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Experimental Assessment of WLED Lamp Performance for Area Lighting Application under Mesopic Photometry System

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Abstract- Human eye response is characterised by photopic spectral luminous efficiency function [V(λ)] and scotopic luminous efficiency function [V′(λ)] for photopic and scotopic vision respectively. In the mesopic zone there are no fixed response characteristics but with the increase of luminance the response shifts from scotopic to photopic region and shifts from photopic to scotopic with the decrease in luminance. Luminance level in various road lighting and area lighting installation lies in the mesopic zone. In this work experimental analysis of different lamp performances in mesopic zone for area lighting installations have been performed in both laboratory and outdoor field applications. It has been found that in both cases, changes in mesopic luminance from photopic luminance occur according to the standard CIE 191:2010. Therefore white light emitting diode (WLED) shows better photometric performance and would deliver better energy efficient performance in the mesopic zone as compared to conventional lamps i.e. high pressure sodium vapour lamp (HPSV).

Keywords: Mesopic Photometry, Area Lighting, Mesopic Luminance

I. INTRODUCTION

The photopic luminous efficiency function V(λ) represents the response of the cone photo receptors at photopic vision while the scotopic luminous efficiency function V′(λ) shows the response of the rod photo receptors at scotopic vision. The region between photopic and scotopic vision is known as mesopic vision. Luminous efficiency function for mesopic vision is dependent on the luminance level[1]. The luminance level of various outdoor lighting and street lighting generally lies in the mesopic region. High pressure sodium vapour (HPSV), metal halide (MH) and white light emitting diodes (WLED) lamps are most commonly used in street and outdoor lighting installations. However, at present WLED lamps are mostly used in urban area lighting considering the mesopic effects[2]. Human eye adaptation also plays an important role in mesopic zones for pedestrian way lighting [3]. The effect of perceived brightness in parking lots instead of existing photometric illuminance as the photometric metric has also been studied previously for different types of lamps such HPSV, MH and WLED [4].

In this work performance of different lamps with different Scotopic/Photopic (S/P) ratios in area lighting scenario under the mesopic luminance range are studied and compared using CIE mesopic photometry system by field measurements in both laboratory set up and actual outdoor application areas. The main objective of this work is to find the most efficient light source in outdoor lighting application areas. Outdoor measurements have been taken in night time, during summer under clear weather. The effect of stray lights has been considered but was found to be negligible over the field of experimental measurements. The performances of these lighting are studied under the mesopic luminance range and compared using CIE 191:2010[1]. The steps of this work involve measurement of photopic luminance and computation of corresponding mesopic luminance.

II. BACKGROUND THEORY

Human eye response is controlled by rod and cone cells which are pre-dominantly active at different luminance levels. Cone cells are responsible for photopic vision and maximum efficacy of the spectral luminous efficiency curve V(λ), as shown in Fig.1 is 683 lumen/watt and occurs at a wavelength of 555nm. Similarly rod cells are responsible for scotopic vision and maximum efficacy of the spectral luminous efficiency curve V′(λ), as shown in Fig.1 is 1700 lm/W and occurs at a wavelength of 507nm. Mesopic vision occurs under luminance levels in between photopic and scotopic vision and controlled by both rod and cone cells. Mesopic vision and mesopic photometry have importance in design and application of road lighting and outdoor area lighting where the light level lies in the mesopic zone. The mesopic spectral luminous efficiency function $V_{mes}(\lambda)$ is defined as the function of Photopic and Scotopic Spectral Luminous Efficiency Functions $V(\lambda)$ and $V'(\lambda)$.

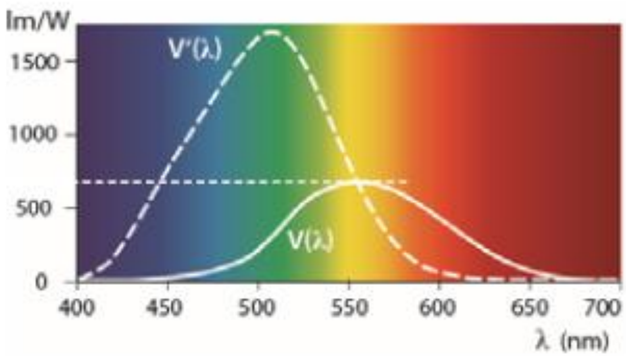

Fig.1: Photopic & Scotopic Luminous Efficiency Function[6]

CIE technical report "Recommended System for Mesopic Photometry Based on Visual Performance", CIE191:2010 [1] is based on peripheral visual performance of tasks and provides the mesopic database to obtain values of the mesopic luminance (L_{mes}) corresponding to some selected photopic luminance (within the range of 0.005 cd/m^2 to 5 cd/m^2) for all relevant S/P ratio of lamps. The mesopic photometry system also defines mesopic luminous efficiency function $V_{mes}(\lambda)$ as a linear combination of photopic luminous efficiency function $V(\lambda)$ and scotopic luminous efficiency function $V'(\lambda)$, the spectral efficiency of which depends on the luminance called as adaptation luminance to which the eyes are adapted. The field of view contributing to the adaptation luminance is called the adaptation field.

The recommended system of mesopic photometry defines $V_{mes}(\lambda)$ as

$$M(m)V_{mes}(\lambda) = mV(\lambda) + (1-m)V'(\lambda) \qquad (1)$$

and

$$L_{mes} = \frac{683}{V_{mes}(\lambda_0)} \int V_{mes}(\lambda) L_e(\lambda) d\lambda \qquad (2)$$

Where,

- M(m) is a normalization function such that $V_{mes}(\lambda)$ attains a maximum value of 1
- $V_{mes}(\lambda_0)$ is the value of $V_{mes}(\lambda)$ at 555 nm
- $L_e(\lambda)$ is the spectral radiance in W.m^{-2}.sr^{-1}.nm^{-1}
- m($0 \le m \le 1$) is adaptation coefficient.

The adaptation coefficient 'm' depends on the visual adaptation conditions of observer and its value can be evaluated by an iterative approach as follows:

$$L_{mes,n} = \frac{m_{n-1} L_p + (1-m_{(n-1)}) L_s V'(\lambda_0)}{m_{(n-1)} + (1-m_{(n-1)}) V'(\lambda_0)} \qquad (3)$$

and

$$m_n = a + b \log_{10}\left(L_{mes,n}\right) \qquad (4)$$

where:

- L_p is the photopic luminance
- L_s is the scotopic luminance
- $V'(\lambda_0)$ is the value of scotopic spectral luminous efficiency function at $(\lambda_0) = 555\ nm$
- a=0.7670, b=0.3334 and
- n is the iteration step.

Mesopic luminance can be calculated from corresponding measured photopic luminance using the database as shown in Table 1. A new corrected photopic luminance table has been developed [5] to use the existing road lighting design procedures and measurement methods by lighting designers in mesopic applications. The authors have also shown that although only photopic vision is involved in on-axis object recognition, still there are numerous reasons for the practical application of the CIE mesopic system which includes the effects of the peripheral vision in case of road lighting. The S/P ratio is characteristic of a lamp's spectral composition and is defined as,

$$S/P\ ratio = \frac{K'_m \int S_\lambda(\lambda) V'(\lambda) d\lambda}{K_m \int S_\lambda(\lambda) V(\lambda) d\lambda} \qquad (5)$$

Where,

- K'_m=1700 lm/W is the maximum spectral luminous efficacy for scotopic vision
- K_m=683lm/W is the maximum spectral luminous efficacy for photopic vision
- S_λ=Spectral Power Distribution of the Light Source

Table1: Values of Mesopic system as a function of photopic luminance and S/P ratio [1]

		Photopic luminance / cd·m^{-2}						
	S/P	**0,01**	**0,03**	**0,1**	**0,3**	**1**	**3**	**4,5**
LPS ~	**0,25**	0,002 5	0,014 5	0,070 5	0,246 7	0,913 0	2,926 5	4,478 2
	0,35	0,003 5	0,017 4	0,075 0	0,254 5	0,925 3	2,936 7	4,481 2
	0,45	0,004 5	0,019 8	0,079 3	0,262 0	0,937 3	2,946 8	4,484 2
HPS ~	**0,55**	0,005 7	0,022 0	0,083 4	0,269 3	0,949 2	2,956 8	4,487 2
	0,65	0,006 9	0,023 9	0,087 3	0,276 4	0,960 8	2,966 6	4,490 1
	0,75	0,007 9	0,025 8	0,091 1	0,283 3	0,972 2	2,976 3	4,492 9
	0,85	0,008 8	0,027 5	0,094 7	0,290 1	0,983 5	2,985 9	4,495 8
	0,95	0,009 6	0,029 2	0,098 3	0,296 7	0,994 5	2,995 3	4,498 6
	1,05	0,010 4	0,030 8	0,101 7	0,303 2	1,005 4	3,004 6	4,501 4
MH warm white ~	**1,15**	0,011 1	0,032 3	0,105 1	0,309 6	1,016 1	3,013 9	4,504 1
	1,25	0,011 8	0,033 8	0,108 3	0,315 8	1,026 7	3,023 0	4,506 8
	1,35	0,012 5	0,035 3	0,111 5	0,322 0	1,037 1	3,031 9	4,509 5
	1,45	0,013 2	0,036 7	0,114 7	0,328 0	1,047 3	3,040 8	4,512 2
	1,55	0,013 8	0,038 1	0,117 8	0,333 9	1,057 5	3,049 6	4,514 8
	1,65	0,014 5	0,039 5	0,120 8	0,339 8	1,067 4	3,058 2	4,517 4
	1,75	0,015 1	0,040 8	0,123 8	0,345 5	1,077 3	3,066 8	4,520 0
	1,85	0,015 7	0,042 1	0,126 7	0,351 2	1,087 0	3,075 3	4,522 5
	1,95	0,016 3	0,043 4	0,129 5	0,356 8	1,096 6	3,083 6	4,525 0
	2,05	0,016 9	0,044 6	0,132 4	0,362 3	1,106 0	3,091 9	4,527 5
	2,15	0,017 4	0,045 9	0,135 2	0,367 7	1,115 4	3,100 1	4,529 9
	2,25	0,018 0	0,047 1	0,137 9	0,373 1	1,124 6	3,108 2	4,532 3
MH day-light ~	**2,35**	0,018 5	0,048 3	0,140 6	0,378 4	1,133 8	3,116 2	4,534 7
	2,45	0,019 1	0,049 5	0,143 3	0,383 6	1,142 8	3,124 1	4,537 1
	2,55	0,019 6	0,050 6	0,145 9	0,388 8	1,151 7	3,131 9	4,539 5
	2,65	0,020 1	0,051 8	0,148 5	0,393 9	1,160 5	3,139 6	4,541 8
	2,75	0,020 7	0,052 9	0,151 1	0,398 9	1,169 3	3,147 3	4,544 1

III. EXPERIMENTAL SET UP FOR MEASUREMENT OF PHOTOPIC LUMINANCE

Experiments were carried out by using different light sources of various spectral compositions at both laboratory and outdoor field environments. Photopic luminance was measured over a defined area with 13X6 grid points. Each point specific photopic luminance is then converted to corresponding mesopic luminance using Table 1. This process is repeated for all the six types of lamps shown in Table 2. However for outdoor experiment it was possible to repeat the experiment for only two combinations.

A. Laboratory Measurements

The indoor area has been divided into 13x6 grid points with dimension of 0.5m x 0.5 m. The luminaires were mounted at a height of 3.0m on an adjustable pole. Specifications of the lamps used in this experiment (HPSV, MH and four different WLED with different S/P ratio) i.e. lamp power consumption, Luminous Flux output, Colour Rendering Index (CRI), Correlated Colour Temperature (CCT) are shown in Table 2. S/P Ratio of the lamps is measured using Scotopic/Photopic Meter of "SOLAR Light", Model No. SL3101. Point specific luminance in each grid point has been measured by "Konica Minolta" Luminance Meter, LS 110A. A programmable power supply of GwINSTEK, PSM 6003 is used to maintain constant supply voltage to the lamps throughout the experimental procedure. The luminance meter was fixed at a height of 1.2m at a distance of 7m from the centre of the grid. For measurement of S/P ratio, the luminaires were mounted in vertical position, with the sensors of the Scotopic/Photopic Meter facing them. Both the sensor of the meter and the centre of the luminaire were positioned at a height of 1.2m. The distance between thekkkk meter and the luminaire was fixed at 7m. The luminaires were mounted at vertical frame and the meter was positioned using a tripod as shown in Fig.2.

Table 2: Light Source Specification

Source	**Luminous Flux (lumen)**	*S/P*	*CCT(K)*	*Rated Power(W)*
HPSV	6000	0.48	2300	70
MH	5600	1.346	3570	70
LED1	6000	2.026	6000	50
LED2	6000	2.018	5580	50
LED3	6000	1.496	3320	50
LED4	6000	1.948	4385	50

Fig.2 Experimental Set-up for Indoor Measurements

B. *Field Measurements*

The outdoor area was illuminated with HPSV and 6000K LED (depicted as LED1) luminaires that were used previously in the indoor measurements. Luminaires were mounted on a standard 9m pole. The same grid area of 6mx2.5m was chosen with 13x6 grid points. The meters were mounted at a fixed height of 1.2m and at distance of 7m from the grid-centre using a tripod. As the same luminaires were used for outdoor measurements, the S/P ratio and CCT have been considered as same.

IV. COMPUTATION OF MESOPIC LUMINANCE

Photopic luminance was measured using luminance meter for all 6 types of lamps in both laboratory and outdoor lighting conditions. These point specific photopic luminance is then converted to corresponding mesopic luminance using the CIE 191:2010 Table as shown in Table 1. Required S/P ratio of the lamps has already been measured using S/P meter. All these luminance values for all combinations are compared to understand performance of different lamps with respect to CIE mesopic photometry system. One set of data for HPSV lamp is only shown here in Table 2.

V. PERFORMANCE ANALYSIS OF LAMPS

Six different types of lamps have been considered for the comparative study of lamp performance in mesopic photometry. All photopic and mesopic luminance values for all combinations are compared to understand performance of different lamps with respect to CIE mesopic photometry system.

Table3: Computation of Mesopic Luminance from Photopic Luminance for 70W HPSV Lamp

Photopic Luminance (cd/m^2)						Mesopic Luminance (cd/m^2)					
A	**B**	**C**	**D**	**E**	**F**	**A**	**B**	**C**	**D**	**E**	**F**
0.65	0.88	1.14	1.42	1.40	1.03	0.60	0.83	1.08	1.36	1.34	0.97
0.74	0.88	1.18	1.57	1.54	1.29	0.69	0.83	1.12	1.51	1.48	1.23
0.74	0.92	1.28	1.78	1.84	-	0.69	0.86	1.22	1.72	1.79	-
0.75	0.93	1.44	2.08	2.29	-	0.70	0.87	1.38	2.03	2.24	-
0.76	1.03	1.58	2.33	3.00	2.19	0.71	0.97	1.52	2.28	2.95	2.13
0.80	1.05	1.69	2.55	4.03	2.11	0.75	0.99	1.63	2.50	4.01	2.05
0.92	1.05	1.77	2.80	3.86	3.14	0.86	0.99	1.71	2.75	3.83	3.09
0.81	1.04	1.68	2.46	3.37	2.74	0.76	0.98	1.62	2.41	3.33	2.68
0.78	1.04	1.54	2.84	3.28	3.06	0.73	0.98	1.49	2.79	3.23	3.01
0.81	1.04	1.55	2.63	3.27	2.79	0.75	0.98	1.49	2.58	3.23	2.74
0.75	1.03	1.39	2.51	3.05	2.64	0.70	0.97	1.33	2.46	3.00	2.59
0.75	0.98	1.47	2.59	3.18	2.94	0.70	0.92	1.41	2.54	3.13	2.89
0.72	0.95	1.65	2.99	3.39	1.78	0.67	0.89	1.59	2.94	3.35	1.72

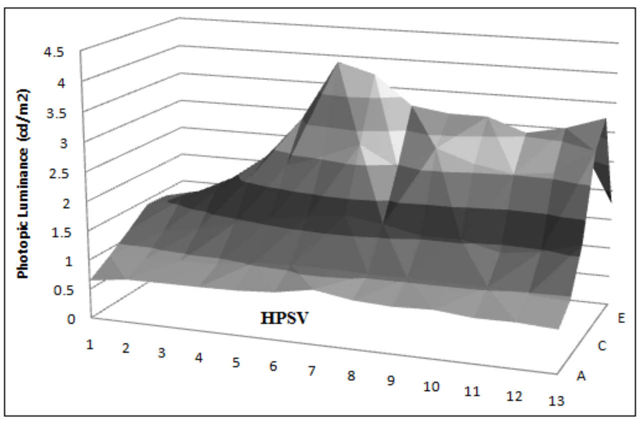

Fig.3 Photopic Luminance Distribution Luminance for HPSV

Luminance distribution for HPSV lamps for the entire field has been plotted from the data given in Table 2 and shown in figure 3 and 4. Here it is clear that although the nature of distribution remains same in both the cases, point specific values have been reduced in mesopic region.

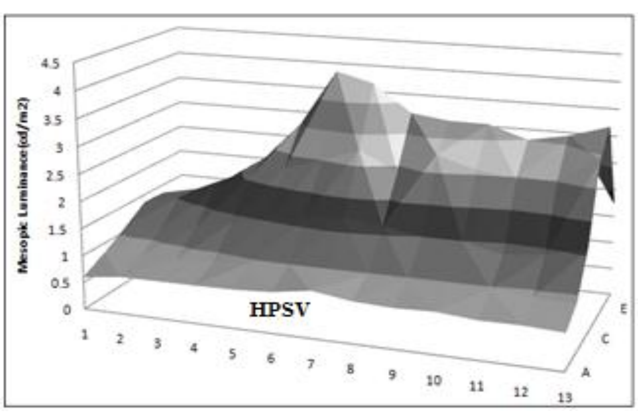

Fig.4 Mesopic Luminance Distribution Luminance for HPSV

The distribution of photopic and mesopic luminance over the field of measurement for HPSV (lowest S/P ratio) and LED1 (highest S/P ratio) are shown below in Figure 5 and 6. It can be inferred that the values of photopic luminance is greater than mesopic luminance for HPSV lamp which has a CCT <2000K and S/P ratio 0.48. With the increase in CCT the S/P ratio of lamps also increases. Consequently, with increase in S/P ratio mesopic luminance values also increase with respect to mesopic values. For LED1, having CCT 6000K and S/P ratio 2.026, difference between mesopic and photopic luminance is maximum. Again as we approach towards photopic zone from mesopic, the differences between luminance values become narrower and within the photopic range, the difference vanishes.

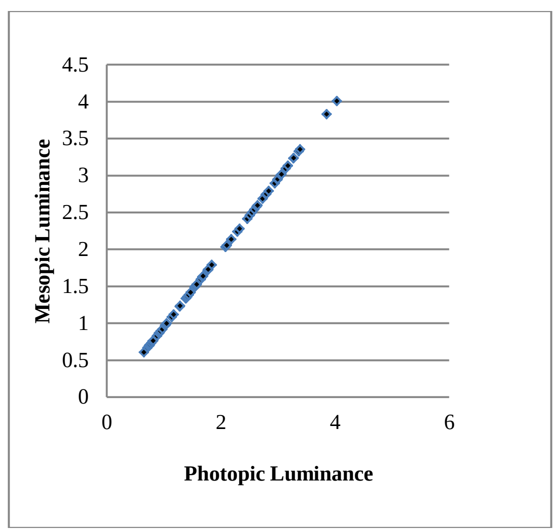

Figure 5: Mesopic vs Photopic Luminance (in cd/m^2) for HPSV

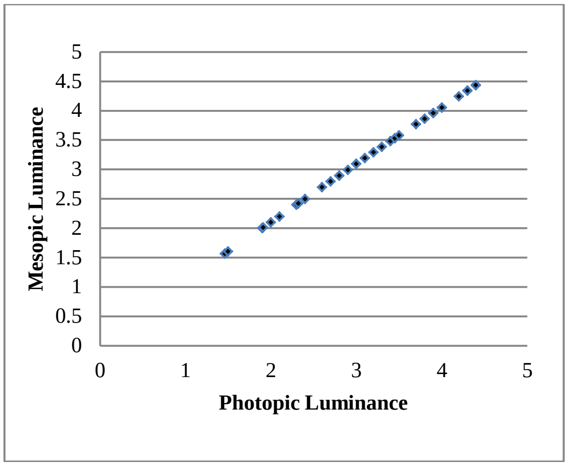

Figure 6: Mesopic vs Photopic Luminance (in cd/m^2) for LED1

Similar results have been obtained for all the lamps under experiment. Thus, we can infer that there is a direct relation between relative value shift between photopic and mesopic luminance in the mesopic zone and the S/P ratio of the lamps. As the S/P ratio of the source increases, the mesopic luminance becomes significantly higher than the corresponding photopic luminance. Lamps having low S/P ratio (such as HPSV) shows poor performance in the mesopic zone than WLED with higher S/P ratio. LED1 having highest CCT of 6000K and highest S/P ratio shows best performance in the mesopic zone.

Average photopic and mesopic luminance of the entire indoor and outdoor area of measurements have been plotted in Figure 7 and 8. From the plots it is very evident that the in case of the lamps with higher S/P ratio (i.e. MH and WLED) average luminance value is more in mesopic photometry system. So for designing any lighting schemes under mesopic zone lamps with higher S/P ratio i.e. MH and WLED will be more efficient than lamp with lower S/P ratio i.e. HPSV lamps.

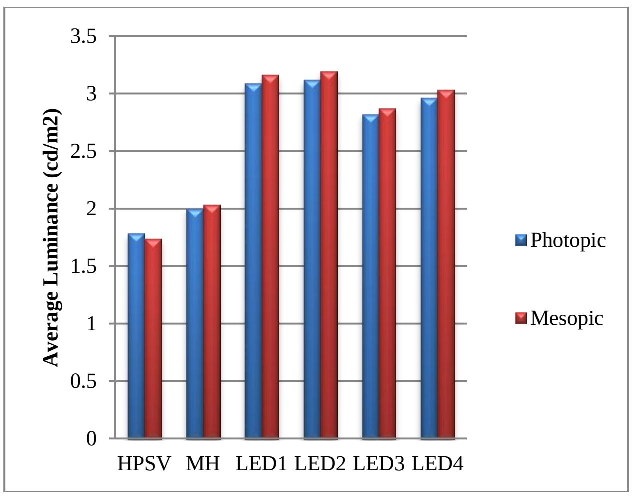

Figure8: Comparison of average luminance in indoor

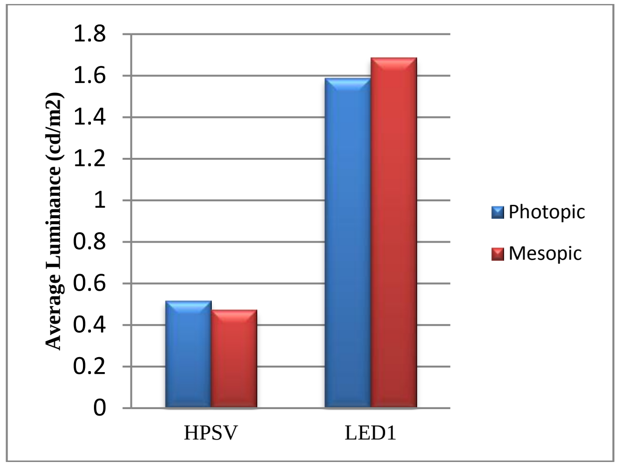

Figure7: Comparison of average luminance in outdoor

VI. CONCLUSIONS AND FUTURE SCOPE

Lamps having lower S/P ratio, such as HPSV, have lower effective luminance in the mesopic zone. Thus, human eye would perceive less brightness in this environment. On the other hand lamps having higher S/P ratio will be more effective in mesopic region. Therefore while designing any lighting system under mesopic illumination level, to achieve same brightness; higher wattage lamps would be required in case of lamps having lower S/P ratio, leading to more energy consumption. Thus, for efficient energy management, use of these lamps in mesopic zones would not be recommended. Lamps having higher S/P ratio, such as 6000K WLED, shows significantly better performance among all. These lamps, thus would deliver better energy efficient performance in the mesopic zone.

Although HPSVs are in wide use in area lighting, due to their robust construction, good luminous efficacy and good lifespan, but in the mesopic zone they seem to perform poorer than WLEDs with high S/P ratios. Therefore LEDs are emerging as light sources in outdoor application areas with wide application range due to shape and size-flexibility, widest range of CCT and CRI. Also, in this case the WLEDs having high S/P ratio (the highest 2.026 in comparison to 0.48 of HPSV), showed better luminous performance in the mesopic zone. Thus, this study recommends usage of LEDs for area lighting applications for better mesopic performance and better energy management.

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