: “warm” CCT fixed-LEDs offer a 3.4-fold (236%) reduction in MSV⁽ⁿ⁾ compared to cool-LEDs (Table S3) and are the preferable choice for evening use.

We then assessed two active mitigation strategies. The first, tunable LED lamps, function as a “night mode” for room illumination. They offer an optimal solution: providing beneficial “cool” light (high CCT) by day¹⁶ and shifting to “warm” light (low CCT) in the evening, at which point their MSV⁽ⁿ⁾ (0.2–3.1%) is comparable to or better than fixed “warm” lamps.

The second strategy, BLF lenses, yielded more nuanced results that help clarify the current controversy²⁰. Our calculations showed that most ophthalmic BLF lenses provide negligible circadian benefit. However, two “brown-tinted” models (Swanwick, THL Sleep) provided excellent MSV⁽ⁿ⁾ and melanopic illuminance reduction (Tables 3 and 4), which we attribute to their filtering of the 480–500 nm range. This finding is supported by recent clinical data^{22,29} and suggests that only BLF lenses with this specific filtering profile should be recommended for sleep improvement.

Finally, our results, while consistent with Cain et al.¹, diverge from some earlier, small-sample studies^{26,30}. We challenge the conclusion that home lighting is insufficient for melatonin suppression^{30,31}, as our measured illuminance for modern lamps ($\sim 55 \text{ lx}$) meets the 50 lx threshold. We attribute this discrepancy to our larger ($n = 52$) and more contemporary lamp sample, which better reflects the current lighting environment.

It is essential to acknowledge the limitations of this study. The reported MSV⁽ⁿ⁾ values are *in silico* calculations, not direct physiological measurements, and are predicated on two primary assumptions: (1) a 30- to 90-min evening exposure duration, and (2) a luminance normalization equivalent to a 75W incandescent lamp. Consequently, the calculated MSV⁽ⁿ⁾ and melanopic illuminance represent an estimate of the average response. This model does not account for the substantial inter-individual variability in light sensitivity that has been reported^{1,3}, the mechanisms of which remain unknown. Therefore, our results may represent a typical response for a healthy adult (18–35 years) and may not reflect individual experiences, which are known to be influenced by numerous factors^{2,3}.

Our analysis confirms a direct correlation between CCT and photobiological risk: lamps with higher correlated color temperatures (CCTs) exhibit a greater blue-light hazard. Incandescent lamps presented the lowest values, while cool-spectrum CFLs and LEDs were the highest. These results align with previous findings linking short-wavelength-enriched spectra to increased photobiological risk^{32,33}.

Blue-light filtering lenses markedly reduced hazard values, though their effectiveness was highly variable. Certain online products (e.g., Swanwick, Healthlist) achieved profound reductions of nearly three orders of magnitude, even under cool LED illumination. In contrast, several clinically validated filters (e.g., BlueProtect, Anti Blu-Ray) offered only marginal attenuation, leaving hazard values close to unfiltered conditions. These findings emphasize that only high-quality, clinically tested filters provide meaningful protection against blue-light hazard, while many consumer-marketed lenses often fail to deliver.

This study analyzed multiple circadian and photobiological parameters, but its scope did not include color fidelity. While color fidelity is critical for visual tasks, its inclusion would have greatly expanded a manuscript that already integrates numerous indices (CAF, LER, CER, MSV, melanopic/photopic illuminance, and blue-light hazard). We therefore focused on parameters most relevant to circadian regulation. Future research should systematically examine color fidelity and its trade-offs with circadian efficacy and blue-light mitigation.

In conclusion, the increasing prevalence of LED home lighting is likely to have a measurable effect on the human circadian rhythm compared to the era of incandescent-only illumination. These effects, however, can be effectively mitigated by the deployment of tunable (“circadian”) LED lamps and the use of “brown” BLF glasses.

Data availability

All data generated or analyzed during this study are included in this article (and its Supplementary Information files).

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Author contributions

Research idea and study design: ET. Data acquisition: ET, CMYR. Data analysis/interpretation: ET, CMYR, RLW. Supervision or mentorship: RLW. Manuscript drafting: ET, CMYR, RLW. Critical revision and final approval: ET, CMYR, RLW, HJSA, AKDA.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

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