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Effects of Light Spectrum on Luminance Measurements in Underground Coal Mines

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Abstract

Lighting regulations for luminance in U. S. coal mines are verified in the field by using a luminance photometer calibrated to the Standard Illuminant A light source. Significant measurement errors can exist when measuring light sources that are dissimilar to light sources used to calibrate the photometer. This paper quantifies the measurement errors when measuring these dissimilar light sources commonly used in U.S. underground coal mines—an LED, a CFL with a clear cover, a CFL with an amber cover, and a tungsten halogen. The impact of photometer quality was also evaluated. Three different luminance measuring instruments of high, medium, and low quality were compared—a PR-650, LS-100, and PMEX, respectively. The PMEX was under evaluation for measuring luminance compliance in U.S. underground coal mines. The PR-650 was used as the referent to which the other photometers were compared. The PMEX error ranged from −17.0% to −26.5% with the highest error for the amber CFL. The LS-100 closely matched the luminance measurement for the LED and halogen; however, it had a percent error of −10.4% for the amber CFL. After the initial experiment, MSHA made improvements to the PMEX resulting in the PMEX-MSHA. The experiment was replicated using the new photometer and the newer PR-670. After repeating the experiment, the measurement errors ranged from −16% to −19% for the PMEX-MSHA, thus indicating an improvement over the PMEX. These results show that the spectral content of a light source and the photometer quality can greatly impact the accuracy of luminance measurement.

Keywords

mine lighting; underground mining; luminance

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IX.Disclaimer

The findings and conclusions in this paper are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention. Mention of any company or product does not constitute endorsement by NIOSH.

III. Definitions

A. *StandardIlluminantA* is a Commission Internationale de l'Eclairage (CIE) defined standard illuminant incandescent light with a tungsten filament and a correlated color temperature (CCT) of 2856K that is used to calibrate photometric devices [1].

B. *Luminance* is generally considered to be what people see when light is reflected back off of an object or, in other words, the human perception of brightness. It is defined by the Illuminating Engineering Society (IES) as the quotient of the luminous flux at an element of the surface surrounding the point and propagated in directions defined by an elementary cone containing the given direction, by the product of the angle of the cone and the area of the orthogonal projection of the element of the surface on a plane perpendicular to the given direction [2]. The measurement of luminance is dependent on both the surface area and reflectance of the area [3]. Because luminance is the amount of light returning from a surface and measured from a fixed angle, the measurement value does not change with distance from the surface since the area increases along with the distance [4].

C. *Standard photometric observer function* is intended to represent the visual perception of the average human eye [6]. This mathematical function is of an "ideal observer having a relative spectral responsivity curve that conforms to the spectral luminous efficiency function for photopic vision $V(\lambda)$"[5].

D. *Spectral power distribution* (SPD) is the level of radiant power of each wavelength in the visible portion of the electromagnetic spectrum present in a light source [1]. Although the SPD quantifies spectral content of light, SPD is not necessarily an accurate indicator of the overall color or appearance of a light source.

E. *Spectral mismatch correction factor* (F*) is "the factor by which the readings of a physical photometer may be multiplied in order to correct for the error caused by differences between the relative spectral responsivity of the photometer and the photometric observer function that it is intended to simulate when the photometer is used to measure a light source having a relative spectral power distribution different from that of the source with which the photometer was calibrated … Most photometers are designed to simulate the $V(\lambda)$ function and are calibrated using a source corresponding to CIE standard Illuminant A" [5].

IV. Introduction

In an underground mine, proper lighting is a critical factor for maintaining a safe work environment. While miners work beneath the earth, all sources of light are artificial. Not surprisingly, underground mines are considered to be one of the most difficult places to light [7]. Yet maintaining proper illumination is crucial for the safety of the people who work there. As such, the United States government regulates lighting in underground mines by specifying luminance levels achieved through area lights and machine lights to 0.21 cd/m^2 (0.06 fL), as set by the Federal Mine Safety and Health Act of 1977 [8]. The Mine Safety and Health Administration (MSHA) is responsible for enforcing these regulations. These luminance levels are set to provide adequate illumination for miners to safely accomplish their work. The regulations stipulate that a photometer is to be used to verify that luminance levels meet requirements and that the photometer be color corrected to the CIE Spectral Luminous Curve [8]. In order to measure luminance levels and enforce regulations, a Quantum Instruments PMEX luminance photometer was being evaluated by MSHA. However, significant error sources arise from the use of luminance meters in the mine environment, which include accidental, systematic, short term, constant, and probable errors, among many others [3]. Coal mines in particular present a challenge due to large variations in the spectral and reflective properties of coal [9]. Many other factors can affect luminance meter measurements, including the accuracy of the meter, surface wetness, the orientation of the meter and distance to the measurement surface, and the surface texture [9] [10]. For instance, a prior study showed a very large variation in the luminance measurements that ranged from a −42.9% luminance change when the coal rib was wetted up to a 66.7% luminance change when the photometer distance was decreased from 1.5 m (5 ft.) to 0.6 m (2 ft.) [10]. The prior study had some limitations in that only a single light-emitting diode (LED) light source was used, while mine lighting also uses fluorescent, incandescent, and halogen light sources. Secondly, the measurement errors pertaining to the spectral content of the light were not quantified. These factors call into question the reliance on using a handheld photometer for luminance measurements in an underground mining environment and the use of luminance as a basis for compliance with mine lighting regulations [10].

The spectral content of light can be an important factor when measuring luminance. The human eye follows a particular spectral sensitivity curve in ideal lighting, as described by the CIE standard observer [2], and is most sensitive to the middle wavelengths of light. The peak sensitivity of the human visual perception of brightness is at 555 nm, more commonly known as yellow-green. The human eye is much less visually sensitive to the shorter and longer wavelengths—blue and red, respectively. The photopic vision curve shown in Fig. 1 illustrates average spectral sensitivity of the human eye. However, the eye does not always respond to spectral light consistent with the photopic curve. In darkness, with luminance below 0.001 cd/m^2 (0.0003 fL), the eye's spectral sensitivity to light shifts to the scotopic vision curve [2]. The peak sensitivity of this curve instead occurs at 507 nm, which is much closer to blue [11]. Furthermore, the shift also reduces the ability of the eye to perceive fine details or distinguish colors. In between photopic and scotopic vision, such as that experienced in the relatively dim light of underground mines with luminance between 0.001 and 10 cd/m^2 (0.0003 and 2.92 fL), the eye follows the mesopic vision curve seen in Fig. 1 [2]. This curve also shifts to the lower spectral wavelengths; however, with mesopic vision some detail and colors are still discernible. When in an underground mine with dim lighting, the human eye experiences mesopic vision, which is also the range in which the MSHA luminance level is specified within the regulation. Yet the standard photometer follows the photopic curve, leading to a possible misrepresentation of what the human eye perceives.

Most photometers are calibrated using the Standard Illuminant A and attempt to closely follow the sensitivity of the human eye such that the measurements are consistent and have a meaningful representation to human vision. Photometers follow the sensitivity of the photopic curve, yet not all light sources contain the same spectral content. Mismatch in spectral sensitivity is frequently the most common source of error in using luminance meters [12]. Due to this phenomenon, luminance meters can produce large errors in readings when used to measure sources of light that greatly vary in spectral content. For this reason, there is another type of photometer called a spectroradiometer, which measures the spectral radiometric power at each wavelength of the visible spectrum. Measurements using a spectroradiometer are, thus, spectrally balanced across the spectrum and typically produce the most accurate photometric readings [6]; however, these devices are considerably more expensive.

The spectral power distributions of a fluorescent light and an LED light can be seen in Fig. 2. While both of these light sources may appear to produce a similar color of cool-white light, their spectral content is clearly very different. To the human eye, they would likely appear very similar, but the difference in spectral power may cause an error in the luminance value measured by a photometer due to the spectral mismatch. Therefore, the primary objective of this study was to determine the potential impact on accuracy in measuring luminance in underground coal mines when the light source SPD is taken into account.

V. Methods

A. Luminance Measurement Instruments

There were three different instruments used to measure luminance in this study: the Photo Research PR-650 SpectraScan Colorimeter and two photometers—the Konica Minolta LS-100 and the Quantum Instruments Photo Meter PMEX. There are major differences in the design, complexity, and accuracy of each instrument that can be indicated by their costs in U.S. dollars, as seen in Table I. An overview of each instrument follows.

The PR-650 is a spectroradiometer that measures spectral power distribution and colorimetry, as well as luminance, and has a spectral range of 380 to 780 nm. It has a 1° measurement field of view and a 7° viewing angle through the lens. This photometer was chosen as the reference given that it accurately measures luminance over a wide range of spectral content. It separates the light into its constituent wavelengths and measures the spectral irradiance for every nanometer of light wavelength; thus, it differs from filter photometers in that it is very accurate, and calibration to Illuminant A is not needed. The PR-650 specifications are a luminance measurement range of 3.4–17,000 cd/m^2, a spectral accuracy of ± 2 nm, and a luminance accuracy of ± 2% at 2856 K.

The Konica-Minolta LS-100 photometer has a through-the-lens viewing system that visually indicates the circular area to be measured. It has a 1° measurement field of view and a 9° viewing angle through the lens. It also has the ability to handle color correction factors to adjust the spectral response of the photometer for more accurate measurements for a variety of light sources that have different spectral characteristics. The LS-100 specifications are a luminance measurement range of 0.001–299,900 cd/m^2, a spectral accuracy of 2% at 2800 K, and an electrical display accuracy of ± 2% of ± 2 digits of the displayed value.

The Quantum Instruments Photo Meter PMEX was selected because it is being evaluated by MSHA for measuring luminance in the field. It has an acceptance angle of 25° when reading luminance. Placing the photometer at a distance of 1.5 m (5 ft.) from a rib as required by MSHA [8] results in a circular measurement area having a radius of 0.33 m (13.3 in). The photometer does not have a viewing system that visually indicates the circular area to be measured. It also does not have the ability to utilize color correction factors that adjust the spectral response of the photometer for more accurate measurements given a variety of light source types. The PMEX specifications are a luminance measurement range of 0.01–99,900 cd/m^2, a spectral accuracy of 7% at 2800 K, and an electrical display accuracy of ± 1% of ± 2 digits of the displayed value. The PMEX specified minimum measurement distance was not defined by the manufacturer.

Note that spectral accuracy is an indicator of the photometer quality, where greater than 6% is poor quality, between 3% and 6% is medium quality, and less than 3% is high quality [13]. The LS-100 and PMEX are filter photometers calibrated to Illuminant A. Significant measurement errors can occur when measuring light sources that differ greatly from Illuminant A. A summary of the specifications for the devices used in this experiment can be seen in the table below.

A Photo Research, Inc. model RS-3 reflectance standard was used to verify the accuracy of the instruments. The RS-3 is a diffuse reflectance standard with reflectivity ranging from 98% to 100% throughout the visible light spectrum. The accuracy was determined by using Equation (1):

$$\rho = L/\pi E \tag{1}$$

where ρ is reflectance, L is luminance, and E is illuminance. This equation was used to calculate the reflectance of the RS-3 reference standard given the luminance measured by the instrument.

B. Light Sources

Three light sources were measured in the experiment: an LED area light, a compact fluorescent light (CFL) with a clear protective lens and with an amber protective lens, and a tungsten-halogen light with an IR filter lens. The CFL and tungsten-halogen lights measured are commonly used on mining machines.

The LED light source was the battery-powered GD-929 15-watt LED work light. The light was made up of a 20-LED array and a reflector. The CFL uses a Marathon Universal Alto 120-volt, 25-watt tubed-type lamp by Phillips Lighting. The tungsten-halogen is a 12-volt, 50-watt MR16 lamp by Eye Lighting International.

The relative spectral power distribution measurements of each light source can be seen in Figs. 3 through 6. The graphs show the variation in spectral content from the Standard Illuminant A to which most photometers are calibrated. Each distribution graph was normalized for clarity.

C. Experimental Layout

The experiment was conducted in MSHA’s light laboratory located in Triadelphia, WV. The three photometers were directed at a diffuse surface target painted black (Sherwin-Williams 1145 Interior Emerald Flat Latex paint 6258 Tricorn Black B1-Black OZ-10) that resulted in

4% reflectivity and closely approximated the reflectance and diffuse properties of coal. The reflectivity of the target was verified with the PR-650. The light sources used in the experiment were directed at the target at the same angle and at a distance to allow for greater than 3.43 cd/m^2 (1 fL) of luminance reflected from the surface, which is the minimum luminance measurement capability of the PR-650. In order to keep the same measurement area for each photometer reading, the photometers were placed at different distances from the target. The PMEX, with the widest field of view at 25°, was placed closest to the target at 0.24 m (9.5 in), giving a measurement area of 0.009 m^2 (13.85 in^2). To keep the measurement area constant through the experiment, the LS-100 and PR-650, which both have a 1° measurement angle, were each placed at 6.10 m (240 in) from the target. A diagram of the general experimental layout is shown in Fig. 7. Note that the instruments were aimed at the exact same target area.

D. Procedures

Each light was mounted on a tripod and positioned to illuminate the target. The light sources were positioned at the same angle to the target, and the direct light from the sources was blocked from the photometers such that the only light visible was that from the reflected surface.

For each of the four lighting scenarios, the light was allowed to warm up for 30 minutes in order to reach steady state. Then the spectral power distribution was measured using the PR-650, as can be seen in Figs. 3 through 6. Next, the luminance of the surface target was measured for each lighting scenario using all three photometers. The summary of those results can be seen in Fig. 8. The luminance readings from the PR-650 were assumed to be the most accurate value of luminance, as it is the only photometer that is spectrally balanced. Therefore, these readings were used as the reference point for the LS-100 and PMEX readings. When not in use the photometers were moved out of the way to avoid interference with each other’s readings.

VI. Results and discussion

The results from the luminance measurements can be seen in Fig. 8. The luminance percent error with respect to the PR-650 is shown in Fig. 9.

The PMEX has a much higher spectral mismatch than the LS-100, so it is not unexpected that for each light source the PMEX had the largest percentage of error with respect to the PR-650. This error ranged from about −17.0% to −26.5%. The largest percentage error occurred for the CFL amber light source. This was anticipated given that the SPD of this light source varies the most from Illuminant A, which the PMEX photometer uses for calibration. The halogen light source had the next highest error of about −21%, and the LED had the lowest error of about −17%. Thus, the general trend is that the percent error increases the more dissimilar the SPD of the measured light source is compared to Illuminant A.

The ramifications are that field measurement of luminance with the PMEX could incorrectly indicate that lighting is not in compliance with the required 0.21 cd/m^2 (0.06 fL) of luminance, and consequently, MSHA could issue a citation for noncompliance. The CFL amber light source, which had the largest percent error of −26.5%, is commonly used on roof bolter machines. Thus, these machines would be susceptible to erroneous low-luminance measurements. Conversely, field measurements with a positive error could falsely indicate compliance when insufficient luminance is present—thus creating a hazardous situation that could contribute to an accident.

There is not a single SPD for white LEDs because there are various types of LEDs that include phosphor-based, hybrid, RGB, and violet-pumped, with each having different spectral content. The correlated color temperatures (CCT) of white LEDs typically range from 2500 K to 7000 K. This is in stark contrast to a single reference spectra Illuminant A that can represent incandescent light sources. To address LEDs, the ClE technical committee TC 1–85 is updating CIE publication 15:2004 (Colorimetry) to include a set of typical white-light LED reference spectra that will be designated as Illuminant L1, L2, etc., for various types of LEDs [14]. Similarly, fluorescent lights also differ in terms of SPD and CCT. For instance, a cool white fluorescent light could have a CCT of 4300 K, while a fluorescent daylight could have a CCT of 6500 K. There are reference spectra for fluorescent lights that include Illuminant F2 for cool white and F7 for daylight fluorescent lights.

One option to account for SPD variations is to use a spectroradiometer for luminance measurements; however, these can be costly and impractical. Using a spectroradiometer in the field could affect its stability, given that the largest influence of spectroradiometer stability is the environment and treatment of the instrument. Specifically, movement and temperature changes need to be kept to a minimum to maintain calibrations. Secondly, it could be costly to purchase multiple spectroradiometers or good quality luminance photometers such as the LS-100. The cost factors for a spectroradiometer and a medium-quality luminance meter with a spectral error < 3% would be about 77 and 7.6 times greater, respectively, as compared to a low-grade photometer with a spectral mismatch of > 6%.

A. Testing the PMEX-MSHA

Since the publication of the conference proceedings version of this paper [15], MSHA helped the manufacturer to design a modified version of the PMEX—the PMEX-MSHA. NIOSH and MSHA conducted additional evaluations of this new photometer to establish its performance relative to existing photometers.

These evaluations followed the same measurement protocol and layout as shown in Fig. 7 with a few exceptions. One exception was the use of an improved surface target for evaluating the photometers. The target was a matte grey circle with approximately 50% diffuse reflectivity, which was verified with an Extech EA33 light meter. This level of reflectivity is similar to that exhibited by rock dust commonly used in underground coal mines. To evaluate any improvements in measurements, an unmodified PMLX was used for comparison because the PMEX originally used was altered for another purpose. The PMLX is equivalent to the PMEX except it displays values in metric units instead of English units. A PR-670 spectroradiometer was used for this test as the luminance referent because it has a better spectral accuracy than the PR-650. Finally, the halogen light used in the evaluation was a General Electric MR16 50-watt bulb. Its SPD is shown in Fig. 10. Unlike the Eye Lighting International halogen light, the GE halogen does not have an IR filter, and as can be seen in Fig. 10, its SPD much more closely resembles Illuminant A.

The results from the luminance measurements can be seen in Fig. 11. The luminance percent error with respect to the PR-670 is shown in Fig. 12. The PMLX possessed the highest percentage of luminance error ranging from about −21% to −34%. The largest percent error was observed with the CFL clear and amber lights, as expected given that the SPDs are the most dissimilar compared to Illuminant A. The second largest error was observed with the LED. The halogen had the lowest error, which appears to be consistent with its SPD matching more closely to Illuminant A.

By comparison, the PMEX-MSHA had less error than the PMLX. The luminance error ranged from about −16% to −19%—much smaller than the range of the PMLX and less than that of the PMEX, which was −17% to −26.5%. The largest error occurred with the CFL lighting conditions. The LED and halogen lights had similarly low errors of −16.0% and −16.4%, respectively.

B. Limitations

The measurements in this study were conducted in a controlled laboratory environment that minimized the effects from confounding variables that might not be controllable or identifiable in the field. The laboratory measurements were, therefore, of a narrow scope, targeting error sources due to the different SPDs of commonly used underground mine light sources. Further field measurements are needed to investigate the additional effects from other factors that have a major effect on luminance measurement, including surface wetness, the orientation of the meter and distance to the measurement surface, and the surface texture [10].

The results of this research are limited to only four light sources commonly used on underground coal mining machines. The research did not investigate multiple types of fluorescent, halogen, and white LED light sources that could also be used on a mining machine. A unique spectral mismatch correction factor would need to be determined for each type of light. It is technically feasible to generate spectral mismatch correction factors for every type of light used on a mining machine; however, the practicality for field measurements is uncertain. The practicality becomes even more uncertain because multiple types of light sources could be used on a single mining machine, so spectral mismatch correction factors would be needed for every combination of lighting type. A simple example indicates the practicality for every lighting combination: Assume there are an incandescent light, warm-white and cool-white fluorescent lights, an LED light, and a halogen light. These five types of light sources result in 128 combinations, each with a unique spectral mismatch correction factor, assuming differences are significant among the combinations. Therefore, the research presented in this paper did not address luminance measurement errors given the various combinations of dissimilar light source types.

Next, the measurements were taken with multiple photometers. Representative samples of each photometer would be needed to determine measurement differences among photometers of a given make and model. Thus, the percentage errors will likely vary from unit to unit.

Lastly, all of the luminance meters were calibrated for the photopic condition which is a standard practice and required by the lighting regulations. However, the mine lighting conditions are mesopic and additional measurement error will occur because mesopic luminance is not being measured.

VII. Concluding Remarks

This research serves to advance the practice of mine lighting measurements by investigating and quantifying the effect that the light source spectral power distribution has on luminance measurements from different photometers.

The data presented in this study indicate that the spectral power distribution of the light source is a significant source of error when measuring luminance. Specifically, the PMEX luminance error ranged from −17.0% to −26.5% for the various light sources. Based on the limited data collected, it appears that it is impractical to use a handheld PMEX photometer to make accurate luminance measurements of a coal surface when the light source SPD differs from that of Illuminant A. This is not unique to the PMEX and would apply to other photometers calibrated to Illuminant A and used for luminance measurements. The luminance error will be the greatest for low-quality photometers that have a higher spectral mismatch. For instance, the LS-100 has a lower spectral mismatch so the luminance error in this study ranged a significantly smaller amount—from 4.0% to −10.0% (Fig. 9).

A. PMEX-MSHA Remarks

The PMEX luminance errors had a range of about 10% between the different light sources measured in the original study, and the PMLX about 13%, while the modified PMEX-MSHA measurement errors only ranged 3%. This is a significant improvement to the variations caused by the spectral mismatch error of measuring different light sources with the same photometer. Given a variation of 3%, even though the PMEX-MSHA under predicted the correct value of luminance, a spectral mismatch correction factor could be used to adjust the reading to within a consistent and acceptable range of tolerance.

While the PMEX-MSHA performed better than the unmodified variants available from Quantum Instruments, the meter still possessed a luminance error from −16% to −19% compared to the PR-670 among lighting conditions. This is a point of concern when addressing compliance to minimum luminance requirements specified in the regulation. If the luminance value was at the required minimum level, yet the photometer registered a value at 16% below that threshold, then a citation could be issued for noncompliance when the true measurement was actually compliant with the regulation. Furthermore, while the issue of spectral mismatch is satisfactorily addressed, the many variables from field measurements of luminance are still present [10], and surface variables are still an important consideration that call into question the use of luminance as a metric for enforcing compliance with lighting regulations, regardless of the spectral improvements to the modified PMEX-MSHA.

VIII. Acknowledgements

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This paragraph of the first footnote will contain the date on which you submitted your paper for review. It will also contain support information, including sponsor and financial support acknowledgment. For example, “This work was supported in part by the U.S. Department of Commerce under Grant BS123456.”

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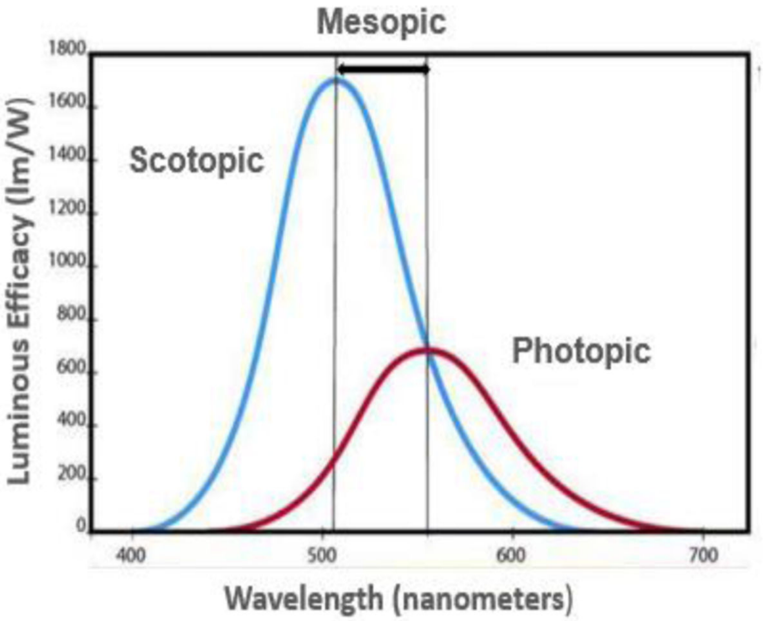

Fig. 1.

Spectral response curves of the human eye for photopic, mesopic, and scotopic conditions.

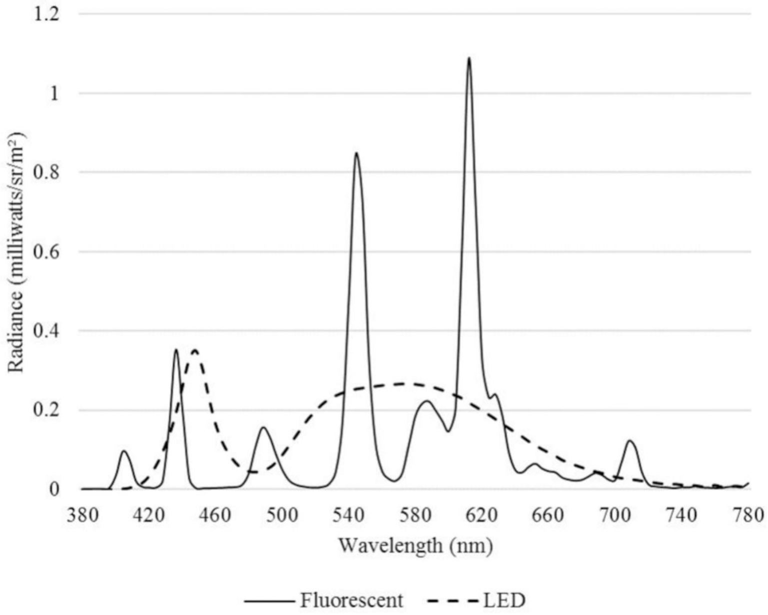

Fig. 2.

Spectral power distributions of typical fluorescent and LED cool-white light sources.

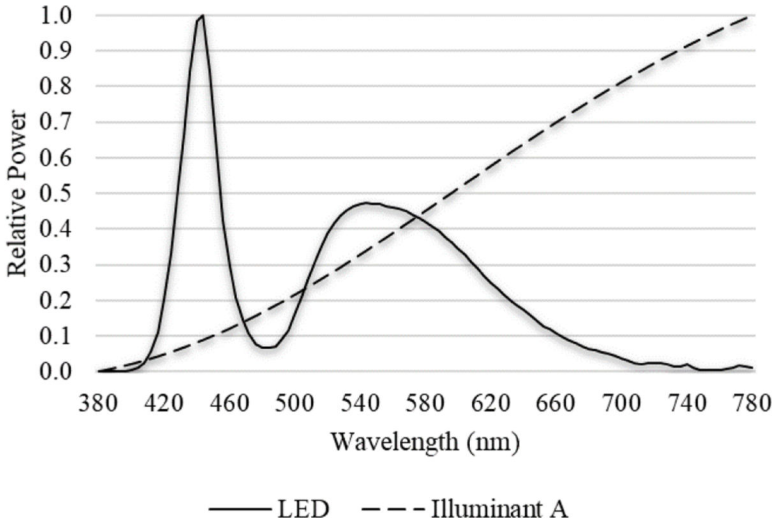

Fig. 3.

Relative spectral power distribution of the GD-929 LED light compared to Illuminant A.

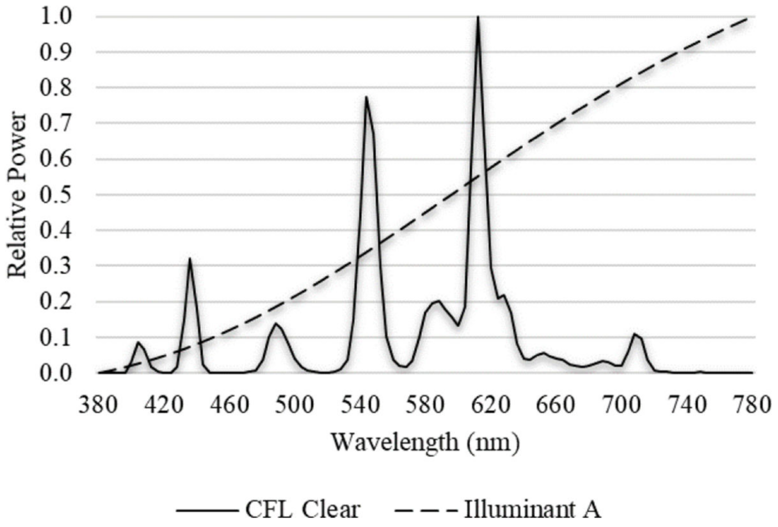

Fig. 4.

Relative spectral power distribution of the CFL light with the clear globe compared to Illuminant A.

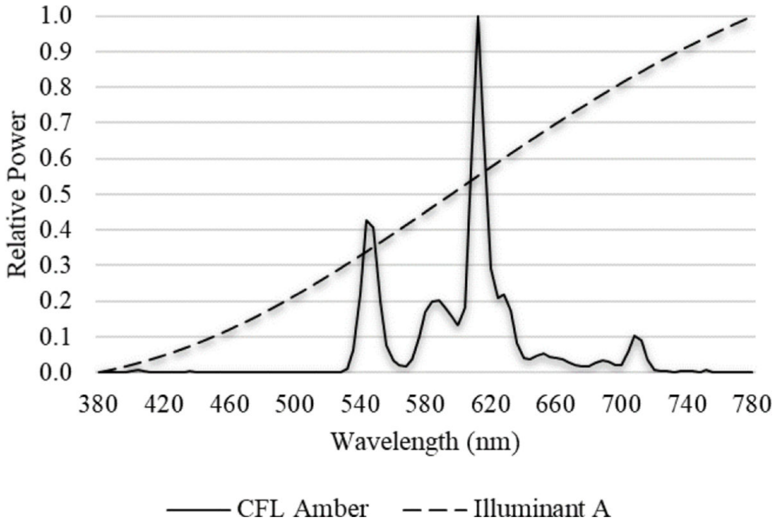

Fig. 5.

Relative spectral power distribution of the CFL light with the amber globe compared to Illuminant A.

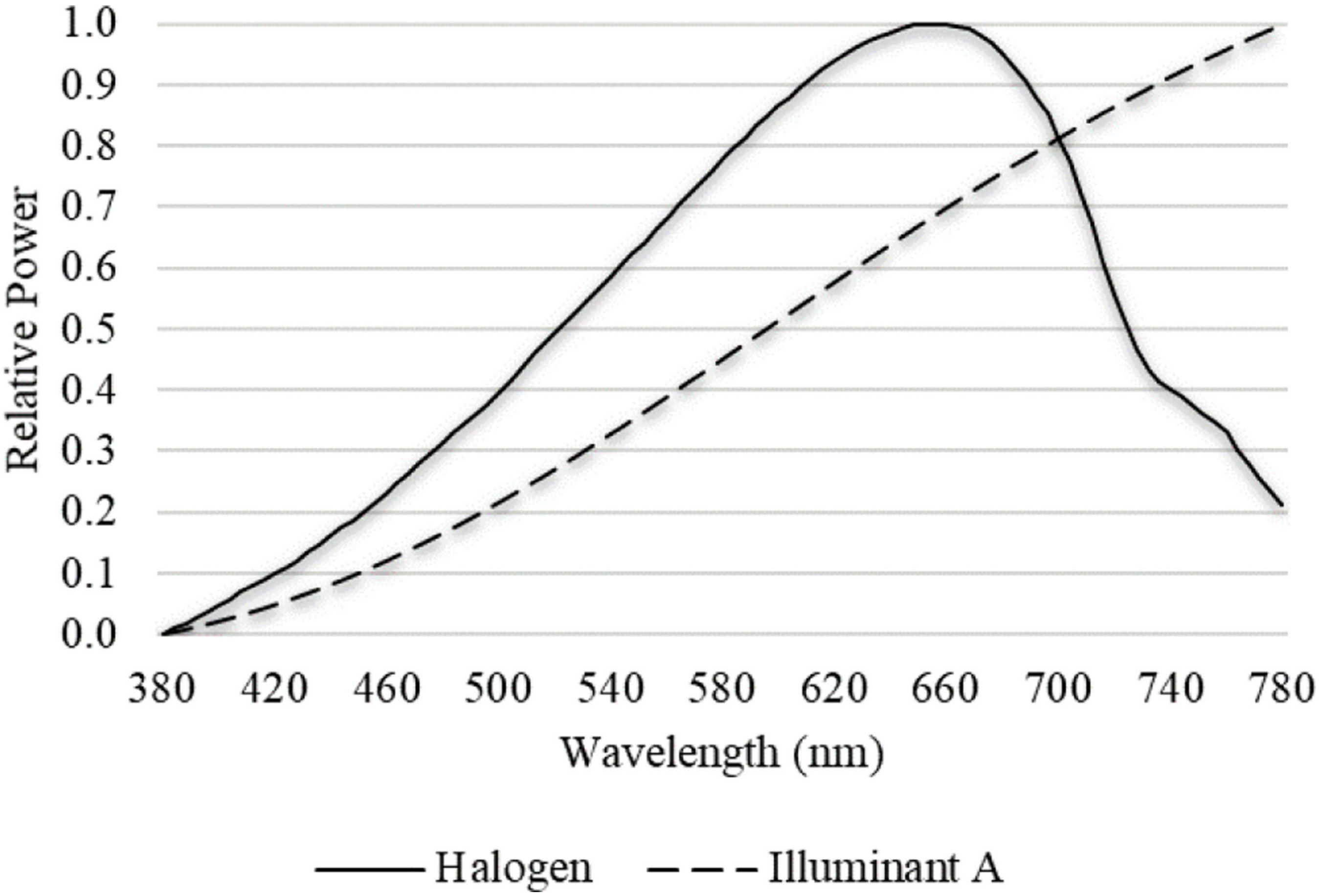

Fig. 6.

Relative spectral power distribution of the tungsten halogen light with IR filter compared to Illuminant A.

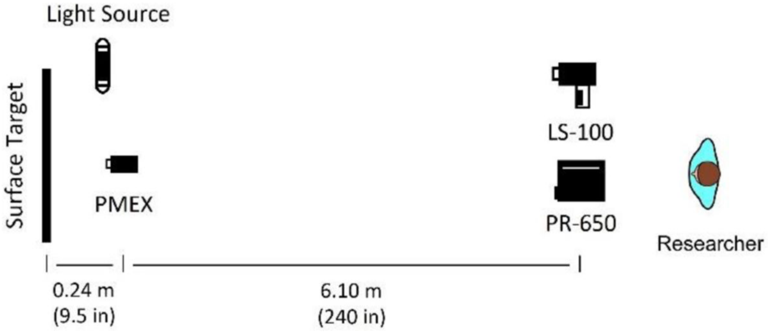

Fig. 7.

Layout at MSHA's light laboratory (not to scale).

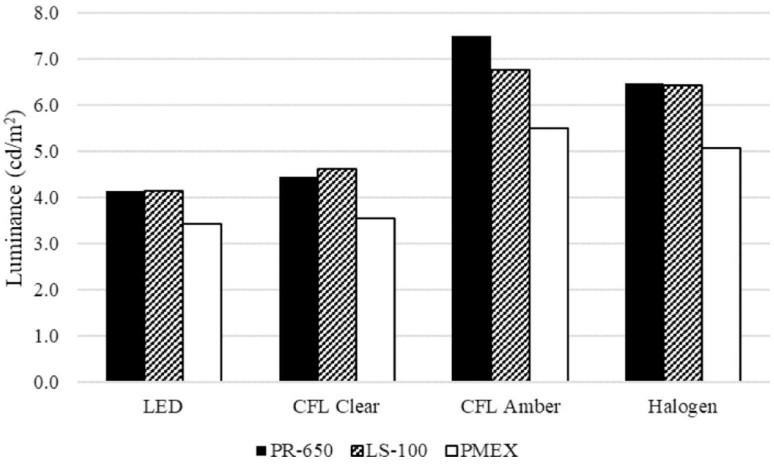

Fig. 8.

Luminance measurements for each light source and photometer.

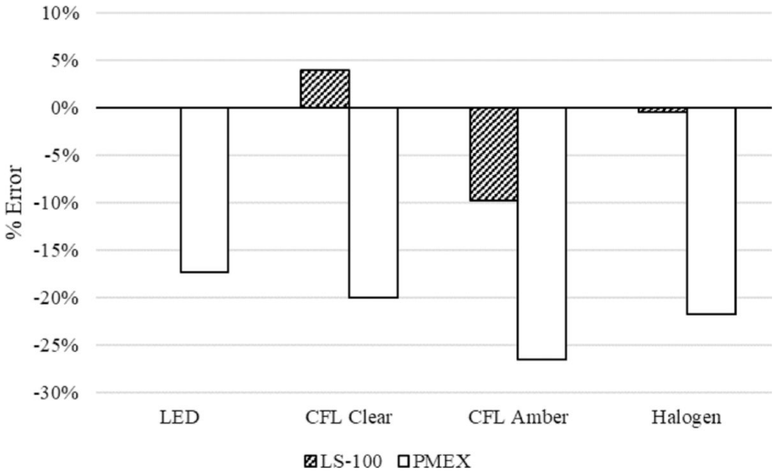

Fig. 9.

Luminance percent error deviation from the PR-650 measurement. Note that the percent error for the LS-100 LED reading is nearly zero and is not omitted.

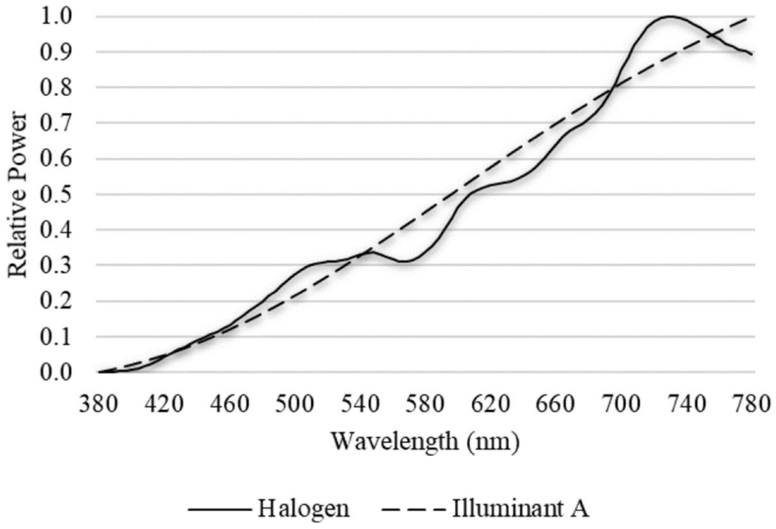

Fig. 10.

Relative spectral power distribution of the new tungsten halogen light (GE) compared to Illuminant A.

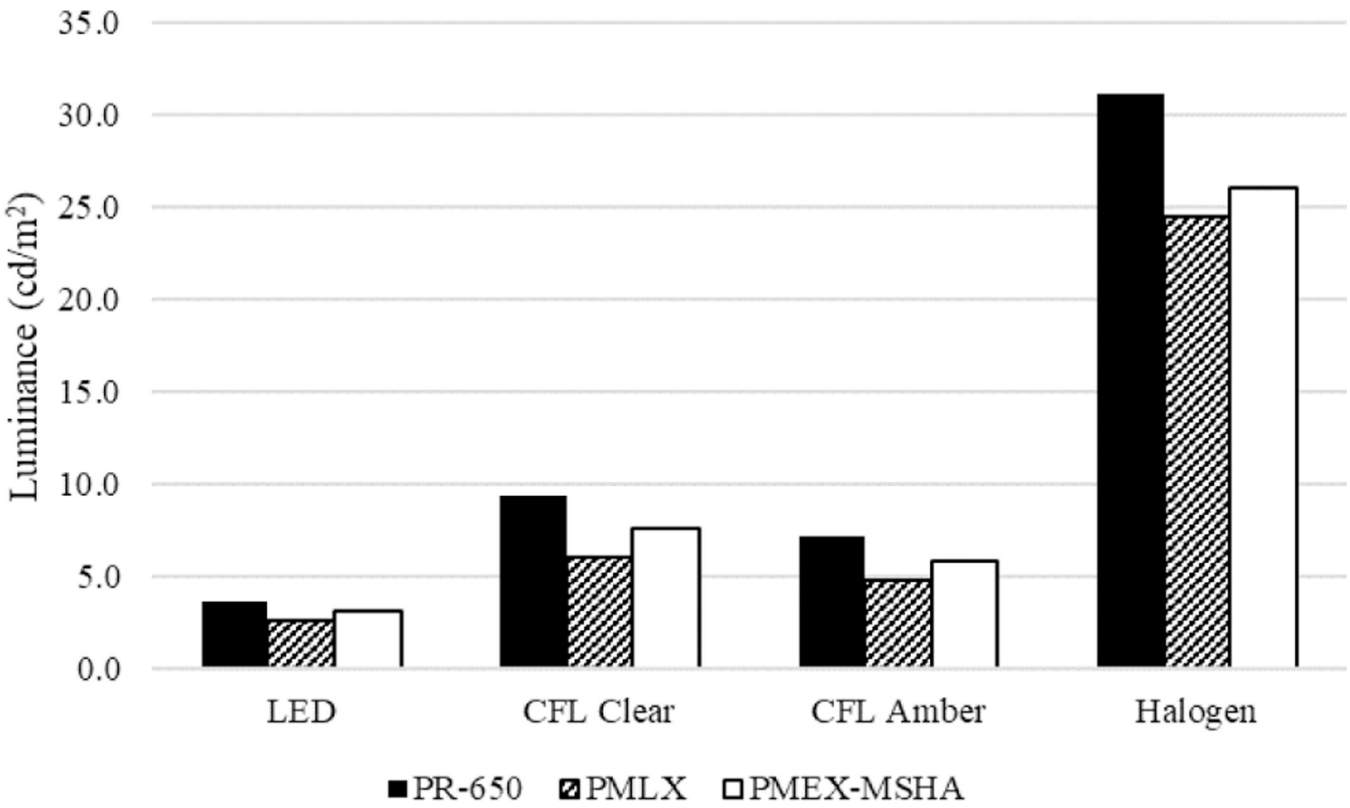

Fig. 11.

Luminance readings from each of the light sources and photometers used in the PMEX-MSHA evaluation.

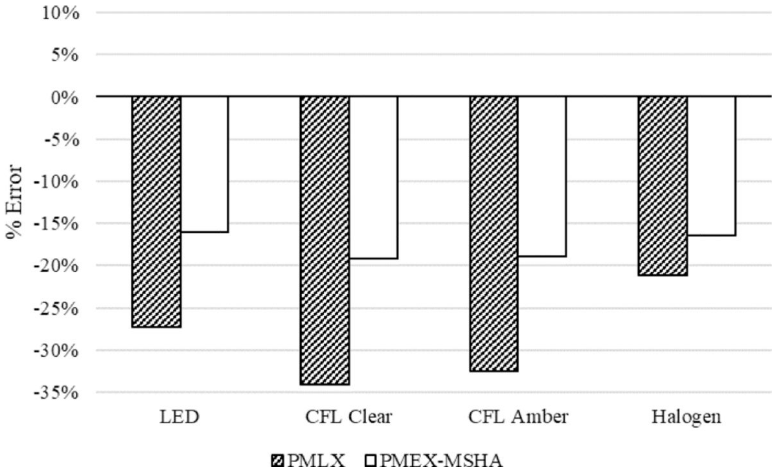

Fig. 12.

Luminance percent error deviation from the PR-670 measurement.

Table I.

Summary of specifications for the luminance measurement instruments used in this study.

	PR-650	**LS-100**	**PMEX**
Spectral Accuracy	± 2 nm	± 2%	± 7%
Luminance Range (cd/m^2)	3.4 – 17,000	0.001 – 299,900	0.01 – 99,900
Cost (USD)	$38.5 k	$3.8k	$0.5k

Table II.

Lighting parameters that include dominant wavelength (nm), correlated-color temperature (CCT) and the scotopic/photopic ratio (S/P).

Light	Dominant Wavelength (nm)	CCT (K)	CRI R_a	S/P
LED	481	7059	68	0.801
CFL (Clear)	582	2800	82	0.453
CFL	587	1937	72	0.247
(Amber) Tungsten-halogen	582	3054	97	1.470

Table III.

Summary of specifications for the luminance measurement instruments used in the PMEX-MSHA study.

	PR-670	**PMLX**	**PMEX-MSHA**
Spectral Accuracy	± 1 nm	± 7%	± 7%
Luminance Range (cd/m^2)	0.2 – 17,190	0.01 – 99,900	0.0 – 34.2
Cost (USD)	$25k	$0.5	TBD

Table IV.

Lighting parameters for PMEX-MSHA evaluation lights that include dominant wavelength (nm), color-correlated temperature (CCT), and the scotopic/photopic ratio (S/P).

Light	**Dominant Wavelength (nm)**	**CCT (K)**	**S/P**
LED	481	7059	0.801
CFL (Clear)	582	2800	0.453
CFL (Amber)	587	1937	0.247
Tungsten-halogen (GE)	730	3060	1.599