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Outdoor Lighting: Visual Efficacy

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Introduction

Fixed outdoor lighting supports nighttime activities including transportation, recreation, and business. As with any lighting system, outdoor lighting should maximize the benefits to people while minimizing cost. Luminous efficacy (photopic lumens per watt) is perhaps the most common measure of the benefit-cost ratio for any lighting system. Systems with high luminous efficacy are presumed to maximize the benefit of “seeing” (lumens) for the cost of electric power (watts). Indeed, in the race to improve LED system performance, much attention has been given to improving luminous efficacy. Generally speaking, however, *all* of the attention has been focused on increasing benefit-cost ratio without questioning the utility and appropriateness of the benefit-numerator of the luminous efficacy calculation.

This issue of *ASSIST recommends* discusses a new, unified system of photometry (Rea et al. 2004). This system better characterizes the benefit-numerator in the luminous efficacy calculation for outdoor lighting systems used for nighttime illumination while staying within the constraints of conventional photometry (see Appendix A for more details about the unified system of photometry). By better characterizing “seeing” under nighttime applications, it is possible to better optimize, and thereby reduce the cost, of operating lighting systems at night, including LED outdoor lighting systems. The unified system of photometry, in fact, changes the economics of light source selection for nighttime applications.

Background

The human visual system utilizes two classes of photoreceptors, rods and cones. Cones are used exclusively for processing visual information under “daytime” light levels found outdoors during the day and in nearly all indoor applications illuminated by electric lighting systems. Under starlight, only rods provide visual information. There is, however, a range of light levels, known as the mesopic region, where both rods and cones provide input to the visual system. As light levels increase from starlight to daytime levels, the relative contribution of the two classes of photoreceptors to the visual system shifts from rod-only to cone-only input. Rods and cones are tuned to different parts of the electromagnetic spectrum. Thus, depending upon the light level, rods and cones provide a different overall spectral sensitivity to light (Rea 2000). This would be of academic interest only, except that most of the prescribed outdoor light levels provided by electric lighting systems are in the mesopic range. Since light sources differ in their spectral power distributions, light sources will vary in terms of their visual effectiveness depending upon the prescribed light level. Thus, a light source does not have a single value of *visual efficacy*, but rather its ability to provide "seeing per watt" depends upon the amount of available light.

Commercial photometry is based entirely upon the photopic luminous efficiency function (CIE 1994), which differentially weights the effectiveness of wavelengths in the electromagnetic spectrum, peaking at 555 nm with a half-bandwidth of about 90 nm (Figure 1). This function represents the combined spectral response of just two of the three types of cones found in the human retina. More precisely, the photopic luminous efficiency function is based upon the long (L) and middle (M) wavelength sensitive cones found in the fovea and ignores the S-cone spectral sensitivity as well as that of the rods. Although the current system of photometry (CIE 1994) accommodates the scotopic luminous efficiency function

(Figure 1), representing the spectral sensitivity of rods, it is never used in commercial photometry.

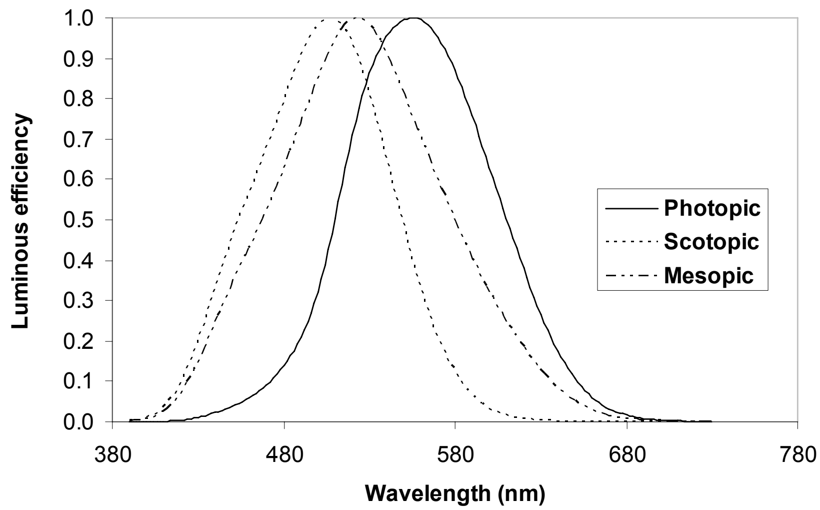

Figure 1. Photopic, scotopic, and one mesopic luminous efficiency functions.

The unified system of photometry (Rea et al. 2004; see Appendix A) integrates both the scotopic and photopic luminous efficiency functions into a complete system that can be utilized across the entire range of light levels available to the human visual system. This system differentially weights the scotopic and photopic luminous efficiency functions depending upon light level (Figure 1). Figure 1 also shows, for illustration only, a mesopic luminous efficiency function composed of 60 percent scotopic and 40 percent photopic luminous efficiency. The system is based upon psychophysical studies of human vision and preserves the fundamental tenet of additivity required of any luminous efficiency function from scotopic to photopic through the mesopic region. Additivity requires that given two lights, A and B:

If light A visually matches light B, then a composite light made up of pA + qB will also match lights A and B, if p and q are fractional amounts whose sum is unity.

Proposed System

The proposed system is quite simple to use. It is, in effect, a system for choosing among commercially available light sources to deliver the same unified, rather than photopic, photometric quantity.

Step 1

Determine the appropriate light level from among those levels recommended by organizations such as the Illuminating Society of North America (IESNA; see for instance *American National Standard Practice for Roadway Lighting RP-8-00* [IESNA 2000]).

For example, consider a local road in a low pedestrian conflict area (i.e., an area with minimal pedestrian traffic) with R1 pavement type (10 percent reflectance typical). The IESNA-recommended maintained average horizontal illuminance for such conditions is 3 lx (Table 1; IESNA 2000).

Table 1. IESNA recommended maintained average horizontal illuminance levels (lx) for different types of roads, pavement, and pedestrian conditions (excerpt from IESNA 2000).

Road and Pedestrian Conflict Area		Pavement Classification		
Road	**Pedestrian conflict area**	**R1**	**R2 & R3**	**R4**
Freeway Class A		6 lx	9 lx	8 lx
Freeway Class B		4 lx	6 lx	5 lx
Expressway	High	10 lx	14 lx	13 lx
	Medium	8 lx	12 lx	10 lx
	Low	6 lx	9 lx	8 lx
Major	High	12 lx	17 lx	15 lx
	Medium	9 lx	13 lx	11 lx
	Low	6 lx	9 lx	8 lx
Collector	High	8 lx	12 lx	10 lx
	Medium	6 lx	9 lx	8 lx
	Low	4 lx	6 lx	5 lx
Local	High	6 lx	9 lx	8 lx
	Medium	5 lx	7 lx	6 lx
	Low	3 lx	4 lx	4 lx

Step 2

Pick a particular light source appropriate for the application to deliver that illuminance. Each light source can be characterized by its scotopic-to-photopic (S/P) ratio; see Table 2 for a convenient listing of S/P ratios of commercially available light sources used in outdoor lighting applications. For example, consider a 400 W clear high pressure sodium (HPS) lamp. From Table 2, the corresponding S/P ratio is 0.66.

Table 2. S/P ratio of commercially available light sources.

Low pressure sodium	0.25
High pressure sodium (HPS) 250 W clear	0.63
HPS 400 W clear	0.66
HPS 400 W coated	0.66
Mercury vapor (MV) 175 W coated	1.08
MV 400 W clear	1.33
Incandescent	1.36
Halogen headlamp	1.43
Fluorescent Cool White	1.48
Metal halide (MH) 400 W coated	1.49
MH 175 W clear	1.51
MH 400 W clear	1.57
MH headlamp	1.61
Fluorescent 5000 K	1.97
White LED[1] 4300 K	2.04
Fluorescent 6500 K	2.19

[1] The S/P ratios of phosphor-converted white LEDs are bin and manufacturer specific.

Step 3

From Table 3, locate the intersecting cell for the chosen base light level and the particular light source S/P ratio and identify the unified luminance value. Note that the base light levels in Table 3 are expressed in photopic luminance (cd/m^2) rather than illuminance (lx). To obtain luminance from illuminance, multiply illuminance by the reflectance of pavement and divide by pi (π = ~3.1416). In the example above, for a recommended illuminance of 3 lx, the corresponding luminance will be ~0.1 cd/m^2 (L = 3 lx × 0.10 ÷ 3.1416 = 0.096 cd/m^2). Thus, the *unified* luminance produced by the 400 W HPS lamp is approximately 0.0747 cd/m^2 (intersection of S/P ratio of 0.65 and photopic luminance of 0.1 cd/m^2).

By searching through Table 3, it is possible to find other cells with the same, or nearly the same, unified luminance value. These cells indicate both a light source and a photopic light level that provide equivalent photometric levels of unified luminance. For example, a light source with an S/P ratio of 1.55 (e.g., a 400 W clear MH lamp has an S/P ratio of 1.57; Table 2) will produce nearly the same unified luminance (0.0711 cd/m^2) at a photopic luminance of 0.05 cd/m^2. The corresponding photopic illuminance can be calculated by simply dividing luminance into the reflectance of the pavement and multiplying by pi (~3.1416). In the example, the photopic illuminance of the 400 W MH lamp that results in nearly the same unified luminance as the 400 W HPS clear lamp at 3 lx (photopic) will be:

Photopic illuminance (MH lamp) = 0.05 cd/m^2 × 3.1416 ÷ 0.10 = 1.57 lx

At nearly the same unified luminance, which indicates photometric equivalency, the 400 W MH light source will require only half the photopic illuminance of the 400 W HPS clear light source for this example application. Theoretically then, and if designed carefully, fewer MH lamps would be needed to meet the illuminance requirement for this application, thus potentially reducing the power and associated cost that would be required by the 400 W HPS light source.

It is important to remember that choosing a light source involves a number of decisions, including the life, lumen maintenance, and color criteria required by a given application. Lamps should not be selected solely based upon their unified luminance and S/P ratio without considering all design criteria.

Appendix B gives a closed-form expression for calculating unified luminance based on the photopic light level and the S/P ratio of interest. This closed-form expression was used to generate the values listed in Table 3. It is worth noting that the calculations of unified luminance in the mesopic region are bound to the range between 0.001 cd/m^2 and 0.6 cd/m^2. For photopic luminances equal to or greater than 0.6 cd/m^2, the unified luminance simply equals the photopic luminance.

Table 3. Values of unified luminance for different base light levels and S/P ratios.

	Base light level (photopic luminance (cd/m²))											
S/P	**0.001**	**0.01**	**0.02**	**0.03**	**0.04**	**0.05**	**0.06**	**0.07**	**0.08**	**0.09**	**0.10**	**0.12**
0.25	0.0003	0.0026	0.0054	0.0084	0.0115	0.0149	0.0185	0.0223	0.0264	0.0308	0.0355	0.0457
0.35	0.0004	0.0036	0.0075	0.0115	0.0158	0.0203	0.0250	0.0300	0.0353	0.0408	0.0467	0.0591
0.45	0.0005	0.0047	0.0095	0.0146	0.0199	0.0255	0.0313	0.0373	0.0436	0.0501	0.0568	0.0711
0.55	0.0006	0.0057	0.0115	0.0176	0.0239	0.0304	0.0371	0.0441	0.0512	0.0586	0.0661	0.0818
0.65	0.0007	0.0067	0.0135	0.0205	0.0278	0.0351	0.0427	0.0505	0.0584	0.0665	0.0747	0.0917
0.75	0.0008	0.0076	0.0154	0.0234	0.0315	0.0397	0.0480	0.0565	0.0651	0.0739	0.0827	0.1007
0.85	0.0009	0.0086	0.0174	0.0262	0.0351	0.0441	0.0532	0.0623	0.0716	0.0809	0.0902	0.1092
0.95	0.0010	0.0096	0.0192	0.0289	0.0386	0.0483	0.0581	0.0678	0.0776	0.0874	0.0973	0.1170
1.05	0.0011	0.0106	0.0211	0.0316	0.0420	0.0524	0.0628	0.0731	0.0834	0.0937	0.1040	0.1244
1.15	0.0012	0.0115	0.0229	0.0342	0.0453	0.0564	0.0674	0.0782	0.0890	0.0997	0.1104	0.1315
1.25	0.0013	0.0125	0.0247	0.0367	0.0486	0.0602	0.0717	0.0831	0.0943	0.1054	0.1164	0.1380
1.35	0.0014	0.0134	0.0265	0.0392	0.0517	0.0640	0.0760	0.0878	0.0994	0.1109	0.1222	0.1444
1.45	0.0015	0.0144	0.0282	0.0417	0.0548	0.0676	0.0801	0.0923	0.1043	0.1161	0.1277	0.1504
1.55	0.0016	0.0153	0.0300	0.0441	0.0578	0.0711	0.0841	0.0967	0.1091	0.1212	0.1330	0.1561
1.65	0.0017	0.0162	0.0317	0.0465	0.0607	0.0745	0.0879	0.1009	0.1136	0.1260	0.1381	0.1616
1.75	0.0018	0.0171	0.0333	0.0488	0.0636	0.0779	0.0917	0.1050	0.1180	0.1307	0.1430	0.1669
1.85	0.0019	0.0180	0.0350	0.0511	0.0664	0.0812	0.0953	0.1090	0.1223	0.1352	0.1478	0.1720
1.95	0.0020	0.0189	0.0366	0.0533	0.0692	0.0843	0.0989	0.1129	0.1265	0.1396	0.1524	0.1769
2.05	0.0021	0.0198	0.0383	0.0555	0.0719	0.0875	0.1024	0.1167	0.1305	0.1439	0.1568	0.1817
2.15	0.0022	0.0207	0.0398	0.0577	0.0745	0.0905	0.1057	0.1203	0.1344	0.1480	0.1611	0.1862
2.25	0.0023	0.0216	0.0414	0.0598	0.0771	0.0935	0.1090	0.1239	0.1382	0.1520	0.1652	0.1906
2.35	0.0024	0.0225	0.0430	0.0619	0.0796	0.0964	0.1122	0.1274	0.1419	0.1558	0.1693	0.1949
2.45	0.0025	0.0233	0.0445	0.0640	0.0821	0.0992	0.1154	0.1308	0.1455	0.1596	0.1732	0.1990
2.55	0.0026	0.0242	0.0460	0.0660	0.0846	0.1020	0.1185	0.1341	0.1490	0.1633	0.1770	0.2030
2.65	0.0027	0.0251	0.0475	0.0680	0.0870	0.1048	0.1215	0.1373	0.1524	0.1669	0.1807	0.2070
2.75	0.0028	0.0259	0.0490	0.0700	0.0894	0.1074	0.1244	0.1405	0.1557	0.1703	0.1843	0.2107

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Table 3. Values of unified luminance for different base light levels and S/P ratios (cont.).

	Base light level (photopic luminance (cd/m²))											
S/P	**0.14**	**0.16**	**0.18**	**0.20**	**0.22**	**0.24**	**0.26**	**0.28**	**0.30**	**0.32**	**0.34**	**0.36**
0.25	0.0573	0.0704	0.0849	0.1009	0.1184	0.1373	0.1574	0.1788	0.2012	0.2246	0.2487	0.2736
0.35	0.0728	0.0877	0.1037	0.1209	0.1392	0.1585	0.1787	0.1998	0.2217	0.2442	0.2674	0.2912
0.45	0.0864	0.1026	0.1197	0.1377	0.1565	0.1760	0.1963	0.2172	0.2387	0.2607	0.2831	0.3060
0.55	0.0983	0.1156	0.1335	0.1521	0.1713	0.1911	0.2113	0.2320	0.2532	0.2747	0.2966	0.3188
0.65	0.1092	0.1273	0.1459	0.1649	0.1844	0.2043	0.2245	0.2451	0.2659	0.2871	0.3085	0.3301
0.75	0.1191	0.1379	0.1570	0.1764	0.1961	0.2161	0.2363	0.2567	0.2773	0.2981	0.3190	0.3401
0.85	0.1283	0.1477	0.1672	0.1869	0.2068	0.2268	0.2470	0.2672	0.2876	0.3081	0.3286	0.3492
0.95	0.1368	0.1566	0.1765	0.1965	0.2165	0.2365	0.2566	0.2767	0.2969	0.3170	0.3372	0.3574
1.05	0.1448	0.1651	0.1853	0.2054	0.2255	0.2456	0.2656	0.2856	0.3055	0.3254	0.3452	0.3651
1.15	0.1523	0.1730	0.1935	0.2138	0.2339	0.2540	0.2739	0.2937	0.3135	0.3331	0.3526	0.3721
1.25	0.1593	0.1803	0.2010	0.2215	0.2417	0.2617	0.2816	0.3013	0.3208	0.3402	0.3594	0.3786
1.35	0.1661	0.1873	0.2082	0.2288	0.2491	0.2691	0.2888	0.3084	0.3277	0.3469	0.3658	0.3847
1.45	0.1724	0.1940	0.2150	0.2357	0.2560	0.2759	0.2956	0.3150	0.3341	0.3531	0.3718	0.3903
1.55	0.1785	0.2003	0.2215	0.2422	0.2625	0.2824	0.3020	0.3213	0.3402	0.3590	0.3774	0.3957
1.65	0.1843	0.2063	0.2276	0.2484	0.2687	0.2886	0.3081	0.3272	0.3460	0.3645	0.3827	0.4007
1.75	0.1899	0.2120	0.2335	0.2543	0.2746	0.2944	0.3138	0.3328	0.3514	0.3697	0.3877	0.4054
1.85	0.1952	0.2175	0.2391	0.2599	0.2802	0.3000	0.3193	0.3381	0.3566	0.3747	0.3924	0.4099
1.95	0.2003	0.2228	0.2444	0.2653	0.2856	0.3053	0.3244	0.3432	0.3615	0.3794	0.3969	0.4141
2.05	0.2053	0.2279	0.2496	0.2705	0.2907	0.3103	0.3294	0.3480	0.3661	0.3838	0.4012	0.4182
2.15	0.2100	0.2327	0.2545	0.2754	0.2956	0.3152	0.3341	0.3526	0.3706	0.3881	0.4052	0.4220
2.25	0.2146	0.2374	0.2592	0.2801	0.3003	0.3198	0.3387	0.3570	0.3748	0.3922	0.4091	0.4257
2.35	0.2190	0.2419	0.2637	0.2847	0.3048	0.3242	0.3430	0.3612	0.3789	0.3960	0.4128	0.4291
2.45	0.2233	0.2463	0.2682	0.2891	0.3092	0.3285	0.3472	0.3652	0.3828	0.3998	0.4164	0.4325
2.55	0.2275	0.2505	0.2724	0.2933	0.3134	0.3326	0.3512	0.3691	0.3865	0.4034	0.4198	0.4357
2.65	0.2315	0.2546	0.2765	0.2974	0.3174	0.3366	0.3551	0.3729	0.3901	0.4068	0.4230	0.4388
2.75	0.2354	0.2585	0.2805	0.3014	0.3213	0.3404	0.3588	0.3765	0.3936	0.4101	0.4261	0.4417

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Table 3. Values of unified luminance for different base light levels and S/P ratios (cont.).

	Base light level (photopic luminance (cd/m^2))											
S/P	**0.38**	**0.40**	**0.42**	**0.44**	**0.46**	**0.48**	**0.50**	**0.52**	**0.54**	**0.56**	**0.58**	**0.60**
0.25	0.2990	0.3250	0.3514	0.3782	0.4053	0.4327	0.4604	0.4883	0.5164	0.5446	0.5730	0.60
0.35	0.3154	0.3400	0.3650	0.3904	0.4160	0.4419	0.4681	0.4944	0.5210	0.5477	0.5745	0.60
0.45	0.3293	0.3529	0.3768	0.4010	0.4254	0.4500	0.4749	0.4999	0.5251	0.5504	0.5759	0.60
0.55	0.3413	0.3640	0.3870	0.4102	0.4336	0.4571	0.4809	0.5047	0.5287	0.5528	0.5771	0.60
0.65	0.3519	0.3739	0.3961	0.4184	0.4409	0.4635	0.4862	0.5091	0.5320	0.5551	0.5782	0.60
0.75	0.3613	0.3827	0.4042	0.4258	0.4474	0.4692	0.4911	0.5130	0.5350	0.5571	0.5792	0.60
0.85	0.3700	0.3907	0.4116	0.4325	0.4534	0.4745	0.4955	0.5166	0.5378	0.5589	0.5802	0.60
0.95	0.3777	0.3980	0.4182	0.4385	0.4589	0.4792	0.4995	0.5199	0.5403	0.5606	0.5810	0.60
1.05	0.3849	0.4047	0.4244	0.4442	0.4639	0.4836	0.5033	0.5229	0.5426	0.5622	0.5818	0.60
1.15	0.3915	0.4109	0.4301	0.4494	0.4685	0.4876	0.5067	0.5257	0.5447	0.5637	0.5826	0.60
1.25	0.3976	0.4165	0.4354	0.4541	0.4728	0.4914	0.5099	0.5283	0.5467	0.5650	0.5833	0.60
1.35	0.4033	0.4219	0.4403	0.4586	0.4768	0.4949	0.5129	0.5307	0.5486	0.5663	0.5839	0.60
1.45	0.4087	0.4268	0.4449	0.4628	0.4805	0.4981	0.5156	0.5330	0.5503	0.5675	0.5845	0.60
1.55	0.4137	0.4315	0.4492	0.4667	0.4840	0.5012	0.5182	0.5351	0.5519	0.5686	0.5851	0.60
1.65	0.4184	0.4359	0.4532	0.4703	0.4873	0.5040	0.5207	0.5371	0.5534	0.5696	0.5857	0.60
1.75	0.4228	0.4400	0.4570	0.4738	0.4904	0.5067	0.5229	0.5390	0.5549	0.5706	0.5862	0.60
1.85	0.4271	0.4440	0.4606	0.4771	0.4933	0.5093	0.5251	0.5408	0.5562	0.5715	0.5867	0.60
1.95	0.4310	0.4477	0.4640	0.4802	0.4960	0.5117	0.5272	0.5424	0.5575	0.5724	0.5871	0.60
2.05	0.4348	0.4512	0.4673	0.4831	0.4987	0.5140	0.5291	0.5440	0.5587	0.5732	0.5876	0.60
2.15	0.4384	0.4545	0.4703	0.4859	0.5011	0.5162	0.5309	0.5455	0.5599	0.5740	0.5880	0.60
2.25	0.4419	0.4577	0.4733	0.4885	0.5035	0.5182	0.5327	0.5469	0.5610	0.5748	0.5884	0.60
2.35	0.4451	0.4607	0.4760	0.4910	0.5057	0.5202	0.5343	0.5483	0.5620	0.5755	0.5888	0.60
2.45	0.4483	0.4636	0.4787	0.4934	0.5079	0.5220	0.5359	0.5496	0.5630	0.5762	0.5892	0.60
2.55	0.4513	0.4664	0.4813	0.4957	0.5099	0.5238	0.5375	0.5508	0.5639	0.5768	0.5895	0.60
2.65	0.4541	0.4691	0.4837	0.4980	0.5119	0.5255	0.5389	0.5520	0.5649	0.5775	0.5899	0.60
2.75	0.4569	0.4716	0.4860	0.5000	0.5138	0.5272	0.5403	0.5531	0.5657	0.5781	0.5902	0.60

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References

Commission Internationale de l'Éclairage (CIE). 1994. *Light as a true visual quantity: Principles of measurement.* Vienna: Commission Internationale de l'Éclairage, 1994.

He Y., A. Bierman, and M. Rea. 1998. A system of mesopic photometry. *Lighting Research Technology*. 1998; 30:175-81.

He Y., M. Rea, A. Bierman, and J. Bullough. 1997. Evaluating light source efficacy under mesopic conditions using reaction times. *Journal of the Illuminating Engineering Society*. 1997; 26:125-38.

Illuminating Engineering Society of North America (IESNA). 2000. *American National Standard Practice for Roadway Lighting. RP-8-00.* New York, NY: Illuminating Engineering Society of North America.

Rea, M.S. (editor). 2000. Illuminating Engineering Society of North America *Lighting Handbook: Reference and Application*, 9th edition. New York, NY: Illuminating Engineering Society of North America.

Rea, M.S., J.D. Bullough, J.P. Freyssinier-Nova and A. Bierman. 2004. A proposed unified system of photometry. *Lighting Research and Technology* 36(2): 85-111.

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About ASSIST

ASSIST was established in 2002 by the Lighting Research Center at Rensselaer Polytechnic Institute to advance the effective use of energy-efficient solid-state lighting and speed its market acceptance. ASSIST's goal is to identify and reduce major technical hurdles and help LED technology gain widespread use in lighting applications that can benefit from this rapidly advancing light source.

Appendix A: The Unified System of Photometry

The unified system of photometry was described by Rea et al. (2004) in *Lighting Research and Technology*. Below is a synopsis of that paper. For details, see:

> Rea, M.S., J.D. Bullough, J.P. Freyssinier-Nova and A. Bierman. 2004. A proposed unified system of photometry. *Lighting Research and Technology* 36(2): 85-111.

The goal of the proposed unified system of photometry is to allow for the specification of a luminous stimulus for any spectral power distribution and at any light level. One impetus for this system was psychophysical studies showing that the visual effectiveness of some light sources used in nighttime applications are misestimated by conventional photometry in terms of energy efficiency and visual safety. A unified system of photometry would help to more accurately characterize different light sources at any light level, facilitating the specification of effective lighting systems for different applications, including those used outdoors at night.

The current system of photometry utilizes two luminous efficiency functions, the scotopic and the photopic luminous efficiency functions. Either system can be used to characterize a light source; however, the selection of a luminous efficiency function for measurements depends upon the class of visual photoreceptors—rods or cones—assumed to be operating in a given application. Many nighttime applications, such as outdoor lighting of parking lots, provide light levels in the mesopic region where both rods and cones work together to provide vision. Therefore, it remains unclear which luminous efficiency function, or a combination, should be used to characterize light sources for nighttime applications that are neither fully photopic or scotopic in nature.

To develop a consistent and practical unified system of photometry, existing models of mesopic vision were reviewed and four issues were considered. First, the system should be based upon human vision, although no photometry system can be entirely synonymous with vision because of its complexities. Second, the system should preserve additivity, a cornerstone of photometry, though many visual responses use visual channels that are non-additive when responding to light. Third, the photopic and scotopic luminous efficiency functions cannot be abandoned; therefore, this new system utilizes both to represent the mesopic luminous efficiency functions, along with additivity. Finally, the system should be easy to use.

The proposed unified system of photometry is based on reaction times to bridge the conventional luminous efficiency functions through the mesopic region. Reaction times were considered more meaningful for tasks such as driving, where detection is more important than brightness perception. Following this and the models of He et al. (1997, 1998), the basis for the unified system is a parameter, *X*, which describes the proportion of photopic luminous efficiency at a given photopic luminance. The relationship between *X* and unified luminance is assumed to be linear between 0.001 cd/m^2 and 0.6 cd/m^2, which allows unified luminance to be calculated using a simple closed-form equation (see Appendix B). Once the mesopic luminous efficiency function, defined in terms of *X*, is known, it is normalized following photometric convention to 683 lm/W at 555 nm to determine the absolute luminance of the adaptation level. Different combinations of light sources and light levels produce equal adaptation levels if they have equal values of *X*. Therefore, *X* can serve as a simple method for trading off light sources and light levels under mesopic (nighttime) conditions, and thereby aid in the selection of light sources for a given application.

Appendix B: Calculating Unified Luminance

The closed-form expression (Rea et al. 2004) for calculating unified luminance is derived from the original formulation by He et al. (1997, 1998) and is based on combinations of photopic and scotopic luminances. The equation takes the form:

$$L = 0.834P - 0.335S - 0.2 + \sqrt{0.696P^2 - 0.333P - 0.56PS + 0.113S^2 + 0.537S + 0.04}$$

where

L is the unified luminance,
P is the photopic luminance, and
S is the scotopic luminance.

S can be calculated from the S/P ratio of the light source as

$$S = (S/P) \times P$$

The values of unified luminance in Table 3 were generated using the closed-form expression. For example, the unified luminance of an HPS light source (S/P ratio = 0.65) at a photopic luminance (P) of 0.10 cd/m^2 and a scotopic luminance (S) of 0.065 cd/m^2 (S = S/P × P = 0.65 × 0.10 cd/m^2 = 0.065 cd/m^2) would be:

$$L = 0.834(0.10) - 0.335(0.065) - 0.2 + \ldots$$

$$\ldots + \sqrt{0.696(0.10)^2 - 0.333(0.10) - 0.56(0.10)(0.065) + 0.113(0.065)^2 + 0.537(0.065) + 0.04}$$

L = 0.0747 cd/m^2

The calculations of unified luminance in the mesopic region are bound to the range between 0.001 cd/m^2 and 0.6 cd/m^2. For photopic luminances equal to or greater than 0.6 cd/m^2, the unified luminance simply equals the photopic luminance.