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Research article

An easy-to-apply method for determining permissible exposure limit of retina to light

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ABSTRACT

Long exposure to intensive artificial light imposes threats to the retina. It is crucial to know the permissible exposure time to prevent photoretinitis. One complicated quantification method is available, which, however, also requires instrumentally measured spectrum and illuminance. We present herein an easy-to-apply formula and a ready-to-use table derived therefrom to determine the permissible exposure limit for any given desk lamp at any viewing distance. One only needs to acquire its color temperature and luminous flux labeled on the product. The method can be used to assist the general public in quickly assessing the potential hazardous status of their desk lamps, if any, and guide the field experts in designing human-eye-friendly lighting.

1. Introduction

Human can hardly imagine life without light. Light is not only necessary for a comfortable life, but also for productivity and safety, making people rely on it more than ever. That in the meanwhile increases the risk of diseases resulting from over-exposure to intensive artificial light [1, 2, 3, 4, 5, 6, 7]. Especially, long exposure to blue-enriched white light might lead to eye diseases, such as cataracts [8, 9], and macular degeneration [10, 11, 12]. Ironically, none of the above can be quantified, except photoretinitis. Thanks to some prior efforts [13, 14, 15, 16, 17, 18, 19], a function was established, with which one would be able to estimate the permissible exposure time of retina to a given light before photoretinitis takes place.

However, calculation using the photoretinitis function is rather complicated even for domain experts. Furthermore, instruments like spectrometers and/or luminometers are often needed to obtain the required spectrum and illuminance. These difficulties greatly hinder the field experts from designing a human-eye-friendly lighting system or the general public from knowing the hazardous status of their lighting environments.

To make it easily accessible to domain experts as well as the general public, we hence present an easy-to-apply formula and four estimation approaches to enable a quick determination of the permissible reading time for any given desk lamp. All the users need to input are the color temperature and luminous flux that is labelled right on the products.

2. Theoretical

2.1. Correlation between permissible reading time and the employed desk lamp

The time permitted for reading a book or else is limited due to the likelihood of photoretinitis, according to the report by ICNIRP [19] (International Commission on Non-Ionizing Radiation Protection). In this research, we supposed that the permissible reading time can be estimated by using the maximum permissible exposure limit (MPE), which is a function of the illuminance, I with a unit of lx, and color temperature, T with a unit of K, of the light that reaches the eyes, as shown below:

$$MPE = f(I, T) \tag{1}$$

The illuminance can be determined instrumentally or according to its correlation with the luminous flux labelled in the studied luminaire and the reading distance per subject, as shown below:

$$I = f(E_L, D) \tag{2}$$

where F_L is the luminous flux (lm) and D the reading distance (cm). The above correlation (2) can be established experimentally, with which an empirical formula can likewise be obtained for the MPE for any subject reading at any given distance with any given desk lamp.

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2.2. Correlation between MPE and photoretinitis function

If the spectrum and illuminance reaching the eyes are known, the corresponding MPE can be calculated using the formula reported by ICNIRP as following:

$$MPE = \frac{100}{E_B} \tag{3}$$

where E_B is the blue light hazard weighted radiation (W•m^{-2}) and 100 is the constant (100 J m^{-2}) [19], as given below:

$$E_B = \sum_{300}^{700} E_\lambda \cdot B(\lambda) \tag{4}$$

where E_λ is the weighted spectral radiance of the given light with a wavelength, λ (nm), and B(λ) the photoretinitis function (W•m^{-2}).

2.3. Origin of photoretinitis function (or blue light hazard function)

Photoretinitis function, or called blue light hazard function, used for determining the MPE of retina upon exposure to a given light was derived by weighting the experimental data from Rhesus monkeys, carried out by Ham's team [15], with the crystalline lens transmittance of human eyes [20], as shown in Figure 1. This action spectrum enables one to calculate the maximum permissible exposure limit of retina to any given light throughout the entire visible range by using the above formula.

3. Experimental

3.1. Maximum permissible exposure limit (MPE) measurement

To establish the empirical formula, we measured the MPE of three light sources, i.e. OLED, LED and CFL with twelve color temperatures, as listed in Table 1. The MPE and color temperature were measured by using a blue hazard quantification spectrometer SRI-100, which was purchased from iboson, as shown in Figure 2. It was carried out at an illuminance of 100 lx with a viewing distance of 40 cm.

3.2. Additional measurement

To verify how accurate the final empirical formula predicts the MPE for any given desk lamp with a known luminous flux and color temperature at any viewing distance against that measured instrumentally, six additional desk lamps with a wide color-temperature span were prepared. They were CFLs with a labelled 2,690 and 6,500 K, LEDs with a labelled 2,960 and 5,980 K and OLEDs with a labelled 1,710 and 4,000 K. Their MPEs were measured following the same procedure described above.

4. Results and discussion

Figure 3 correlates the instrumentally measured MPEs with the color temperatures of the studied lighting devices at 100 lx. Taking OLED for example, the MPE increased from 1,970 to 51,500 s, as the color temperature decreased from 4,100 to 1,700 K. As to LED, the MPE increased from 1,290 to 3,700 s, as the color temperature decreased from 6,200 to 2,800 K. The exposure limit (MPE) increases with the decrease of color temperature, almost independent of the lighting technology, regardless of OLED, LED and CFL. By using ORIGIN software, an empirical formula ($R^2 = 0.99$) correlating the MPE and color temperature has been derived as shown below.

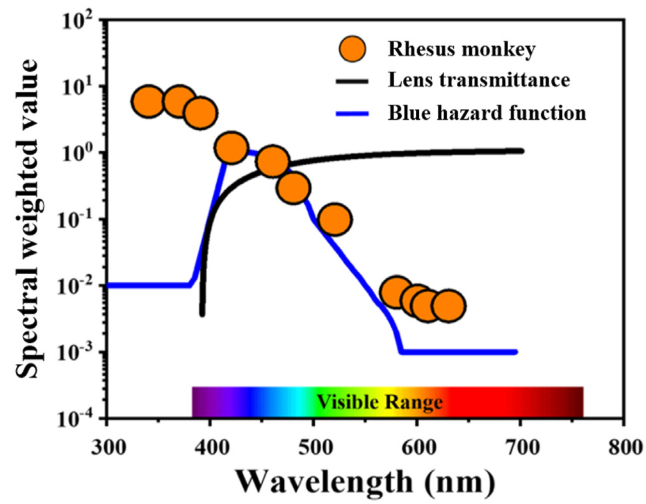

Figure 1. Photoretinitis function, or called blue light hazard function (in blue line) used for determining the MPE of retina upon exposure to a given light. It was originally derived by weighting the experimental data from Rhesus monkeys (in orange line), carried out by Ham's team [17], with the crystalline lens transmittance of human eyes (in black line) [20].

Table 1. The light sources used were OLED, LED and CFL each with four, three and five experimentally measured color temperatures, respectively. The resulting MPEs and color temperatures at 100 lx were used to determine the desired empirical formula.

Light source	Color temperature (K)	MPE (s)
OLED	1,740	51,500
	2,410	11,600
	3,110	3,130
	4,100	1,970
LED	2,760	3,770
	3,000	3,150
	6,190	1,290
CFL	2,640	4,910
	2,860	3,440
	3,270	3,330
	6,100	1,180
	6,510	1,170

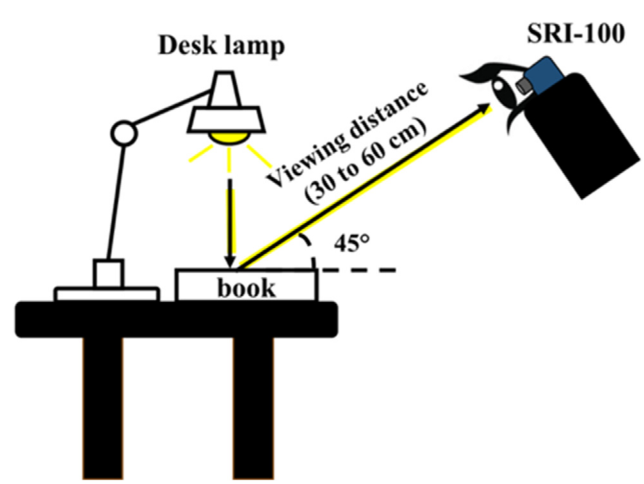

Figure 2. Schematic diagram of the measurement by using a blue hazard quantification spectrometer SRI-100.

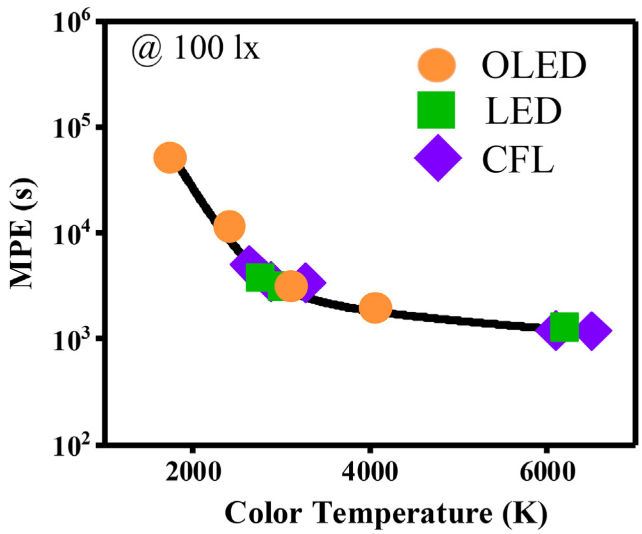

Figure 3. Correlation between the instrumentally measured MPEs and the color temperatures of the studied lighting devices at 100 lx. As seen, MPE is a strong function of color temperature, almost independent of the lighting technology, regardless of OLED, LED or CFL.

$$\mathrm{MPE(seconds)} = 4.07\times10^{2} + 2.8\times10^{7}\exp\left[\frac{-T}{2.81\times10^{2}}\right] + 5.04\times10^{3}\exp\left[\frac{-T}{3.42\times10^{3}}\right] \tag{5}$$

Figure 4 correlates the instrumentally measured MPEs with the color temperatures of the studied lighting devices at illuminance varying from 20 to 200 lx. Taking the 1,700 K OLED for example, the MPE decreased from 348,000 to 34,500 s as the illuminance was increased from 20 to 200 lx. As to the 3,000 K LED, its corresponding MPE decreased from 15,700 to 1,550 s. By combining with Formula (5), the empirical formula that correlates MPE, illuminance and color temperature has been established as shown below.

$$\mathrm{MPE(seconds)} = \frac{100}{I}\left\{4.07\times10^{2} + 2.8\times10^{7}\exp\left[\frac{-T}{2.81\times10^{2}}\right] + 5.04\times10^{3}\exp\left[\frac{-T}{3.42\times10^{3}}\right]\right\} \tag{6}$$

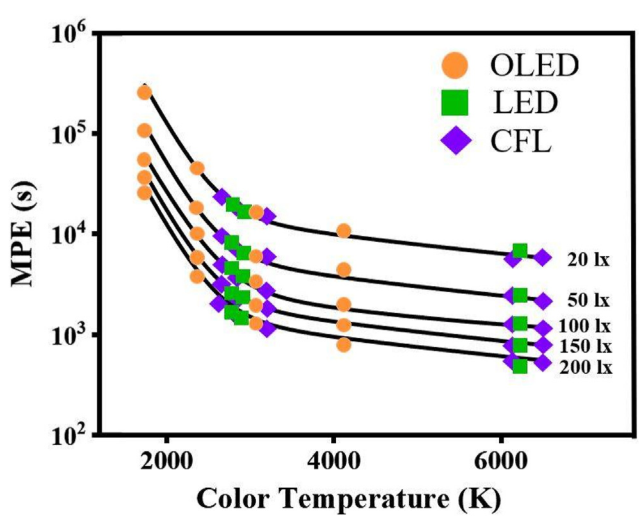

Figure 4. Correlation between the instrumentally measured MPEs and the color temperatures of the studied lighting devices at illuminance varying from 20 to 200 lx.

Figure 5 correlates the experimentally measured illuminance with the labelled luminous flux for a given desk lamp with different LED bulbs at viewing distances varying from 30 to 60 cm. Overall speaking, the measured illuminance increased almost linearly with the increase of luminous flux at all the studied viewing distances. At 30 cm, for example, the measured illuminance increased from 350 to 840 lx as the labelled luminous flux increased from 500 to 1,300 l m.

Figure 6 correlate the I/F_L with reading distance in terms of (a) 1/D and (b) $1/D^2$. Overall speaking, the illuminance measured (I) per luminous flux (F_L) decreased as the reading distance (D) increased. By using ORIGIN software, a determination coefficient, R^2, was obtained, which was 0.99 for the fitting curve of I/F_L *vs* 1/D, while 0.95 *vs* $1/D^2$. Since the curve fits better with 1/D, the corresponding correlation is hence determined as shown below.

$$\frac{I}{F_L} = \frac{22}{D} \tag{7}$$

By substituting Formula 7 into Formula 6, the desirable easy-to-apply Formula 8 is obtained, which is shown below:

$$MPE = \frac{D}{F_L}\left\{1.85\times10^{3} + 1.29\times10^{8}\exp\left[\frac{-T}{2.81\times10^{2}}\right] + 2.29\times10^{4}\exp\left[\frac{-T}{3.42\times10^{3}}\right]\right\} \tag{8}$$

Figure 7 shows that the MPE of a given desklamp can be precisely predicted as long as its color temperature and luminous flux are correctly provided. As seen, the MPEs of the six additional desklamps, calculated using Formula (8), fall right on the curve and are in good accordance with the instrumentally measured counterparts (dotted). Taking the 2,690 and 6,500 K CFLs for examples, the calculated MPEs are 1,720 and 470 s at a viewing distance of 40cm, while 1,570 and 496 s from measurement. The respective discrepancy is +10% and -5%. Herein, a positive discrepancy value means overestimation, and so is true vice versa. As to the 2,960 and 5,980 K LEDs, the calculated MPEs are 497 and 278 s, while 462 and 300 s from measurement, with a respective discrepancy of +7% and -8%. For the 1,710 and 4,000 K OLEDs, the calculated MPEs are 68,700 and 2,190 s, while 77,800 and 2,130 s from measurement, with a respective discrepancy of -12% and +3%.

4.1. Applications

Several applications are: (1) calculation by using the proposed formula (Formula 4), four additional approaches can be applied to estimate

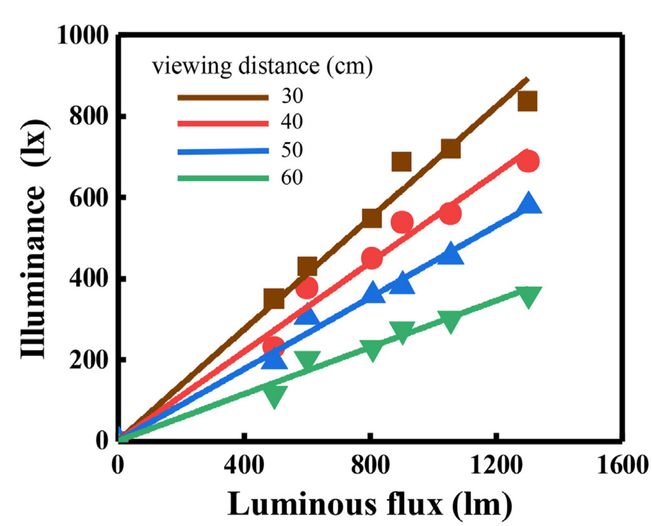

Figure 5. Correlation between the experimentally measured illuminance (I) and the luminous flux (FL) of a given desk lamp with different LED bulbs at a viewing distance varying from 30 to 60 cm.

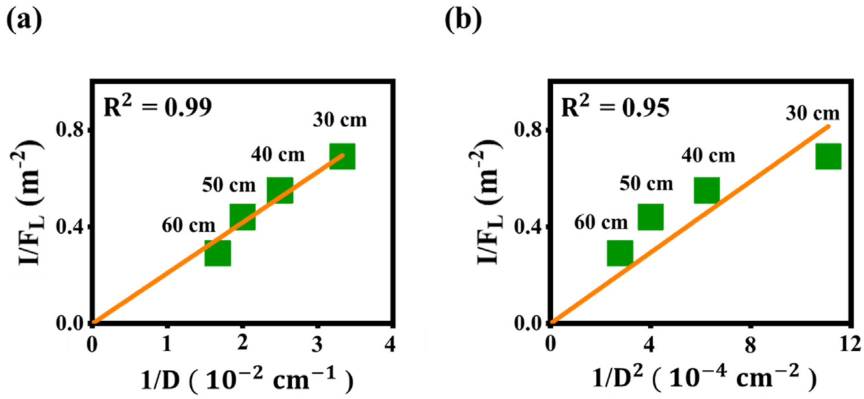

Figure 6. Correlation between the I/F_L with reading distance in terms of (a) 1/D and (b) $1/D^2$.

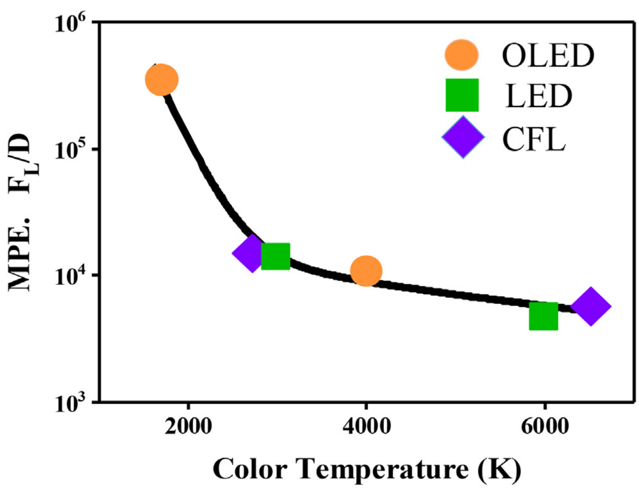

Figure 7. The instrumentally measured MPE(s) (dotted) at a 40 cm distance away from the book (or desk) by using the blue hazard quantification spectrometer, SRI-100, against those generated using the empirical formula (in curve) for the lighting devices of OLED, LED and CFL by inputting their labelled color temperature and luminous flux.

the permissible reading time for any given desk lamp. They are (2) table reading, (3) approximation, (4) interpolation, and (5) chart reading (Figure 8, Table 2) according to the data generated by using Formula 4. The details are given below.

(1) Calculation by using the proposed formula

Table 2 exemplifies the calculation results from using the proposed formula, Formula 4, for the permissible reading time in terms of maximum exposure limit (MPE) under desk lamps with a color temperature (CT) from 1,600 to 6,500 K and luminous flux from 100 to 1,600 l m at a viewing distance of 40 cm. The calculation can easily be extended to desk lamps with any other color temperature and luminous flux at any other viewing distance.

(2) Table reading

The tabulated data (MPEs) in the table (Table 2) enables one to promptly access the permissible reading time for any given desk lamp. For example, if one has a 3,000 K LED desk lamp with a luminous flux of 1,200 l m, the permissible reading time is 462 s with a viewing distance of 40 cm according to the table. The permissible reading time can be re-calculated simply by multiplying by D/40 if the viewing distance (D) is

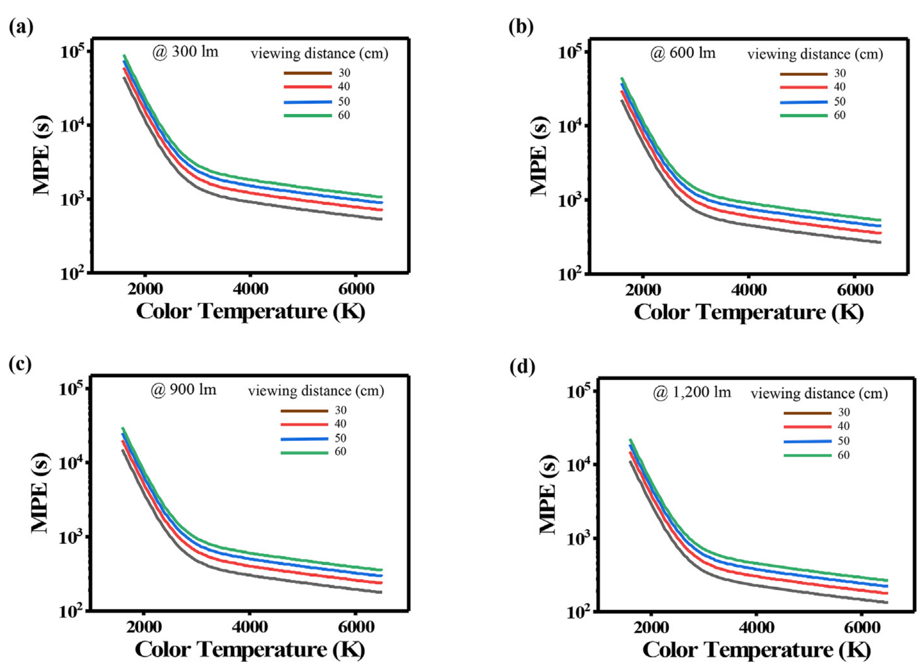

Figure 8. Maximum permissible exposure limit (MPE) of retina under lights with a color temperature from 1,600 to 6,500 K and a luminous flux of (a) 300, (b) 600, (c) 900, and (d) 1,200 l m, with a viewing distance varying from 30 to 60 cm.

Table 2. Calculation results from using the proposed formula for the permissible reading time in terms of maximum exposure limit (MPE) under desk lamps with a color temperature (CT) from 1,600 to 6,500 K and a luminous flux from 100 to 1,600 l m at a viewing distance of 40 cm.

CT (K)	100	200	400	600	800	1,000	1,200	1,400	1,600
	Luminous flux (lm)								
1,600	180,177	90,088	45,044	30,029	22,522	18,018	15,015	12,870	11,261
1,700	127,999	64,000	32,000	21,333	16,000	12,800	10,667	9,143	8,000
1,800	91,401	45,701	22,851	15,234	11,425	9,140	7,617	6,529	5,713
1,900	65,718	32,859	16,430	10,953	8,215	6,572	5,477	4,694	4,107
2,000	47,684	23,842	11,921	7,947	5,961	4,768	3,974	3,406	2,980
2,100	35,008	17,504	8,752	5,835	4,376	3,501	2,917	2,501	2,188
2,200	26,088	13,044	6,522	4,348	3,261	2,609	2,174	1,863	1,631
2,300	19,801	9,901	4,951	3,300	2,475	1,980	1,650	1,414	1,238
2,400	15,359	7,679	3,840	2,560	1,920	1,536	1,280	1,097	960
2,500	12,210	6,105	3,053	2,035	1,526	1,221	1,018	872	763
2,600	9,969	4,984	2,492	1,661	1,246	997	831	712	623
2,700	8,364	4,182	2,091	1,394	1,046	836	697	597	523
2,800	7,207	3,604	1,802	1,201	901	721	601	515	451
2,900	6,364	3,182	1,591	1,061	796	636	530	455	398
	Luminous flux (lm)								
3,000	5,741	2,871	1,436	957	718	574	479	410	359
3,100	5,275	2,637	1,319	879	659	527	440	377	330
3,200	4,918	2,459	1,230	820	615	492	410	351	307
3,300	4,640	2,320	1,160	773	580	464	387	331	290
3,400	4,417	2,208	1,104	736	552	442	368	315	276
3,500	4,233	2,116	1,058	705	529	423	353	302	265
3,600	4,078	2,039	1,020	680	510	408	340	291	255
3,700	3,944	1,972	986	657	493	394	329	282	247
3,800	3,825	1,912	956	637	478	382	319	273	239
3,900	3,717	1,858	929	619	465	372	310	265	232
4,000	3,618	1,809	905	603	452	362	302	258	226
4,100	3,526	1,763	882	588	441	353	294	252	220
4,200	3,439	1,720	860	573	430	344	287	246	215
4,300	3,357	1,678	839	559	420	336	280	240	210
4,400	3,278	1,639	820	546	410	328	273	234	205
	Luminous flux (lm)								
4,500	3,203	1,602	801	534	401	320	267	229	200
4,600	3,130	1,565	783	522	391	313	261	224	196
4,700	3,061	1,530	765	510	383	306	255	219	191
4,800	2,993	1,496	748	499	374	299	249	214	187
4,900	2,927	1,464	732	488	366	293	244	209	183
5,000	2,864	1,432	716	477	358	286	239	205	179
5,100	2,803	1,401	701	467	350	280	234	200	175
5,200	2,743	1,371	686	457	343	274	229	196	171
5,300	2,685	1,343	672	448	336	269	224	192	168
5,400	2,629	1,314	657	438	329	263	219	188	164
5,500	2,574	1,287	644	429	322	257	215	184	161
5,600	2,522	1,261	631	420	315	252	210	180	158
5,700	2,470	1,235	618	412	309	247	206	176	154
5,800	2,420	1,210	605	403	303	242	202	173	151
5,900	2,372	1,186	593	395	297	237	198	169	148
	Luminous flux (lm)								
6,000	2,325	1,162	581	387	291	232	194	166	145
6,100	2,279	1,140	570	380	285	228	190	163	143
6,200	2,235	1,117	559	372	279	223	186	160	140
6,300	2,192	1096	548	365	274	219	183	157	137
6,400	2,150	1075	537	358	269	215	179	154	134
6,500	2,109	1055	527	352	264	211	176	151	132

Table 3. Validation of the proposed easy-to-apply method comparing with the instrumental approach. The proposed method can be realized by using directly the empirical formula, by interpolating or estimating from the tabulated data.

Viewing distance = 40 cm					
Luminaires		Maximum permissible exposure-limit (s)			
Light source	F_L (lm)	Instrumental approach	Empirical formula (deviation)*	Interpolation (deviation)*	Estimation (deviation)*
2,700K CFL	495	1,573	1,690 (+7%)	1,760 (+12%)	1,394 (–11%)
6,500K CFL	448	496	470 (–5%)	485 (–2%)	527 (+6%)
3,000K LED	1,200	462	478 (+4%)	478 (+4%)	478 (+4%)
6,000K LED	840	300	277 (–8%)	279 (–7%)	291 (–3%)
1,700K OLED	180	77,759	71,111 (–9%)	81,646 (+5%)	90,978 (+17%)
4,000K OLED	165	2,131	2,193 (+3%)	2,442 (+15%)	1,809 (–15%)

otherwise different from 40 cm. Taking 60 cm for example, the permissible reading time can be converted from 462 to 693 s.

(3) Approximation

An approximation approach can be applied if the given desk lamp does not have a color temperature or luminous flux value matching exactly the same tabulated in the table. Taking a 4,000 K OLED for example, it has a luminous flux of 165 l m. By rounding it up to 200 l m, one can get a permissible reading time of 1,810 s from the table (Table 2). Whilst, it is 2,130 s from measurement and 2,190 s from the empirical formula. The respective underestimation is 15% and 17%. Taking a 2,960 K LED with a luminous flux of 1,200 l m for example, the approximated MPE is 479 s if by rounding its color temperature to 3,000 K. It is 462 s from measurement and 497 s from empirical formula, the respective discrepancy is 4% and -4%. The approximation approach can also be applied if the given desk lamp does not have a matching color temperature and luminous flux. Taking a 2,690 K CFL with a luminous flux of 495 l m for example, the approximated MPE is 2,090 s if by rounding its color temperature to 2,700 K and luminous flux to 400 l m. It is 1,570 s from measurement and 1,720 s from the empirical formula, the respective discrepancy is 33% and 22%.

(4) Interpolation

The above approach may yield a permissible time with a large discrepancy. To minimize, an interpolation approach can be applied. Taking the same 4,000 K OLED with a 165 l m luminous flux for example, via interpolation [(200/165) × MPE@200 l m; (100/165)× MPE@100 l m], the resultant MPE is 2,190 s, while 2,130 s from measurement and 2,190 s from the empirical formula. The respective discrepancy decreases from -15% to +3% and from -17% to +0%. Taking the same 2,960 K LED for example, the MPE is 498 s by interpolation [MPE@3, 000 K + (MPE@2,900K-MPE@3,000K) × (3000 − 2960)/(3000 − 2900)], while 462 s from measurement and 497 s from the empirical formula. The respective discrepancy varied from +4% to +8% and from -4 % to 0.2%. For the same 2,690 K CFL with a luminous flux of 495 l m, the MPE obtained via double-interpolation is 1,720 s, while 1,570 from measurement and 1,720 s from the empirical formula. The respective discrepancy decreases from +33% to +9 % and from 22% to 0%.

The above double-interpolation was done as shown below:

$$\mathrm{MPE@2,690K,400lm} = \mathrm{MPE@2,700K,400lm} + \frac{(2700-2690)}{(2700-2600)} \times (\mathrm{MPE@2,600K,400lm} - \mathrm{MPE@2,700K,400lm})$$

$$\mathrm{MPE@2,690\,K,495lm} = \frac{400}{495} \times \mathrm{MPE@2,690K,400lm}$$

(5) Chart reading

Figures 8(a-d) show the MPEs calculated using the empirical formula for lighting with a color temperature from 1,600 to 6,500 K, a luminous flux from 300 to 1,200 l m and a viewing distance from 30 to 60 cm. With the curves, one can readily access the permissible reading time for any given light within the above ranges. For example, if a 3,000 K LED with a luminous flux of 1,200 l m is employed with a viewing distance of 40 cm, an about 500-second MPE can be read from Figure 8(d). The MPE can also be re-calculated by multiplying by D/40 and 1,200/F_L if the respective viewing distance (D) and luminous flux (F_L) are otherwise different from 40 cm and 1,200 l m. Taking an 80-cm reading distance and an 800 l m luminous flux for example, the permissible reading time can be prolonged from 500 to 1,500 s ($\mathrm{MPE@80cm,800lm} = \frac{80}{40} \times \frac{1,200}{800} \times \mathrm{MPE@40cm,1,200lm}$).

It is noteworthy that the MPE listed in Table 3 is significantly different from one another. It ranges from 300 to 77,800 s, an about 200 times difference. Among all, only the 1,700 K OLED permits a longer than 60 min reading time, which is 77,800 s (~22 h) at a 40 cm viewing distance or 58,350 s (~16 h) at 30 cm. The longer than 60-minute reading time can be attributed to both its blue light-less nature and the built-in low luminous flux.

5. Conclusion

To conclude, we have presented in this study an easy-to-apply formula to enable a quick determination of permissible reading time for any given desk lamp without the need of any spectrometer. Four more easy-to-use approaches derived therefrom can be applied to acquire the same without going through the tedious computation. All one needs to input are the viewing distance and the color temperature and luminous flux labelled on the products. It is shocking to know that nearly all the current desk lamps possess intense blue-emission and high brightness, and therefore should not be permitted longer than an hours of reading time. The formula and ready-to-use table can assist the general public in quickly assessing the potential hazardous status of their desk lamps or searching for a proper one. They can also guide the field experts in designing human eyes friendly lighting. Numerous optometry-based researches can henceforth be boosted and bring forward betterment in safeguarding human health.

Declarations

Author contribution statement

Jwo-Huei Jou: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Jing-Hsiu Chen: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data.

Jin-Ting Lin, Ming-Hui Cheng: Analyzed and interpreted the data; Wrote the paper.

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Data availability statement

Data included in article/supp. material/referenced in article.

Declaration of interest's statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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