Nominal CCT is an insufficient predictor of melanopic efficacy: statistical evidence from measured neutral-white LED light sources

Maciej Listowski,* Piotr Bałdyga, Błażej Gajewski, and Irena Fryc

Bialystok University of Technology, Faculty of Electrical Engineering, Wiejska 45D, 15-351 Bialystok, Poland

Received May 21, 2026; accepted June 30, 2026; published June 30, 2026

Abstract—Nominal Correlated Color Temperature (CCT) is widely used to specify neutral-white LED luminaires, yet it is insensitive to the melanopic pathway governing circadian entrainment. This study statistically characterizes the melanopic Daylight Efficacy Ratio (m-DER, CIE S026/E:2018) across 279 measured 4000 K commercial LED spectra from the EMPIR/PNNL databases. The m-DER distribution is non-normal and wide (0.419–0.722; SD = 0.051); CCT explains only 16 % of within-class variance (Pearson $r = 0.395$, $r^2 \approx 0.156$; Spearman $\rho = 0.470$). Seven percent of products fail the CIE PS001:2024 daytime threshold (m-EDI ≥ 250 lx at E = 500 lx). A novel asymmetry is identified: the Duv-m-DER correlation is significant above the Planckian locus ($\rho = -0.333$) but negligible below it ($\rho = 0.071$, $p = 0.477$). These findings strongly support m-DER disclosure as a necessary step toward reliable human-centric lighting specification.

The primary metric for specifying the light color of white LED luminaires is Correlated Color Temperature (CCT), yet it is entirely insensitive to the melanopic pathway that regulates human circadian rhythms. Intrinsically photosensitive retinal ganglion cells (ipRGC), with peak sensitivity near 480 nm, project to the suprachiasmatic nucleus [1]; chronic underexposure is linked to circadian phase delay and elevated cardiometabolic risk. Because CCT is colorimetric rather than spectroradiometric, two 4000 K sources can differ substantially in the 450-500 nm band, driving ipRGC stimulation while appearing identical on any product label. The CIE S026/E:2018 [2] formalizes this with the melanopic Daylight Efficacy Ratio (m-DER) and melanopic Equivalent Daylight Illuminance m-EDI (eq. 1), the circadian stimulus in D65 equivalent lux. The CIE PS001:2024 [3] and Brown et al. [4] recommend m-EDI ≥ 250 lx during active hours, translating at E = 500 lx to m-DER ≥ 0.500 - a threshold absent from any current product label.

$$m - EDI = E \cdot m - DER \tag{1}$$

Prior work confirms CCT is an unreliable melanopic proxy [7,8]: Esposito and Houser [7] found up to 123 lx variation in m-EDI at fixed CCT using simulated spectra, while Trinh et al. [8] quantified m-DER across 2800 K−5100 K, but the broad range masks within-class variability. The research gap is therefore precise: no study has statistically characterized the m-DER distribution exclusively within the 4000 K nominal CCT LEDs using measured commercial spectral power distributions (SPDs), assessed the fraction failing CIE PS001:2024 at standard office illuminance, or tested whether the Duv-m-DER relationship differs between sources above and below the Planckian locus. This study fills that gap by providing the first statistical characterization of m-DER within n = 279 4000 K nominal CCT LEDs - the first empirical estimate of the non-compliance rate under CIE PS001:2024 at E = 500 lx, and the first report of an asymmetric Duv-mDER correlation structure that differs fundamentally between sources above and below the Planckian locus.

The SPDs were drawn from the EMPIR (PhotoLED) and PNNL Lighting Product databases (calibrated, traceable spectroradiometric measurements). Products with nominal CCT = 4000 K were pre-selected; those outside the ANSI C78.377 [9] 7-step quadrangle bin in CIE1976 *u'v'* were excluded, yielding n = 279 SPDs (Fig. 1a,b). For each SPD S(λ), CCT and Duv were computed per CIE 015:2018 using the Robertson method for CCT and the signed distance to the Planckian locus in *u'v'* for Duv. The melanopic Daylight Efficacy Ratio was calculated per CIE S026/E:2018 [2] as m-DER (eq. 2), where $s_m(\lambda)$ is the CIE melanopic action spectrum and $s_{eqlum}(\lambda)$ is the normalization constant relative to the D65 reference illuminant.

$$m - DER = \frac{\int_{380}^{780} s_{eqlum}(\lambda) \cdot s_m(\lambda) d\lambda}{\int_{380}^{780} s_{D65}(\lambda) \cdot s_m(\lambda) d\lambda} \tag{2}$$

$$s_{eqlum}(\lambda) = \frac{\int_{380}^{780} s_{D65}(\lambda) \cdot V(\lambda) d\lambda}{\int_{380}^{780} S(\lambda) \cdot V(\lambda) d\lambda} S(\lambda) \tag{3}$$

The m-EDI = E · m-DER was evaluated at E = 500 lx (EN-12464-1 office target). All spectral integrals were computed over 380−780 nm at 1 nm resolution per

* E-mail: maciej.listowski@pb.edu.pl

CIE S026/E:2018 [2]; the melanopic action spectrum $s_m(\lambda)$ was used in its tabulated form as defined in CIE S026/E:2018 [2]. The sample was stratified by sign of Duv: Duv < 0 (n = 103) and Duv ≥ 0 (n = 176).

Normality was assessed using the Shapiro-Wilk and Kolmogorov-Smirnov tests ($\alpha = 0.05$). Associations were quantified by Spearman ρ (permutation test, 10 000 replicates) and Pearson r; effect size by R^2. Regression lines use the Theil-Sen estimator (bootstrap CI, 5 000 replicates). The non-compliance rate is reported with exact binomial 95 % CI.

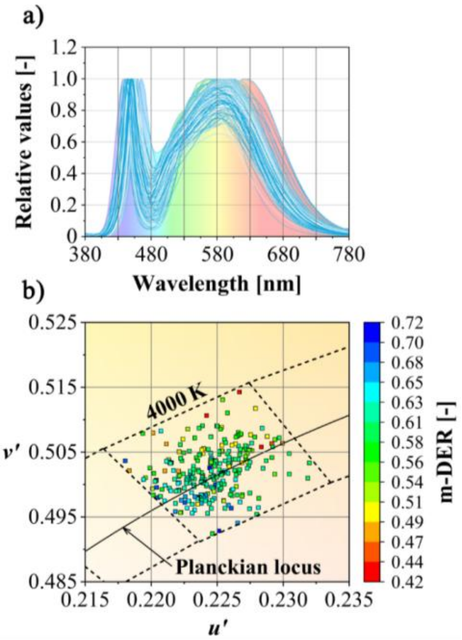

Fig. 1. a) Normalized SPDs of 279 LED sources at nominal CCT = 4000 K, color coded by m DER; b) chromaticity in CIE1976 *u'v'* with ANSI C78.377 quadrangle, point color = m-DER value.

Table 1 summarizes descriptive statistics. The m-DER distribution (Fig. 2a,b) is left skewed ($\gamma_1 = -0.895$) and leptokurtic; both S-W (W = 0.938, $p < 0.001$) and K-S (D = 0.136, $p < 0.001$) tests reject normality. The m DER range exceeds 0.30, corresponding to a 1.7-fold biological difference in melanopic stimulus between extremes of the same CCT class. Seven percent of products (n = 20) yield m-EDI < 250 lx at E = 500 lx, falling below the CIE PS001:2024 daytime threshold. The minimum recorded m-EDI is 209.6 lx, representing a 16 % deficit relative to the recommendation. Table 2 reports Spearman and Pearson correlations. The m-DER CCT correlation (ρ = 0.470, r = 0.395, both $p < 0.001$) explains $R^2 \approx 16$ % (based on Pearson $r^2 = 0.156$) of m-DER variance. The m-DER-Duv correlation is statistically insignificant in the Duv < 0 subgroup (ρ = 0.071, $p = 0.477$; r = −0.021), confirming that chromaticity position cannot predict melanopic level for pinkish white sources (Duv < 0). The near-zero magnitude of both coefficients is the key finding; the opposing signs of ρ and r reflect the non-monotonic rank structure of this subgroup rather than a genuine directional effect, and are consistent with the absence of any meaningful Duv-m-DER relationship below the Planckian locus.

Table 1. Descriptive statistics of m-DER and m-EDI (E = 500 lx) for n = 279 LED sources, CCT = 4000 K.

Statistic	m-DER [-]	m-EDI [lx]
Mean	0.595	297.6
Median	0.605	302.6
Q1	0.574	287.1
Q3	0.628	313.8
Min	0.419	209.6
Max	0.722	361.4
IQR	0.054	26.8
SD	0.051	25.4

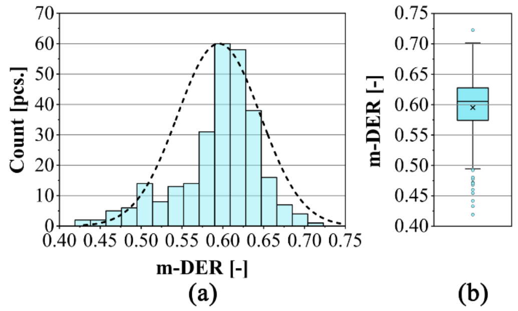

Fig. 2. (a) Histogram of m-DER distribution with fitted normal distribution envelope (dashed curve); (b) box plot (line = median, × = mean, whiskers = Q1 1.5IQR / Q3+1.5IQR, dots = outliers). The m-DER = 0.500 marks the threshold equivalent to m-EDI = 250 lx (CIE PS001:2024) at E = 500 lx.

Table 2. Spearman ρ and Pearson r correlations of m-DER with CCT and Duv (*p < 0.001; n.s. not significant).

Subgroup (n)	m-DER/CCT		m-DER/Duv	
	ρ	r	ρ	r
Full (279 pcs.)	0.470*	0.395*	-0.351*	-0.358*
Duv < 0 (103 pcs.)	0.421*	0.322*	0.071 n.s.	-0.021 n.s.
Duv ≥ 0 (176 pcs.)	0.468*	0.396*	-0.333*	-0.333*

Figure 3 visualizes both relationships: m-DER vs CCT (left) shows a positive trend with wide within-class spread, while m-DER vs Duv (right) reveals the asymmetric pattern - a clear negative slope above the Planckian locus and none below. The contrast between subgroups is structural: above the Planckian locus, phosphor-blend variation drives the negative Duv-m-DER slope, whereas below the locus the red-enriched phosphor systems of pinkish-white sources decouple blue-pump output from chromaticity. Any predictive model based on chromaticity alone will therefore underestimate melanopic uncertainty for Duv < 0 products.

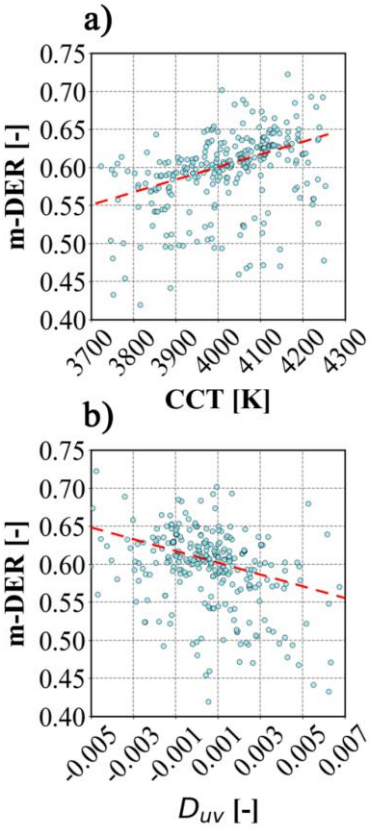

Fig. 3. a) Scatter plots of m-DER vs CCT and b) m-DER vs Duv for n = 279 LED sources. Lines: Theil-Sen regression.

The within-class m-DER spread (range 0.303, SD = 0.051) confirms that nominal CCT = 4000 K is an insufficient melanopic predictor, extending simulation-based findings [7] to measured commercial spectra. The left-skewed distribution means biologically suboptimal products arise more frequently than a Gaussian model predicts: 7 % of products fail the CIE PS001:2024 threshold at E = 500 lx − a risk entirely invisible from current product labels. Over 84 % of within-class m-DER variance is independent of chromaticity, and the asymmetric Duv-m-DER structure suggests pinkish-white sources constitute a distinct phosphor family whose melanopic output is decoupled from chromaticity. The 1.7-fold biological difference between extreme products of the same CCT class is large enough to determine whether an occupant receives the recommended circadian dose at standard office illuminance. Specifiers can mitigate this risk at no additional cost by requesting mDER data from manufacturers; the metric is unambiguously defined by CIE S026/E:2018 and can be derived from any calibrated SPD already required for photometric certification [5]. Mandatory m-DER disclosure - analogous to existing CRI Ra requirements - is strongly recommended as a necessary step toward systemic improvement in human-centric lighting specification.

Principal limitations are non-probabilistic sampling and restriction to a single CCT bin. Both the EMPIR/PhotoLED and PNNL databases draw predominantly from products available in European and North American markets, which may over-represent phosphor technologies common in those regions; generalization to other markets should be made with caution. These results establish that m-DER or full SPD reporting is necessary wherever human-centric lighting outcomes must be assured.

This research was supported by Bialystok University of Technology under grant no. WI/WE-IA/3/2025, funded by the Polish Ministry of Science and Higher Education research subsidy.

References

[1] D.M. Berson, F.A. Dunn, M. Takao, Science **295**, 1070 (2002). doi: 10.1126/science.1067262.

[2] CIE S 026/E:2018 CIE System for Metrology of Optical Radiation for ipRGC-Influenced Responses to Light, CIE, Vienna 2018. doi: 10.25039/S026.2018.

[3] CIE PS 001:2024 Position Statement on Integrative Lighting Recommending Proper Light at the Proper Time 2024. doi: 10.25039/PS.b2twa77g.

[4] T.M. Brown *et al.*, PLOS Biol. **20**, e3001571 (2022). doi: 10.1371/journal.pbio.3001571.

[5] I. Fryc, M. Listowski, R. Supronowicz, C. Martinsons, Energies **18**, 112 (2025). doi: 10.3390/en18010112.

[6] I. Fryc, M. Listowski, R. Supronowicz, D. Mozyrska, E. Rosas, G. Eppeldauer, P. Csuti, A. Ferrero, Opt. Laser Eng. **184**, 108614 (2025). https://doi.org/10.1016/j.optlaseng.2024.108614.

[7] T. Esposito, K. Houser, Sci. Rep. **12**, 20223 (2022), doi: 10.1038/s41598-022-21755-7.

[8] V.Q. Trinh, P. Bodrogi, T.Q. Khanh, Sensors **23**, 5000 (2023), doi: 10.3390/s23115000.

[9] ANSI C78.377-2024, Specifications for the Chromaticity of Solid State Lighting Products, ANSI, 2024.