Methods for Comparing Visual Illumination Between HID and LED Luminaires to Optimize Visual Performance in Low Light Environments

Abstract

In selecting luminaires to deliver a target illuminance, three primary metrics are utilized to describe a products output; Lumens, Candela and Watts. Lumens describe the gross volume of light produced by a source. Candela describes energy delivered from an optical system along a solid angle. Watts describes the amount of energy a system consumes. While useful in describing luminaire gross output, these metrics assume that all luminaires impart an identical visual stimulus to human observers, which is known to be an inaccurate assumption.

The human visual system does not respond to spectral content of light sources uniformly. Because of this, visual response varies greatly between light sources. Further, the human visual system's response to color changes in relation to illuminance levels. At high illuminance levels, vision is primarily in the photopic region. At very low levels scotopic, and at moderately low levels mesopic. Each of these regions imparts a change in spectral response. Yet, standardized metrics of illuminance and photometry do not consider this effect. This is particularly important when comparing light sources with color characteristics that are poor in generating visual response, such as High-Pressure Sodium, to light sources that produce greater visual stimulation, such as LED. Ultimately, regardless of product efficacy (lumens per watt) or calculated foot-candles delivered, light sources that generate the highest visual efficiency will produce higher visual performance for observers.

Introduction

This paper will describe the mechanisms of human visual response, and the critical factors involved in visual stimulation as it relates to light source spectral power distribution, specifically in low light applications (<5Fc (<50lux)), where visual performance is primarily affected by surface luminance (reflected light) within the mesopic range of .01 to 3cd/m².

Further, methods will be reviewed for empirically estimating equivalent illuminance and luminance between sources of disparate spectral energy, to fully realize efficiency gains from application of visually efficient sources over visually inefficient sources, such as High-Pressure Sodium.

This paper will also review differences in optical characteristics of luminaires, and how differences in realized light distribution can affect evaluation of products with identically described beam patterns. Strategies for visualizing and evaluating performance differences will also be provided.

Background

Human visual response varies in response to color and illuminance levels, from very low reflected light (luminance) to very high illuminance conditions. To establish a uniform comparative method of prediction and evaluation, the fundamental measurement metrics for illumination and luminosity of sources is the lumen, candela and lux (or foot-candle). These standards are centered on Human photopic visual response, which assumes that all illuminance levels exceed 50 Lux (5 Fc). This applies to most interior lighting environments but is not aligned with environments where illuminance levels are low, or surface reflectance is <30%. For applications with reduced illuminance, it is necessary to consider mesopic visual response, which includes greater visual efficiency and unique spectral power response characteristics that change how observers perceive light.

Pursuant to defining adjustments to illuminance that reflect human visual response more accurately, the International Commission on Illumination (CIE) technical group 191 (2010) outlined a recommended system for Mesopic photometry based on visual performance [1]. This was followed by the Illuminating Engineering Society (IES) document TM12-12[2]. Further understanding of human visual response was then published in IES TM24-13[3] based on the combined effect of human visual response at illuminance levels over 150lux (15Fc), and the dynamic influence of the Spectral Power Distribution (SPD) of light sources. The applied result of this new understanding is the potential for reducing energy consumption by increasing visual performance through aligning light source SPD delivery to human visual response.

Light Source Technology Factors

Every light source has a unique spectral power distribution signature. There is no such thing as "white light", only light that contains enough spectral range and energy for human observers to perceive color of surfaces and surroundings. While daylight contains a full spectrum of color, from ultraviolet to infrared, artificial light sources generally involve some form of truncated incomplete spectrum that produce a reasonable facsimile of white light. **Figures 1 and 2** illustrate the spectral power distributions of several common light sources used in energy efficient design practice. These abbreviated spectral power distributions can create issues of visual perception and response, as their missing spectral energies interact with human visual responses.

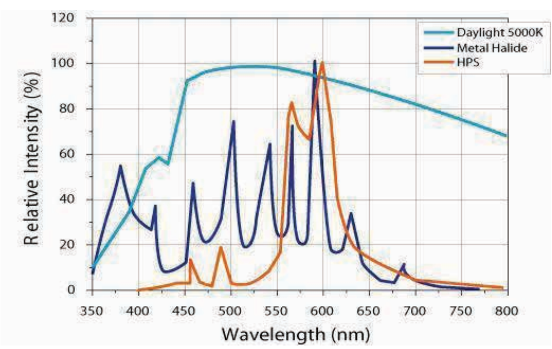

Figure 1 – Spectral Power of Typical HID Lamps
The spectral power produced by HID lamps, in this case Metal Halide and High-Pressure Sodium, when compared to daylight, clearly show a truncated and incomplete spectral emission. This is seen by the human visual system with varying results, from the blue tint of Metal Halide, to the decided yellow-white tint of High-Pressure Sodium.

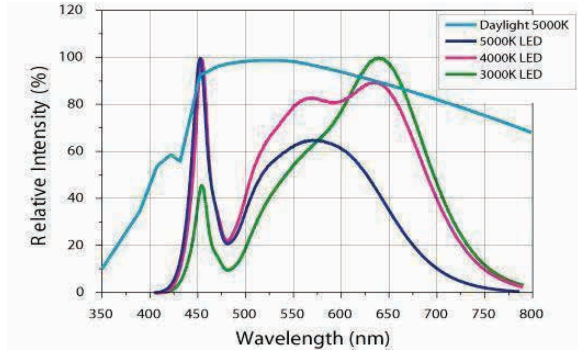

Figure 2 – Spectral Power of Typical LED Sources
The spectral power produced by LED sources also produce incomplete SPD energy. In this case, the difference is perceived as cool white light in the case of the 5000K LED, and warm white for the 3000K LED, while the 4000K LED appears somewhat neutral.

How the SPD content of a light source affects perception of white light is just one part of the effect each has on visual performance. Human physiology involves specific response effects that must be considered, beyond the general perception of white light rendering.

Human Visual Response Factors

The human visual system responds to light in two ways. First, it continually adjusts the size of the iris in response to available illuminance. Second, the retina contains receptors that respond to intensity differences (light and dark contrast), and color content. The response to color is non-uniform and varies between low and high-level retinal illuminance. Low level light response, termed scotopic vision with a peak of 498nm (green-blue), is dominant at luminance levels lower than .01 cd/m², yet remains active always. High level illuminance is termed photopic vision, with a peak of 555nm (yellow-green) and is dominant at luminance (reflected light) levels greater than 3 cd/m², while remaining active at lower levels. The combined visual response of photopic and scotopic vision is dominant when surface luminance (light reflected from surfaces) is between .01cd/m² and 3cd/m² and is termed mesopic, with a peak response of 507nm. Based on this, surfaces with low surface reflectance, illuminated to low levels common to outdoor applications, create conditions supported within the mesopic response region.

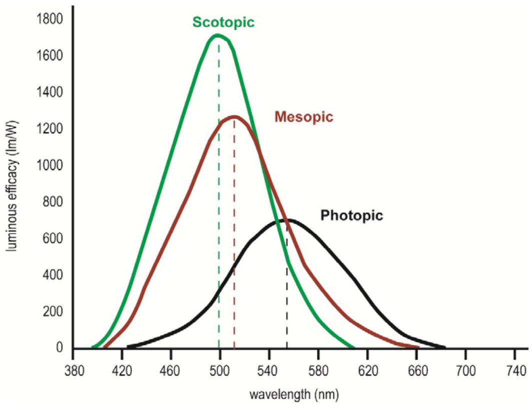

Figure 3 – Human SPD Response to Light
The spectral power distribution of the color of light is measured in wavelength, specifically in nanometers (nm). Photopic Vision (black line) has a peak of 555nm, while Scotopic Vision (green line) has a peak of 498nm. Mesopic response is a combination of the two, with a peak of 507nm.

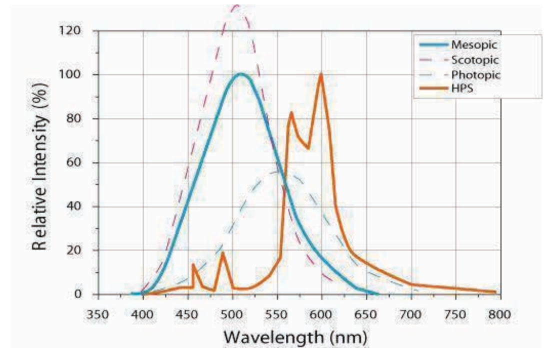

Figure 4 – Comparison of HPS to Mesopic Response
In low light applications (below Photopic range), High Pressure Sodium SPD presents a significant misalignment with Mesopic visual response, and an even greater error in the Scotopic region. The result is poor visual acuity in the form of only partial actual perception of light, requiring illuminance levels be increased significantly to activate Scotopic response.

In Figure 3, the comparison of visual response includes relative efficacy in lm/W. This indicates that the relative visual efficacy is far greater in the scotopic/ mesopic region, than in Photopic vision. This means that the energy required to generate equivalent visual performance diminishes as illuminance levels drop. This is a natural effect required for human vision to be sustained at very low illuminance levels experienced at night, with flexibility to tolerate very high illuminance conditions experienced during full sunlight conditions. In low light application, this presents an opportunity to realize a benefit of visual efficiency by capitalizing on this effect, by utilizing sources that produce a SPD that closely matches these visual response regions.

Since human visual response to the SPD of a light source in non-linear and non-uniform[3], the efficiency of a light source in producing strong visual response (acuity) is dependent on how closely the SPD emission of a light source is to human visual response, at the illuminance levels delivered. If the light source emission (SPD) is misaligned with the visual response SPD at the illuminance level delivered, visual performance will be reduced. The greater this misalignment, the lower the visual performance result will be.

The only strategy available to overcome the loss of visual performance from the misalignment of SPD between visual response and light source emission is to increase actual illuminance levels to compensate. For example, due to the misalignment of the SPD of High Pressure Sodium (Figure 4), a significant increase in illumination level is required to achieve equivalent visual performance. A better approach is to utilize light sources that more closely align and support the visual response. Figure 5 illustrates alignment of LED sources to Mesopic visual response.

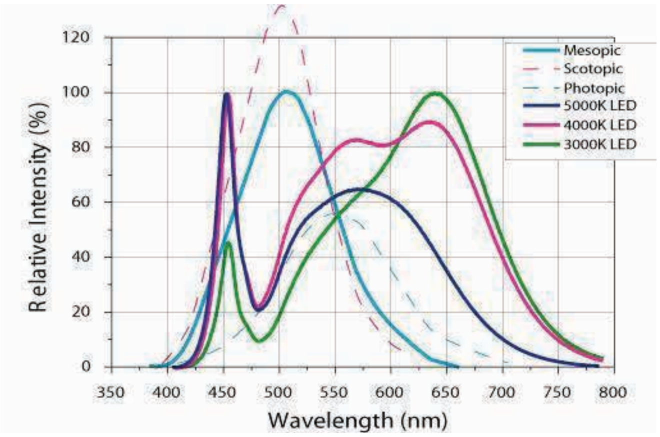

Figure 5 – Comparison of LED to Mesopic Response
LED light sources produce a closer alignment between Mesopic vision and light source SPD production. While these sources are not in perfect alignment, they do offer a significant improvement over High-Pressure sodium.

Optimizing visual performance within the mesopic response region begins with selection of light sources with SPD delivery closely matched to that region. In addition to this physiological response, the Purkninje effect (4), or dark adaptation, indicates that observers respond positively to greenish blue light at very low illuminance levels, and yellow-green tints in high illuminance environments. While mesopic vision is generally of greatest influence in low light conditions and photopic vision is most active in brightly lit spaces, the two often occur within all lighted environments, creating a non-linear perception of light between bright and dimly lighted spaces.

Establishing Equivalent Visual Performance

To quantify the performance differences between light sources for Mesopic illuminance, a method must be devised that considers the Mesopic light performance of a product within the standardized illuminance calculations that are founded on Photopic results. This is necessary to understand how a light source that provides a given result in Photopic terms, performs in applications at a Mesopic level. Without this, the miss-alignment in spectral power produced by a source, such as high-pressure sodium, cannot be accurately evaluated against more suitable sources. Further, at low light levels, it is critical to consider the availability of light to be seen by the eye, in terms of reflected luminance, rather than raw illuminance falling on target surfaces.

To evaluate the effect of a lighting system on visual perception in low light conditions, correction of standard photopic information is required. In this, luminance (reflected light) values are the most critical value, which takes into consideration the reflective properties of the target at levels in the Mesopic region (<3 cd/ m^2). To this end, IES TM12-12 provides detailed instructions and calculations for determining Effective Luminance Factors (ELF). These factors are defined by the following formula:

ELF = Mesopic Luminance ÷ Photopic Luminance

Note that the ELF factor is based on the minimum luminance within a scene, which takes into consideration the adaptation of the observer to the reflected light from surfaces in the lighted area.

Before applying an ELF Factor, one must first determine luminance from a given target as follows:

Luminance (cd/m^2) = (ρ (reflectance of the surface) **÷ π) x E** (Design illuminance in Lux**)**

For example, with a design illuminance of 28 Lux falling onto a concrete surface with a reflectance of 15%, produces the resulting luminance value of:

Using Lux for Illuminance to Calculate Surface Luminance:

$(.15 \div 3.14) \times 28 = 1.338$ (cd/m^2)

Based on the resulting luminance values, the ELF factor (Table 2) can be determined based on the S/P ratio of a specific product (Table 1).

Table 1.0 – Approximate S/P Ratios for Various Sources

Values for several sample products. For actual values to be used in application, S/P ratio information must be obtained for the specific product considered, either by calculation using actual SPD data, captured with an illuminance meter, or from independent lab test data provided by the manufacturer of the luminaire.

Source	S/P Ratio
HPS (2100K)	0.6
PSMH (4300K)	1.5
3000K LED	1.4
4000K LED	1.7
5000K LED	2.0

Table 2.0 – ELF Multipliers Summary for Various S/P Ratios
These multipliers are extracted from TM12-12, which contains greater fidelity, as well as calculation procedures for establishing each value. Data provided in this table and applied using TM12-12 depend on obtaining accurate S/P ratio information for the product being evaluated. Note that the Minimum Design Luminance value is the design minimum for the project, to be applied to all calculations within the application, regardless of actual point-by-point luminance result.

S/P Ratio	Minimum Design Luminance in cd/m²					
	.3	.5	.7	1	2	3
0.60	0.9095	0.9304	0.9428	0.9550	0.9762	0.9872
1.40	1.0834	1.0647	1.0534	1.0422	1.0226	1.0121
1.50	1.1033	1.0802	1.0663	1.0524	1.028	1.0151
1.70	1.1422	1.1106	1.0914	1.0724	1.0387	1.0208
2.00	1.1984	1.1545	1.1279	1.1013	1.0543	1.0293

Applying the ELF factor to the luminance value derived from the calculated standard photopic illuminance values provides insight into the resulting actual visual effect in the Mesopic region to observers.

In an application example with an average illuminance of 28 Lux falling onto a paved surface with a reflectance of 15%, the resulting luminance value is 1.338 cd/m². Assuming a light source with an S/P (Scotopic /Photopic) ratio of 1.0 this value remains 1.338 cd/m². However, when sources differ in S/P ratio, their resulting ELF value applied will reveal the relative visual performance to observers more accurately. For this, a minimum design luminance must be first established. This can be establishing from a desired minimum lux level, and a given surface reflectance. For example, at a minimum lux of 15, the minimum luminance value can be established as follows:

$$(.15 \div 3.14) \times 15 = 0.717\ (cd/m^2)$$

Using this minimum luminance value, the ELF factor can be determined from Table 2.0. In the following example, a High-Pressure Sodium source, with an S/P ratio of 0.6, and ELF factor of .9428 (@ 0.7cd/m² minimum luminance), delivers an effective visual luminance would be perceived as 1.261 cd/m² as follows:

Using Lux for Illuminance to Calculate ELF Luminance:

$$(.15 \div 3.14) \times 28 \times .9428 = 1.261\ ELF\ (cd/m^2)$$

For comparison, a 5000K LED with an S/P ratio of 2.0, resulting in an ELF factor of 1.1279, delivers an equivalent perceived luminance of 1.509. This represents a perceived improvement in visually perceive luminance of 20% over the HPS product calculated to the same 28 Lux Photopic illuminance level. Comparison of multiple light sources and their impact on visual performance can be accomplished by multiple calculations including appropriate photometric data and light loss factors, as shown in Table 3.0.

Table 3.0 – Equivalent Energy and Effective Visual Performance using ELF Correction
The following is a comparison of luminaires mounted 6 meters (20ft) above the floor, with a common LLF (Light Loss Factor) of .75, and an assumed minimum ELF Luminance of 0.7cd/m²
This table illustrates the difference in mesopic visual perception based in ELF luminance, using S/P ratios indicated in Table 1.0 and ELF factors shown in Table 2.0.

Source	Source S/P Ratio	ELF (TM12)	Fixture Output Lumens	Sys. Watts	Efficacy (lm/W)	Energy Diff.	Illuminance Directly Below Luminaire (Lux)	Calculated ELF Luminance (cd/m²)	Diff.
HPS 100W Ref. KPCL1075MT	0.60	0.9428	6,441	130	50	Ref	28.78	1.30	Base
PSMH 100W Ref. KPCH1075MT	1.50	1.0633	6,408	129	50	-0 %	28.28	1.44	+11%
3000K LED Ref. MLLED3WD5BU	1.40	1.0534	3,839	38	101	-68%	28.13	1.42	+9%
4000K LED Ref. MLLED3ND5BU	1.70	1.0914	3,998	38	105	-68%	27.53	1.44	+11%
5000K LED Ref. MLLED3CD5BU	2.00	1.1279	4,258	38	112	-68%	27.75	1.50	+15%

The comparisons in Table 3.0 illustrates that reductions in energy consumption are attainable while increasing usable luminance. Changes in CCT and spectral power of light sources produce gains in visual efficiency. In the examples shown, where the lumen output of HPS (6,441) would appear to indicate a significant difference over the 5,000K LED (4,258), the actual realized difference, due to ELF luminance comparison, is the opposite, with the white LED product delivering a perceived luminance improvement of 15%. The neutral white (4000K) LED produces the same effective luminance as the 100W PSMH product, with 68% less energy.

In applications where photopic vision plays a larger role, the recommendations outlined in IES TM-24-13 is applied to illuminance levels delivered by the lighting system. While TM12-12 is founded on the SPD of light sources within the Mesopic region and focuses on luminance emitted (reflected) from surfaces as the target determinant of equivalence, TM24-13 is based on S/P ratio to establish an EVE (Equivalent Visual Efficiency) factor, which is applied to target illuminance. The results are similar, but distinct. TM-24-13 also includes consideration of spectral effects on accommodation (iris response to brightness), that further enhance evaluation of light source performance. The following is a summary of the same sources compared in Table 3.0, but using TM-24 EVE factors in place of ELF factors:

Table 4.0 – TM24 EVE Multipliers Summary for Various S/P Ratios

These multipliers are extracted from IES TM24-13 for the S/P ratios of the source examples used in this study.

S/P Ratio	EVE Factor
0.60	1.97
1.40	1.00
1.50	.95
1.70	.86
2.00	.75

Using Lux for Illuminance to Calculate Comparable EVE Corrected Illuminance:

Illuminance ÷ EVE Factor = Calculated EVE Illuminance

The purpose of recommendations outlined in TM24-13 is to apply correction factors to reduce applied luminaire power to achieve a desired visual result, based on adjusting CCT of light sources utilized. For purposes of comparison shown in Table 5.0, the EVE factor is applied in the inverse, to produce a comparison consistent with results shown in Table 3.0 utilizing the same example luminaires and ELF multipliers.

Table 5.0 – Equivalent Energy and Effective Visual Performance using EVE Correction

The following is a comparison of luminaires mounted 6 meters above the floor, with a common LLF (Light Loss Factor) of .75

This comparison of light sources illustrates the difference in visual performance based on EVE illuminance, using S/P ratios indicated in Table 1.0 and EVE factors shown in Table 4.0. Note that EVE results are for illuminance, which is very different from luminance used in Table 3.0 luminance calculations.

Source	Source S/P Ratio	EVE (TM24)	Fixture Output Lumens	Sys. Watts	Efficacy (lm/W)	Energy Diff.	Illuminance Directly Below Luminaire (Lux)	Calculated EVE Illuminance (Lux)	Diff
HPS 100W Ref. KPCL1075MT	0.60	1.97	6,441	130	50	Ref	28.78	14.61	Base
PSMH 100W Ref. KPCH1075MT	1.50	1.00	6,408	129	50	-0 %	28.28	28.28	+94%
3000K LED Ref. MLLED3WD5BU	1.40	.95	3,839	38	101	-68%	28.13	29.61	+102%
4000K LED Ref. MLLED3ND5BU	1.70	.86	3,998	38	105	-68%	27.53	32.01	+119%
5000K LED Ref. MLLED3CD5BU	2.00	.75	4,258	38	112	-68%	27.75	37.00	+153%

These results clearly show that white light sources produce the perception of higher effective illuminance exceeding the results achieved in the ELF corrected luminance. This comparison illustrates the results of applying multipliers to include visual performance factors, based on light source S/P ratio, to more accurately predict visual perception of illuminance and luminance. This applies to both photopic application (TM24) and mesopic (TM12) applications. In both cases, light sources with more complete spectrums and higher CCT's generate significantly higher visual performance and perception. In both cases, LED products generate gains in effective visual performance at a significant energy saving over the HID sources, even white MH sources.

In practical application, visual performance and perception includes a combination of mesopic and photopic visual performance factors, dependent on illuminance levels, reflective properties of surfaces, task work involved, and lighting technology applied. For this reason, it is necessary to consider both photopic and mesopic visual factors when comparing light sources with disparate spectral power distributions (CCT color and spectral content included). Neither represent a single answer in predicting visual performance.

In field observation, the appearance of light sources, and brightly illuminated areas are likely to be impacted by the effects illustrated in Table 5.0, where light sources with higher CCT values will appear significantly brighter than sources with truncated spectral distributions and low CCT values, such as HPS. This can produce instances where luminaires with lower raw lumen output product generate significant improvements in visual brightness appearance. When observing surfaces with low luminance, either from reduced illuminance or low reflective qualities, the difference between sources with higher CCTs vs. those with low CCT values will also favor sources with higher CCTs or more complete spectral power, as shown in Table 3.0.

Photometric Dynamics and Effects

While the results shown in Table 3.0 clearly indicate the differences in visually perceived luminance between sources based on light source technology, actual field results will present even greater visual differences due to photometric differences between conventional lamp and LED powered optical systems.
The effect of the iris responding to illuminance, or direct luminance within the visual environment is a complex problem. Glare, or brightness from visible light sources can cause the iris to close, reducing illuminance and visibility in the visual field, specifically in shadow areas or indirectly illuminated spaces.

Selection of light source spectral power distribution, coupled with control of brightness and glare by limiting high angle distribution, are critical considerations in the design of lighting systems. This becomes an even greater factor when illuminance levels are very low, such as those used in exterior illumination designs. Since mesopic vision generally includes the iris being fully dilated to accept all available light, the impact of glare, which causes the iris to close, coupled with the source creating a high enough luminous energy to shift visual response toward the photopic region, creates a blinding effect that obliterates vision by significantly reducing brightness perception in the lighted environment [1, 5].

The most effective strategy for low light applications is to pursue designs with the most uniform illuminated field practical, using optics that limit high vertical angle light output. Maintaining an average to minimum ratio of 3:1 or less[6] is also recommended to produce the least amount of veiling and adaptive reaction under mesopic visual conditions.

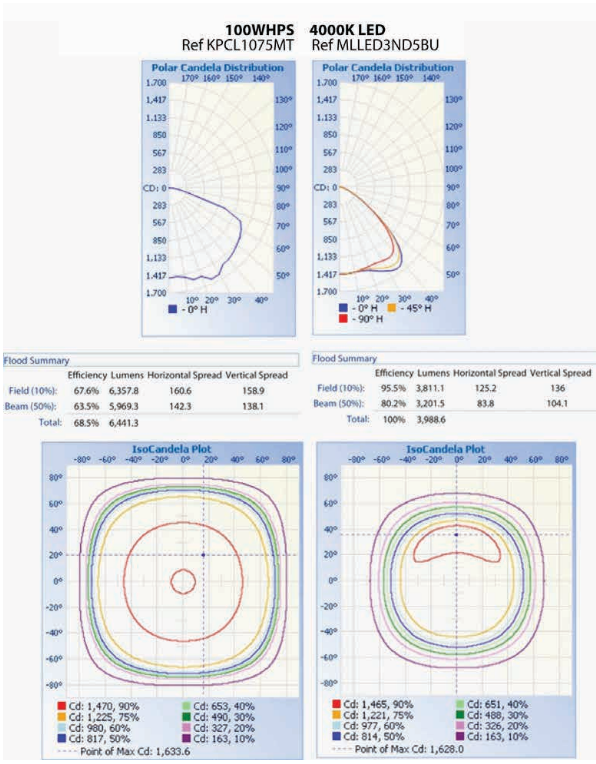

Figure 6 – Comparison of Luminaire Optical Performance HID to LED

An important factor in selection of luminaires that differ in source technology (see figure 5), and the effect these have on optical distribution patterns. Photometric definitions establish beam angle as the angle in which the emitted energy is at 50% of maximum luminance in candela, and field radiance as 10% of maximum. In general terms, the more light a product distributes inside its beam pattern, the more effective it is in producing effective lighting on target surfaces. Greater energy distributed into the surrounding field angles increases chances of objectionable glare and wastes energy illuminating surrounding surfaces above and outside the designated target area.

In the comparison shown in Figure 6, both products share the same peak candela of ~1630, although the HID luminaire has a wider spread of 146 x 138° (NEMA 7x7) compared to the LED product at 84 x 104° (NEMA 6x7). The LED product distributes 80.2% of its energy within its beam (50% of peak cd), while the HID product distributes 63.5% within its beam. The result in field application is that the HPS product may appear to cover a larger area than the LED due to its greater energy emitted at high angles outside the main beam distribution. The HPS product produces a spacing criterion* of 1.58, while the LED product produces a spacing criterion of 1.68. As a result, the LED product can be applied with a wider luminaire spacing, with the same horizontal illuminance at the task level. The HID product will generate lower uniformity, and higher vertical illuminance, perceived as an increase in the appearance of brightness, that may also be the source of glare.

HID technologies tend to produce greater a larger uncontrolled surrounding field illuminance. LED products with similar optical distribution patterns will produce a more uniform beam pattern with less uncontrolled perimeter field illuminance. In consideration of this difference, it may be necessary to select a wider beam pattern LED product compared to an HID luminaire, to produce a similar appearance of brightness in the applied environment. Whether this is necessary to delivering effective task illuminance or luminance, depends on the objectives set for the environment itself.

Due to these factors, and other subtle differences that emerge when comparing applied luminaire performance using disparate light source technologies, it is necessary to utilize simulation software that utilizes actual luminaire photometric test data to generate an accurate evaluation of illuminance and luminance levels attained. However, it is important to note that most design software produces calculated results founded on photopic illuminance, as this is what the photometric data produces. These results will then need to be calibrated to include ELF variables into resulting luminance, using the methods indicated in Tables 2 and 3, to establish effective luminance values and system performance.

* **Spacing Criterion** is a luminaire characteristic derived from the distribution of the direct component on the work plane. A luminaire›s Spacing Criteria are an estimation of the spacing-to-mounting-height ratio needed for a luminaire to produce uniform illuminance on a work plane from a luminaire array.

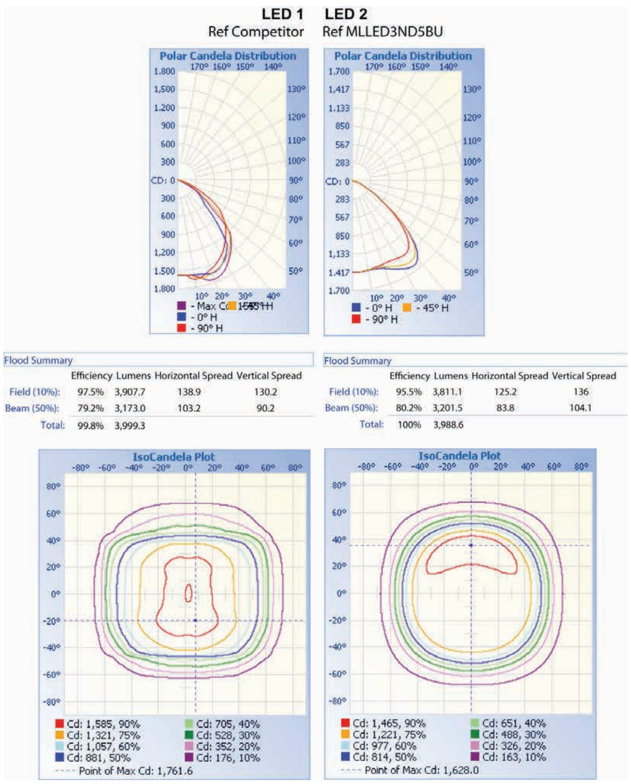

Figure 7 – Comparison of Luminaire Optical Performance LED to LED

Regardless of descriptive terms for luminaire performance, optical design approaches will produce differences between luminaires sharing light source technology. Because of this, it is not possible to assume that any luminaire, regardless of light source technology employed, is equal to another, based on NEMA beam type or beam angle generalizations. For this reason, the only reliable approach to evaluation and selection of luminaires to suit a specific application is through collection of specific product photometric data, applied using computer simulation to the intended application area.

In figure 7, both luminaires produce the same ~4000 lumen output. (LED #2 is shared from Figure 5.) Note that both products share a similar spread in vertical and horizontal angles (NEMA 7x6 - the inversion of the horizontal and vertical angles is imbedded in the photometric files and is irrelevant to this comparison.) LED 1 distributes 79.2% of its energy within its beam (50% max cd), while LED 2 distributes slightly more at 80.2%. However, LED 1 generates more energy directly below the luminaire, with a peak of 1758 candela at 20°, while LED 2 produces a peak of 1628 at 35°. The result in field application is that the LED 1 will produce more light under each luminaire, while LED 2 will generate a more uniform light distributed over the area illuminated with less hot-spots when combined with other luminaires within a grid layout. This is reflected in the spacing criterion, with LED 1 offering 1.40, while LED 2 produces a spacing criterion of 1.68 - indicating it will produce greater uniformity at wider luminaire spacing distances.

Field Measurement Issues

All photometric testing and reporting, including standards of performance stated in foot-candles or lux, are based on photopic illuminance. Further, light meters used in field measurement are calibrated to match the human photopic visual response curve (shown in Figure 3) - which is out of alignment with mesopic visual response. The resulting measurements will not accurately reflect mesopic illuminance for two reasons; 1.) Mesopic visual response is more sensitive, creating a higher perceived brightness than will be shown in photopic meter readings, and 2.) Any light source with spectral energy designed to enhance mesopic visual response will be under reported by meters calibrated for photopic measurement. For this reason, any lighting system optimized for mesopic vision will produce inconsistent field measurements with meters calibrated for photopic response. Unfortunately, there are few meters marketed specifically for measurement of mesopic illuminance, other than for use in lab measurements.

The approach necessary for realizing more accurate visual illuminance response is the application of S/P (Scotopic/Photopic) ratio multipliers to readings obtained with standard photopic meters. Modern meters are available that generate the two variables required; Photopic illuminance and S/P ratio (which is a function of spectral power of the light source employed).

These two values can then be used to ascertain the performance of a lighting system in the mesopic region. This ratio can then be applied as a multiplier to the measured photopic value produced, indicating a more accurate indication of mesopic performance. Lighting systems that generate the greatest advantage in mesopic vision will produce high S/P ratios.

Table 6.0 – Applying S/P Ratio to Photopic Meter Results

Multiplying photopic meter readings by the S/P ratio captured for the same light source provides insight into mesopic illuminance falling onto a surface. Note that this only provides an indicator of possible performance differences of light sources based on CCT generalities. More accurate evaluations of metered readings should include application of ELF and EVE factors described in Tables 3.0 and 5.0, as they apply to illuminance, and luminance and levels outlined.

Source	Photopic Lux (Meter Reading)	S/P Ratio (Table 2.0)	Calculated Mesopic Lux
High-pressure sodium	14.0	0.6	8.4
Metal halide (4300K)	14.0	1.5	21.0
3000K LED	14.0	1.4	19.6
4000K LED	14.0	1.7	23.8
5000K LED	14.0	2.0	28.0

In addition to calibration miss-alignment between mesopic and photopic vision, LED light sources produce spectral power distributions that differ from conventional lamp technologies (as shown in Figure 3.) Most quality digital light meters using silicon semi-conductor receptors and electronic calibration, are unaffected by these differences.

However, low cost meters, older meters using selenium photo cells with analog metering, and meters employing obsolete electronic algorithms created prior to the introduction of LED technology, will produce unreliable and potentially wildly inaccurate field measurement results.

	Handheld Computerized	Handheld LED Calibrated	Handheld Digital	Handheld Analog
Calibration	2015	2012	2001	1972
Sensor	Silicon/Digital	Silicon/Digital	Silicon/Digital	Selenium
Incand Lamp	36.6	36.1	36.4	22
Error	Base	1.4%	0.5%	39.9%
5000K LED	40.1	39.6	39.9	22
Error	Base	1.2%	0.5%	45.1%
S/P Ratio	1.9	n/a	n/a	n/a

Figure 8 – Comparison of Illuminance Meters and Photopic Accuracy
This comparison of common off-shelf meters shows how differences in technology impact both reliability of measurement, and the difference in results based on light source. The computerized meter utilizes software to interpret spectral information collected from its photocell element, translated to produce a wide range of results, including illuminance, CCT and S/P ratio. Low cost handheld light meters may produce reasonable accuracy, but do not collect spectral data (SPD) necessary for calculating visual response beyond basic photopic vision.

For these reasons, mesopic lighting requires special consideration not applicable to regular photopic illuminance applications. Unfortunately, standards stating maximum, minimum, and average illuminance requirements generally assume photopic values, regardless of target illuminance levels. This indicates that field verification of results will be measured with standard photometers tuned for photopic vision, which will not reflect mesopic design considerations. Whether or not mesopic illuminance will be accepted during compliance inspection must be ascertained on a case-by-case basis. Failing that, the result may be over-lighting and wasted energy.

Achieving Maximum System Efficiency and Visual Performance

The steps for attaining maximum energy utilization and efficiency are as follows:

(1) Know where the target illuminance falls within the visual performance range (Mesopic or Photopic).

(2) Choose sources with the highest S/P ratio available for the application to realize the advantage of high Effective Luminance Factor (ELF) and/or Equivalent Visual Efficiency (EVE) benefit.

(3) Choose luminaires and sources with the highest available efficacy.

(4) Select appropriate luminaire photometrics to produce the highest levels of uniformity across the visual field possible with the lowest potential for glare.

Future Work Required

Unfortunately, codes and standards that fail to consider the effect of illuminance levels or SPDs on visual perception leads to poor performance in low light environments - where mesopic vision is a more critical factor. The blindness in standards does not isolate sources that are decidedly poor for mesopic vision, such as high-pressure sodium. This disconnect results in erroneous assumptions, increased energy consumption, and confusion in the perception of light observed in application.

Standards, such as IES RP's, API RP540 Section 7, local and regional regulations do not differentiate between photopic and mesopic visual performance. This results in a metric disconnect that leads designers to select light sources inadequate to visual performance (HPS), while measurement of applied lighting systems is accomplished using instruments that are not suited to the actual application when low level illumination is encountered. To remedy this, future codes, regulations, recommended practices and application standards targeted at prescribing illuminance and luminance values for low light applications under 50Lux (<5Fc) need redressing. By including both mesopic illuminance as well as target luminance values and SPD composition, benefits outlined in this study can be fully applied in reduction of energy through the application of lighting systems, while delivering superior visual performance.

Conclusion

Design and application that includes consideration of human performance factors as a critical component, with all factors of visual performance in application, leads to significant improvements in energy utilization, human visual performance and system operational cost reduction. Application of light sources that are more closely matched to human visual responses at low illuminance levels, coupled with the efficacy gains realized from LED sources, produces the most efficient end-product possible. LED technology not only offers an opportunity to bring these advancements in understanding to practical application, with lower operational cost, the availability of CCT (color) choices to suit controlled blue light emissions, enhanced optical techniques to produce high uniformity, and control of visual brightness effects that are equally beneficial.

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United States (Headquarters)
Appleton™ Grp LLC
9377 W. Higgins Road
Rosemont, IL 60018
United States
T +1 800 621 1506

Canada
EGS Electrical Group Canada Ltd.
99 Union Street
Elmira ON, N3B 3L7
Canada
T +1 888 765 2226

Europe
ATX SAS
Espace Industriel Nord
35, rue André Durouchez,
CS 98017
80084 Amiens Cedex 2, France
T +33 3 2254 1390

Latin America
EGS Comercializadora Mexico
S de RL de CV
Calle 10 N°145 Piso 3
Col. San Pedro de los Pinos
Del. Álvaro Obregon
Ciudad de México. 01180
T +52 55 5809 5049

Australia Sales Office
Bayswater, Victoria
T +61 3 9721 0348

Korea Sales Office
Seoul
T +82 2 3483 1555

China Sales Office
Shanghai
T +86 21 3338 7000

Chile Sales Office
Las Condes
T +56 2928 4819

Asia Pacific
EGS Private Ltd.
Block 4008, Ang Mo Kio Ave 10,
#04-16 TechPlace 1,
Singapore 569625
T +65 6556 1100

Middle East Sales Office
Dammam, Saudi Arabia
T +966 13 510 3702

India Sales Office
Chennai
T +91 44 3919 7300

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