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DEGRADATION OF BIOLOGICAL POTENCY IN LED LIGHT SOURCES WITH LIFETIME

S. Belgers[1], L.J.M. Schlangen[1], R.H. Cuijpers[1], I. Heynderickx[1]
[1] Eindhoven University of Technology, Eindhoven, THE NETHERLANDS
s.belgers@tue.nl

DOI 10.25039/x50.2023.PP003

Abstract

This paper investigates the degradation of biological potency in LED light sources over their lifetime. Biological potency refers to the ability of light to generate biological effects, for instance on sleep, mood, and circadian rhythms. Current lifetime metrics for LEDs typically do not consider the biological potency, despite its relevance for human health and well-being. Therefore, we investigate such metrics and explore blue light hazard changes over the lifetime of LEDs.

Using a dataset of accelerated aging of LEDs, we show that the melanopic equivalent daylight luminance maintenance decreases faster than lumen maintenance, this effect is smaller in LEDs of 4000K versus 2700K. Over lifetime, the melanopic daylight efficacy ratio also decreases, while the blue light hazard does not significantly increase.

Our findings highlight the need to consider changes in biological potency over time in the design and implementation of LED lighting solutions.

Keywords: LED aging, Biological potency, Melanopic equivalent daylight illuminance, Melanopic daylight efficacy ratio, Lumen maintenance, Colourpoint, Chromaticity shift, Blue light hazard

1 Motivation, Objective

Light does not only facilitate visual perception, but also modulates our sleep, our mood, and our circadian rhythm (Vetter et al., 2022). The degree to which light has the ability, or potency, to influence these biological effects is denoted as the biological potency of light. This biological potency strongly depends on the illuminance and spectral power distribution of the light: our biological system is most affected by bright light with increased short-wavelength (blue) content (Joyce et al., 2022; Lucas et al., 2014). Previous research has already described the importance of incorporating this biological potency into lighting solutions. There are clear recommendations with respect to the biological potency of light (Brown et al., 2022; Schlangen et al., 2022), how to incorporate it in the design process of lighting solutions (Houser & Esposito, 2021), and what metrics to apply as suitable proxies for the biological potency (Esposito & Houser, 2022).

As LED light sources age, their lumen output degrades, and their chromaticity changes (Van Driel et al., 2018). Currently, the lifetime of LED light sources is most often determined based on the lumen maintenance, sometimes in combination with the shift in chromaticity. Lumen maintenance is the remaining percentage of lumen output compared to the initial lumen output. The resulting lifetime is determined as the time in burning hours until the lumen maintenance is below a specified amount, often 80% (L_{80} standard) (IES, 2008). Furthermore, the shift in chromaticity of the LED source with age is measured in absolute distance to the initial chromaticity in the CIE 1976 (u′ v′) chromaticity diagram. In the often used ENERGY STAR® specifications state that all light units can have a maximum chromaticity shift of 0.007 (ENERGY STAR®, 2020). Both lifetime specifications primarily rely on visual perception metrics, overlooking the importance of biological potency, and are therefore not suitable as proxies for the biological potency of the light. Hence, the design and implementation of light solutions with suitable biological potency requires different metrics that reflect how the biological potency degrades during aging of the LEDs.

The chromaticity is not a good descriptor of biological potency, as light with the same chromaticity can have different biological potency (i.e., through a different contribution of the spectral distribution in the short-wavelength region) (Esposito & Houser, 2022; Zandi et al.,

2021). The standardly used metrics of biological potency are based on (melanopsin) photoreceptor excitation. The two most common metrics are: (1) the melanopic daylight efficacy ratio (mDER), and (2) the melanopic equivalent daylight (il)luminance (mEDL). mDER is the ratio of the melanopic efficacy of luminous radiation for the test light divided by the melanopic efficacy of luminous radiation for standard daylight D65, and can be considered to be a metric of the biological potency normalised per unit of light (Schlangen et al., 2022). mEDL quantifies the biological potency of light by indicating the amount of standard D65 daylight required to produce equal melanopsin photoreceptor excitation as the test light (CIE, 2020b). Thus, it would be more appropriate to use these metrics for the quantification of the lifetime of LED lighting solutions, especially when biological potency is considered an important aspect of the design.

The spectral changes during LED ageing can not only affect the biological potency but also the BLH. BLH refers to the potential harm caused by exposure to high-energy low-wavelength (blue) light in the range of 400 to 500 nm (ICNIRP, 2013). Light sources with higher blue light emissions can contribute to increased blue light hazard (BLH) and raise concerns about potential eye-related health risks (Ouyang et al., 2020). Consequently, understanding the BLH, evaluating it, and considering it during the full lifetime of LEDs is crucial to ensure eye safety, also on the longer term. Potential changes in BLH can be evaluated by evaluating the blue light hazard efficacy of luminous radiation, which measures the ability of light sources to emit harmful blue light (CIE, 2020a).

This study explores potential changes in how the current LED lifetime metrics relate to the lifetime in terms of biological potency, and explores blue light hazard changes over the lifetime of LEDs.

2 Methods

The data we used are based on the full dataset from Hamon's dissertation (2014). This dataset contains accelerated aging data including the full spectral power distribution at several points in time for a variety of Philips Lumileds pre-production components soldered on a printed circuit board. Spectral data were obtained using an integrating sphere (Labsphere, n.d.). The LEDs were measured at fixed points in time (shown in Table 1). Hourly data were obtained by linearly interpolating between these measured time points. While measurements were performed at several currents, only the measurements at a current of 350mA (i.e., operating current under normal conditions) were included in this study, which was done to prevent double inclusion of LEDs. The aging of the LEDs was accelerated by increasing the ambient temperature to values ranging from 80 degrees Celsius to 120 degrees Celsius and by using driving currents ranging from 350 mA to 1000 mA.

Table 1 – Measurement times in hours

Measurement Time [hours]	0	24	48	96	168	254	500	1000	2000	3000	4000	5000	6000	7000	8000

Table 2 shows an overview of all the included data. For the analysis, data were grouped by correlated colour temperature (CCT) as biological potency and blue light hazard can be vastly different for LEDs with different CCTs. The first group consisted of 30 LEDs with a CCT of 2700K and the second group consisted of 16 LEDs with a CCT of 4000K.

Four batches out of the 8 batches in the original dataset were excluded. Each batch consisted of 16 or more LEDs. Two batches were fully excluded as they were non-white light sources. Two more batches were fully excluded as the aging process did not sufficiently progress within the maximum duration to have lumen degradation below 80% of the initial lumen output, according to the L_{80} standard. From the remaining four batches we included a total of 46 LEDs, while we excluded 12 LEDs as no measurements were provided past the first 100 hours, and we excluded 18 LEDs as their lumen-maintenance-based lifetime (referred to as LM_{80} lifetime) was not between 100 hours and the time of their last measurement.

Table 2 – Overview of included data

Batch ID	Ambient Temperature	Driving current	LED samples in dataset	LED samples in analysis	CCT	Maximum aging duration
1	120	700 mA	21	15	2700K	6000 hours
2	80	700 mA	20	2	2700K	8000 hours
6	100	1000 mA	19	13	2700K	4000 hours
31	100	1000 mA	16	16	4000K	4000 hours

For each LED, lifetime was normalized and expressed on a scale from 0 to 100%, where 0% corresponded to a time of 0 hours and 100% corresponded to the time where a lumen maintenance of 80% of the initial lumen output was reached.

The mEDL maintenance is calculated according to the method for determining lumen maintenance. mEDL was according to the CIE standard (CIE, 2020b) using LuxPy (Smet, 2020). The mEDL maintenance, the mEDL relative to the initial mEDL, is calculated and expressed in percentages, as seen in (1). A one sample t-test is used to evaluate whether the mEDL maintenance is different from the expected value of 80% (L_{80} standard) at the end of the LM_{80} lifetime.

$$\text{mEDL maintenance}_t = \frac{\text{mED}}{\text{mEDL}_{\text{Initial}}} * 100\% \quad (1)$$

For each LED, the mDER at different times was calculated according to the CIE standard (CIE, 2020b) using LuxPy (Smet, 2020). To determine a significant difference, we grouped the LEDs per CCT, and compared the initial mDER with the end-of-lifetime mDER using a paired samples t-test.

Next, we calculated for each LED the initial co-ordinates in the CIE 1976 (u′ v′) chromaticity diagram and the point at the lumen-maintenance based end-of-lifetime according to the CIE standard (CIE, 2018) using LuxPy (Smet, 2020). The shift in chromaticity was determined as the linear distance between these two chromaticity co-ordinates, as seen in (2), and was compared to the value of 0.007 as prescribed by the ENERGY STAR® specifications.

$$\text{Chromaticity shift} = \sqrt{\Delta u'^2 + \Delta v'^2} \quad (2)$$

Finally, the blue light hazard efficacy of luminous radiation was calculated according to the CIE standard (CIE, 2020a) using LuxPy (Smet, 2020). A one-tailed paired samples t-test was used to determine whether blue light hazard significantly increased at end-of-lifetime compared to the initial blue light hazard potential.

3 Results

In this section, we present the findings of our study on the performance and characteristics of LEDs. We discuss the LM_{80} lifetime, the melanopic equivalent daylight luminance maintenance, the melanopic daylight efficacy ratio, the chromaticity shift, and the blue light hazard potential. These results provide insights into the behaviour of LEDs over their operational lifetime and their suitability for different applications.

3.1 Lumen Maintenance based lifetime

The lifetime based on the L_{80} Lumen Maintenance standard (referred to as LM_{80} lifetime) was determined for each LED, and normalised to the range from 0% at the beginning to 100% at the time the lumen maintenance of the LED degraded to 80%. LM_{80} lifetime ranged from 675 to 7142 hours, with an average lifetime of 1290 hours (interquartile range: from 1185 hours to 1978 hours).

3.2 Melanopic equivalent daylight luminance maintenance

The degradation of lumen maintenance and mEDL maintenance during the LM_{80} lifetime of the LEDs grouped by CCT is shown in figure 1.

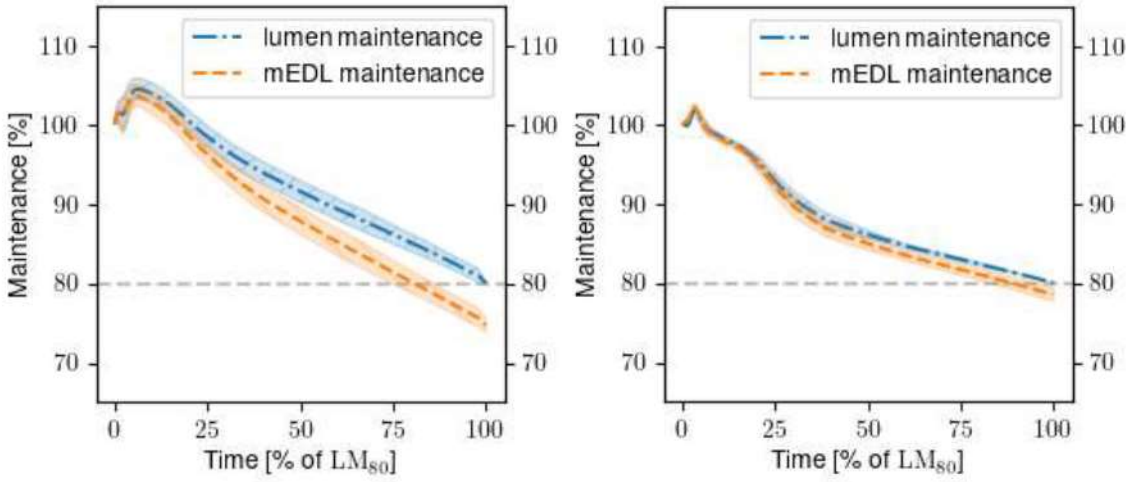

Figure 1 – Degradation of lumen maintenance and mEDL maintenance from initial measurement (0%) to end of LM_{80} lifetime (100%), grouped by LED CCT (Left: 2700K, Right: 4000K). The dashed line represents the mean over all LEDs, while the shaded area gives the 95% confidence interval.

The mEDL maintenance at the end of the LM_{80} lifetime was lower than 80%, which shows that the biological potency degraded faster than the luminance. The mean mEDL maintenance was 74.7% (95% CI: [73.8, 75.6]) for the LEDs with a CCT of 2700K, and 78.7% (95% CI: [77.7, 79.6]) for the LEDs with a CCT of 4000K. To evaluate whether the degradation in biological potency was significantly faster than the degradation in luminance, we performed a one-sample t-test to compare the mEDL maintenance values of all LEDs per CCT-group with the value of 80%. We found a statistically significant difference for both the LEDs with a CCT of 2700K ($t(29) = -11.83$, $p < 0.01$) and the LEDs with a CCT of 4000K ($t(14) = -3.34$, $p < 0.01$).

3.3 Melanopic daylight efficacy ratio

Next, we calculated the initial mDER and its change over lifetime until the end of the LM_{80} lifetime for each LED. This averaged change in mDER – averaged over the LEDs grouped by CCT – over the LM_{80} lifetime is shown in Figure 2.

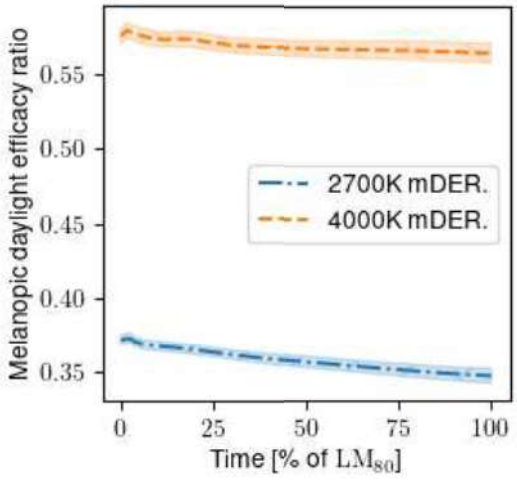

Figure 2 – Change in mDER over time, from initial measurement (0%) to end of LM_{80} lifetime (100%), grouped by LED CCT. The dashed line represents the mean over all LEDs, while the shaded area gives the 95% confidence interval.

Figure 2 shows a clear decrease in mDER over time for both groups of LEDs. For the LEDs with a CCT of 2700K, the initial mDER (M=0.37, SD=0.01) was significantly higher than the mDER at the end of the LM_{80} lifetime (M=0.35, SD=0.01). The mean mDER decreased by 0.02 (95% CI [0.02, 0.03], $t(29)=11.83$, $p < 0.01$). Also for the LEDs with a CCT of 4000K, the initial mDER (M=0.58, SD=0.01) was significantly higher than the mDER at the end of the LM_{80} lifetime (M=0.57, SD=0.01) with a mean decrease of 0.01, (95% CI [0.00, 0.02], $t(16)=3.07$, $p < 0.01$).

3.4 Chromaticity shift

The shift in chromaticity during the LM_{80} lifetime was compared to the maximum shift of 0.007 prescribed by ENERGY STAR® specifications for each LED. In the group of LEDs with a CCT of 2700K 22 out of 30 LEDs met the requirement, whereas in the group of LEDs with a CCT of 4000K 14 out of 16 LEDs met the requirement. All LEDs were within a chromaticity shift of 0.010. While we observed that the chromaticity shift was larger than allowed according to the ENERGY STAR® guidelines, further discussion and interpretation of these findings is beyond the scope of this paper.

3.5 Blue light hazard

The blue light hazard efficacy of luminous radiation was determined over the LM_{80} lifetime of the LEDs to assess potential risks associated with blue light exposure. Figure 3 shows the change in the BLH potential over the lumen-based lifetime, averaged over all LEDs grouped by CCT. As expected, LEDs with a CCT of 4000K (M=0.56, SD=0.02) have higher initial blue light hazard efficacy of luminous radiation than LEDs with a CCT of 2700K (M=0.21, SD<0.01).

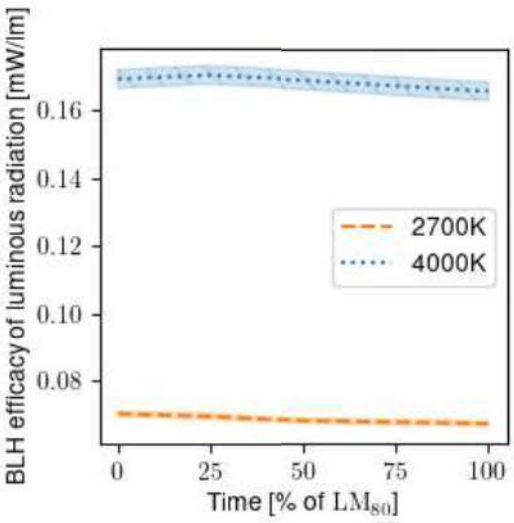

Figure 3 – The blue light hazard efficacy of luminous radiation over time from initial measurement (0%) to end of the LM_{80} lifetime (100%), grouped by CCT with 4000K and 2700K. The dashed lines represent the mean over all LEDs, while the shaded areas give the 95% confidence interval.

The curves in Figure 3 suggest that the BLH potential does not increase over the lifetime. We found no statistically significant evidence that indicated that the means of BLH efficacy of luminous radiation was higher at the end of the lumen-based lifetime compared to the initial values. This was true for LEDs with a CCT of 2700K as well as LEDs with a CCT of 4000K.

However, the means of the BLH efficacy of luminous radiation were not statistically significantly lower at the end of the lumen-based lifetime as compared to the initial values .

4 Discussion and Conclusions

Across lifetime, the melanopic equivalent daylight luminance (mEDL) maintenance decreased more quickly than the lumen maintenance. This effect was smaller for LEDs with a CCT of 4000K than for LEDs with a CCT of 2700K. This finding was in line with the trend that the melanopic daylight efficacy ratio (mDER) decreased over the lifetime of the LEDs, and that this decrease was larger for LEDs with a CCT of 2700K than for LEDs with a CCT of 4000K. Whether these findings can be extrapolated to LEDs with a higher CCT is unclear, but it may suggest that for higher CCTs the effect is even smaller.

Lighting applications for which a low biological potency is desirable, such as pre-bedtime home lighting, frequently use LEDs with a low CCT and low mDER. For these applications it is not detrimental that the mDER of the 2700K en 4000K LED groups decreases over the LM_{80} lifetime, neither is it an issue that the mEDL maintenance decreases quicker than the lumen maintenance. For applications where high biological potency is of importance, LEDs with higher mDER (and usually, higher CCT) are generally used. In these cases, it can be unfavourable if the mEDL maintenance decreases quicker than the lumen maintenance.

Additionally, it has been found that BLH potential did not increase over the lifetime of the LEDs included in the study. This implies that as long as the initial blue light hazard poses no risks it will stay that way across the entire lumen-maintenance based lifetime (LM_{80} lifetime).

As the chromaticity shift of the LEDs included in this study did not always remain within limits of the ENERGYSTAR® guidelines, future studies should attempt to use data on LEDs aged with and without acceleration, as the accelerated aging might emphasise the chromaticity shift and consequently the changes in biological potency of the LM_{80} lifetime of LEDs. Furthermore, future studies could include (blue) narrow-band LEDs as small effects of aging could have larger effects on the biological potency and blue light hazard.

Overall, blue light hazard and biological potency merit to be included in multi-domain simulations and virtual prototyping (digital twinning) of LED chips and luminaires.

5 Acknowledgment

We would like to thank Dr. Hamon for kindly providing us with the experimental dataset and access to his dissertation. Additionally, we would like to thank Dr. Smet for developing the LuxPy package, which included the necessary calculation tools for this paper.

6 Funding

The authors disclosed receipt of the following financial support for the research, authorship and/or publication of this article: This work is (partially) supported by funds from the European Union and the nationals contributing in the context of the ECSEL Joint Undertaking programme (2021–2024) under the grant #101007319.

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