Visual Performance for Incandescent and Solid-State Cap Lamps in an Underground Mining Environment

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***Abstract*—Miners depend most heavily on visual cues to recognize underground mining hazards; consequently, illumination plays a critical role in miners' safety. Some hazards are located in the miners' peripheral field of view (10° to about 60° off axis) or on axis (0°). The objective of this research was to determine if there were visual performance improvements when using solid-state cap lamps with light-emitting diodes (LEDs) as compared to incandescent light bulbs commonly used in miner cap lamps. Recent research has indicated that an increased short-wavelength content of the spectral power distribution of LEDs relative to incandescent lamps improves peripheral visual performance for low-light (mesopic) conditions. The visual performances of nine subjects were quantified by measuring the subjects' speed and accuracy in detecting floor objects located on axis and at ±20° off axis. The objects were located near field (1.83 m) and far field (3.66 m). Upon presentation of the objects, the subjects would count and point to each object using a red-laser pointer. The object detection response time and number of missed objects were recorded. The results of the visual performance comparison for an LED, a prototype LED, and an incandescent cap lamp are presented. There were no missed objects when the subjects used the LED-based cap lamps, but there were three missed-object occurrences when the subjects used the incandescent cap lamp. The mean detection time when using the incandescent cap lamp was 55.3% greater than that of the prototype LED cap lamp and 43.5% greater than that of the LED cap lamp. It can be inferred from these data that the spectral distribution of LED-based cap lamps could enable significant visual performance improvements as compared to incandescent cap lamps.**

***Index Terms*—Cap lamps, mine illumination, mine safety, slip and fall hazards, visual performance.**

I. INTRODUCTION

AN UNDERGROUND mine is the most difficult environment to illuminate according to the Illuminating Engineering Society of North America (IESNA) [1]. It is a dynamic environment that includes dust, confined spaces, low reflective surfaces, and low visual contrasts. Lighting is critical to miners since they depend heavily on visual cues to spot fall of ground, pinning and striking hazards, and slipping and tripping hazards [2]; consequently, illumination greatly affects miners' ability to perform their jobs safely. Typically, a miner's cap lamp is the primary and most important source of light [3].

It can be reasoned that the quality of underground mine illumination is problematic based on Mine Safety and Health Administration (MSHA) accident data, an aging workforce, and recent assessments of mine illumination. First, MSHA injury data for 2000–2004 indicate that there are a high number of accidents involving falls of ground, slips and falls, and powered haulage. These accident categories rank within the top-four highest rates of lost-workday injuries. Slips and trips have the second highest rate of 1.14 injuries per 100 full-time equivalent workers. Lighting, particularly from a cap lamp, plays a critical role for miners as they visually inspect the mine roof, ribs, back, and floor for hazards. Cap lamp lighting is critical for inspecting the mine floor for slip, trip, and fall hazards. Objects associated with these hazards are typically of very low contrast and reflectivity. Second, there are age-related factors that require a better quality of light. Diminished night vision is one of the most common problems experienced by older people because there are changes in the eye that include decreased pupil size, cloudier lens, and fewer rod photoreceptors that are very sensitive to light [4]. The average age of a U.S. miner is about 43 years. Lastly, researchers from Canada [3], Australia [5], India [6], and South Africa [7], [8] have conducted assessments of mine illumination and identified the need to improve the quality of illumination to improve safety.

Prior lighting research approaches have focused on increasing illumination to improve safety. Mine accident rates decreased about 60% when overall illumination was increased from 20 to 250 lx, where 20 lx served as the statistical base [9]. Canadian researchers noted dramatic increases in the ability of miners to see loose rock as the cap lamp illuminance increased [3]. The Canadian study, prompted by Stevenson's Commission inquiry of the high incidence of fatalities at Ontario mines, resulted in new legislation that caused a redesign of cap lamps. However, the downside of increasing illuminance is that it can increase glare if the illuminance at the eye of other people increases. The level of illuminance is a dominant factor in glare produced by an oncoming headlamp [10]. Also, increasing the illuminance increases cap lamp battery loading, thus requiring larger battery capacities.

National Institute for Occupational Safety and Health (NIOSH) research investigates a different approach that does not increase illuminance to improve visual performance. Our research objective was to determine if visual performance, with respect to slip/trip/fall hazard detection, could be improved by using a light-emitting diode (LED) lamp with a visible spectrum containing more of the short wavelengths. At daytime and~

interior light levels, the cone photoreceptors of the eye dominate vision, but as light levels decrease, the rod receptors of the eye that have greater short-wavelength spectral sensitivity than cones play an increasing role in vision. Cool white LEDs emit a "whiter" light with a greater proportion of short-wavelength energy in comparison to the yellowish light of incandescent lighting commonly used for miner cap lamps. Lighting research indicates that, at low-light (mesopic) conditions where rods and cones both contribute to vision, the spectral content can improve peripheral visual performance [11]. LEDs with a visible spectrum containing more of the short wavelengths can enable considerable improvement in peripheral visual performance at mesopic conditions for automotive applications [12]. However, research indicates that, for perturbed environments (i.e., dust, snow, and fog), there is not a statistically significant difference in visual performance when the light is white rather than yellowish [13].

The use of white LED technology for cap lamps has many other advantages such as requiring about half the battery power, having more than 25 times operating life, providing relatively constant light color despite decreasing battery power, and providing outstanding resistance to shock- or vibration-induced failures because there is not a filament that can break [14]. Currently, incandescent bulbs are commonly used for cap lamps. This lighting is characterized by a yellowish light that becomes more yellow as the luminaire ages and as the source voltage decreases, as in the case of a battery-powered cap lamp. The positive aspects of LED technology are outside the scope of this paper, although they are likely to have numerous safety benefits.

It is important to note that there is a wide range of "white" available for LEDs. Warm-white LEDs are similar to incandescent lamps where the correlated color temperature (CCT) is 2700 K or 3000 K. Cool-white LEDs have a CCT higher than 3500 K.

A. *Terminology*

Luminous flux—The time flow rate of light energy similar in concept to horsepower or British thermal unit per hour. The lumen is the unit of luminous flux used by IESNA and the International System of Units (SI) [15].

Illuminance—The measure of the density of luminous flux striking a surface. The IESNA and SI units are footcandle and lux [15], where $1 \text{ lx} = 1 \text{ lm/m}^2$ and $1 \text{ fc} = 1 \text{ lm/ft}^2$.

Luminous intensity—The term describes how a light source distributes the total luminous flux, or lumens, it emits into various portions of the space surrounding the light source. The IESNA and SI unit is the candela [15].

Luminance—In physical terms, luminance is a concept used to quantify the density of luminous flux emitted by an *area* of a light source in a particular direction toward a light receiver such as a human eye [15]. Luminance is closely correlated with a person's perception of brightness. The IESNA and SI unit is candela per square meter.

Luminance contrast—The relationship between luminance of an object and its immediate background [1].

Spectral power distribution (SPD)—The radiant power emitted at each wavelength in the visible region of light (360–770 nm).

II. METHODS

A. *Experimental Design*

A within-subjects design was employed in this study. Presentation of cap lamps was randomly assigned to subjects, and a restricted randomization was used for stimulus order presentation within cap lamps.

The independent variables were as follows:

1) three light sources: an LED cap lamp, an incandescent cap lamp, and a prototype LED cap lamp;
2) four object locations: near field, far field, and two combinations of near field and far field.

The dependent variables quantifying visual performance were as follows:

1) response time to detect objects;
2) number of objects missed (not detected).

B. *Subjects*

NIOSH personnel from the Pittsburgh Research Laboratory (PRL) were the subjects. Miners were not used because of potential expectancy biases that could confound empirical data. Expectancy biases are particularly challenging for lighting research because the variable of study (visible light) is usually observable to the subjects. Miners could easily detect that the light from the LED-based cap lamps is very different from the camp lamp light that they use on a daily basis.

NIOSH subjects that passed vision tests for distance visual acuity, contrast sensitivity, color vision deficiency, and peripheral vision were accepted for the study. Eight male and one female subjects participated. The average age was 47 years, which is comparable to the average U.S. coal miner age of 43 years.

The protocol for this study was approved by the NIOSH Human Subjects Review Board. The subjects signed an informed consent form and were instructed about their right to withdraw freely from the research at any time without penalty.

C. *Experimental Layout and Apparatus*

MIL: The testing was conducted at the Mine Illumination Laboratory (MIL) of NIOSH. The MIL is a simulated underground coal mine environment that is equipped with various test equipment, data acquisition and control systems, and networked computers. The interior is 4.88 m wide by 2.13 m high and is coated with a rough-textured material that has color and reflectivity similar to that of a coal mine. The experimental layout is shown in Fig. 1. Two location categories were established: near field (1.83 m) which is about the distance of two strides for the average male and far field which is at a distance that the floor receives most of the cap lamp light due to the cap lamp mounting angle on the miner's helmet. Near- and far-field object locations were selected based on the risk that they pose to a miner, and they were chosen given the physiology of the

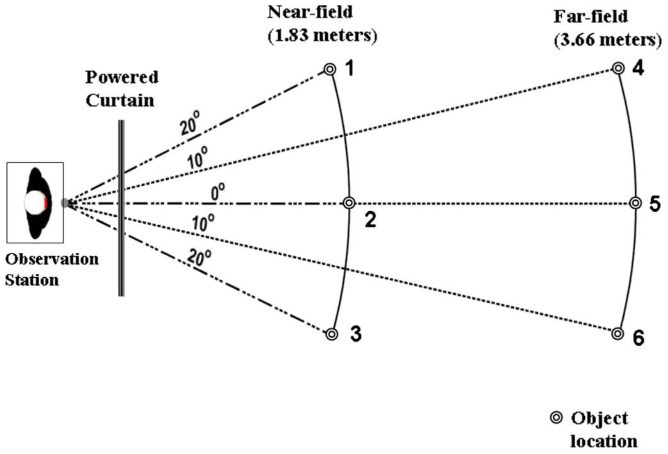

Fig. 1. Experimental layout.

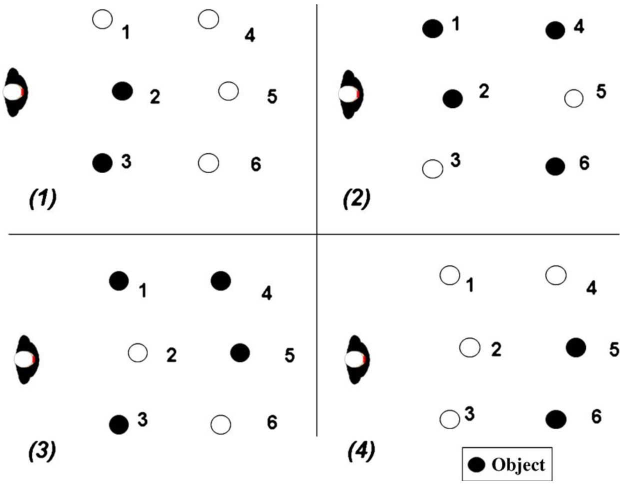

Fig. 2. Four object location patterns.

eye. The on-axis location was selected because it poses the greatest risk for a trip/slip/fall given that it is directly in the path of a walking person. Second, the on-axis location assumes that foveal vision is employed to produce a person's visual perception. When a person's eyes are directed to an image on axis, the image is projected onto the foveal area of the retina. This area is filled with cone photoreceptors that play a critical role for color. The rod photoreceptors are well suited for very dark lighting conditions but do not detect color or fine detail. The highest density of rods is between 10° and 30°; the peak density is at 20°.

Four object location patterns were presented to each subject as shown in Fig. 2. The presentation order was counterbalanced.

Observation Station: The observation station (Fig. 3) was designed to allow all human subjects to be tested at the same eye height with reference to the floor. The eye height of 165.1 cm is based on the 50th-percentile male standing [16]. The station was required to allow test subjects ranging from the 5th-percentile female to the 95th-percentile male to be adjusted to the 165.1-cm eye height when in the seated position. Torso heights for the specified test subjects have a range of 68.6–84.8 cm. The seat was designed to rise 20.3 cm from the lowest position to the highest to accommodate all test subjects. The observation station uses an electric actuator for adjusting the seat height. The height of the miner's helmet with cap lamp and ear protection is independently adjustable from the seat height to accommodate the different torso heights of the subjects. The helmet height is manually adjustable (up to 25.4 cm) with hand-operated clamps. The helmet adjusts fore and aft manually up to 15.2 cm. The seat is adjustable fore and aft and has foldable arm rests. A swivel was incorporated in the station to allow the seat to rotate 180° to conduct two different tests in the MIL without moving the station. There is a fixed foot rest at each end of the platform. Three tabs are located on the helmet post to mount cap lamps for easy changes during the tests. The platform is constructed of wood and steel and outlined with yellow reflective tape to minimize tripping when the human subjects are preparing to be tested. All of the components are a flat-black color to help eliminate any reflections or distractions during testing.

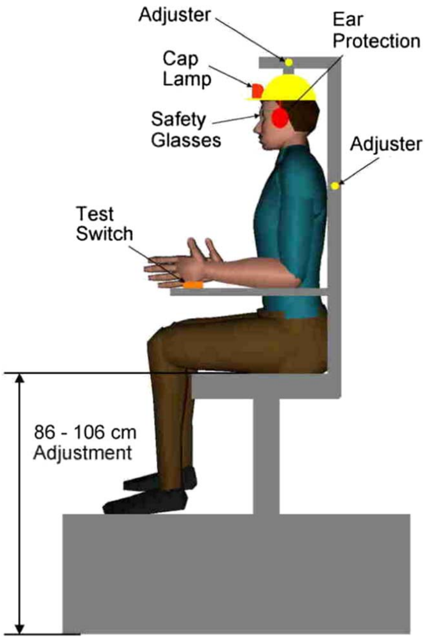

Fig. 3. Observation station.

TABLE I
CAP LAMP ELECTRICAL DATA

Cap Lamp	Battery supply voltage (Vdc)	Current (amps)	Power (watts)
Incandescent	6.1	0.63	3.84
LED	6.1	0.42	2.56
Prototype LED	12.0	0.113	1.56

Cap Lamps: Three cap lamps were used. The electrical data for each cap lamp are listed in Table I. The first was an MSHA-approved cap lamp using a single incandescent bulb as the primary light source. This served as the reference. The second was an MSHA-approved cap lamp with a single phosphor-white LED as the primary light source. The third cap lamp was a laboratory prototype that was jointly developed by NIOSH and the Lighting Research Center of Rensselaer Polytechnic Institute. This prototype uses two phosphor-white LEDs as the primary light source. The prototype LED cap lamp meets the

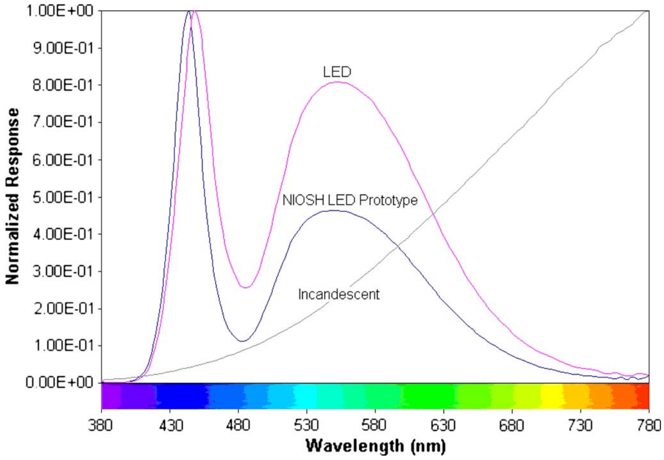

Fig. 4. SPDs for each cap lamp.

photometric requirements specified by MSHA [17]. The cap lamp housing and internal components were selected to have a very high reflectance to mitigate discomfort glare.

Each cap lamp was characterized with respect to its SPD. Fig. 4 shows the SPDs for each cap lamp. It is evident that the LED and prototype LED cap lamps have a greater proportion of short-wavelength light than the incandescent cap lamp. Both cap lamps use a phosphor-white type of LED. Basically, this type is a blue LED with phosphor deposited on top of the die. The phosphor passes a portion of the blue light that mixes with the yellowish green emission of the phosphor; thus, the combination appears white to the eye.

Objects: The objects were made from sections of polyvinyl chloride electrical conduit. Each object was 6.4 cm long with an outer diameter of 3.3 cm and an inner diameter of 2.2 cm. The objects were painted a dark color such that they would have a very low contrast and a reflectivity very similar to an object (mine cable, pipe, or tool) that was coated with the material on the mine floor. This choice also enabled us to easily have a consistent set of test objects with respect to size, shape, contrast, reflectance, and shadow rendering.

The luminance contrast of the objects ranged from -0.11 to 0.09 with respect to the floor. The negative contrast indicates that the object luminance was less than the floor luminance.

Illuminance Distributions: The illuminance levels were measured at each object location (Fig. 1) for each cap lamp. Illuminance is an important factor for visual performance because, in general, visual performance increases as illuminance increases. In this study, it was important that the illuminance distributions be comparable; otherwise, major illuminance differences would be a confounding factor. The initial illuminance distributions had significant variation. For instance, the illuminance at object location 6 was 42% greater with the prototype LED cap lamp than the incandescent cap lamp. Therefore, a diffusion filter was placed over the lens of each cap lamp. This filter was successfully used to realize a more uniform illuminance distribution among the three cap lamps. Table II lists the vertical illuminance distributions for all object locations and cap lamps with diffusion filters. The illuminance measurements were taken perpendicular to the line of view of the subjects.

TABLE II
CAP LAMP ILLUMINANCE AT THE OBJECT LOCATIONS

Object location	Incandescent (lux)	LED (lux)	Prototype LED (lux)
1 (near field)	1.29	1.19	1.14
2 (near field)	1.41	1.27	1.31
3 (near field)	1.15	1.27	1.08
4 (near field)	1.30	1.78	1.19
5 (near field)	1.60	1.82	1.55
6 (near field)	0.92	0.88	1.05
Average (near field)	1.28	1.17	1.17
Average (far field)	1.27	1.49	1.26
Average (all)	1.28	1.34	1.55

D. *Procedure*

The subjects were seated on the observation station, and adjustments were made such that each person had the same eye height of 165.1 cm from the floor. While seated, the subjects wore a hard hat and eye protection. The subjects were given ample time (about 15 min) to adjust to the darkened environment.

A practice (warm-up) session was initially conducted to help subjects learn how to conduct the tests and to become familiar and comfortable with the test apparatus. The procedure was to close a black electrically powered curtain located 0.91 m in front of the subject. When the subject was ready, the curtain was opened, and the PC-based data acquisition started recording time. The subject identified the objects by counting each out loud while pointing to it with a red-laser pointer that was fitted with an image filter that resulted in the image of a hand to appear on the object. This image was about 5.1 cm high and made it easier for the subject to "hit" the object. Two researchers determined that an object was detected once they saw the red-laser-pointer light on the target. The curtain was closed, and the time was recorded when the subject detected the last object.

III. RESULTS

The visual performance results were objectively measured in terms of missed objects and detection time. Twelve data points were collected for each of the nine subjects.

A. *Missed Objects*

Subjects were allotted 15 s to detect the objects. Those objects not found within 15 s were classified as missed. Fig. 5 shows the number of missed objects for all cap lamps and all object locations. There were no occurrences of missed objects for the LED or prototype LED cap lamp. There were three occurrences of missed objects for the incandescent cap lamp. Each miss occurred for object location 2 located at 0° in the near field.

B. *Object Detection Time*

An analysis of variance (ANOVA) was used to evaluate whether there were significant differences for the independent variables. Table III summarizes the ANOVA results that include degrees of freedom (df), sums of squares (SS), mean square (MS), F-ratio (F value), and statistical significance (p).

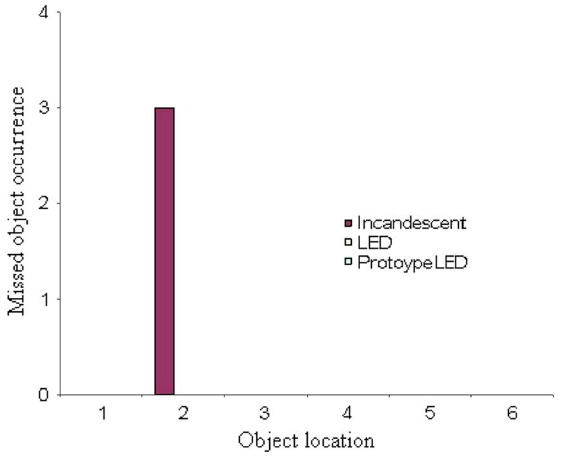

Fig. 5. Missed-object location occurrences. No object misses occurred when subjects used the LED or prototype LED cap lamp.

TABLE III
ANOVA SUMMARY

Source	SS	df	MS	F	*p*
Subject	$3.05x10^{8}$	8	$3.814x10^{7}$		
Cap lamp	$1.128x10^{8}$	2	$5.640x10^{7}$	5.04	0.0201*
Subject x cap lamp	$1.79x10^{8}$	16	$1.119x10^{7}$		
Object pattern	$1.85x10^{8}$	3	$6.168x10^{7}$	6.82	0.0004*
Cap lamp x Object pattern	$9.134x10^{7}$	6	$1.523\ x10^{7}$	1.68	0.1378
Subject x Cap lamp x Object pattern	$6.33x10^{8}$	70	9049254		

*p<0.05

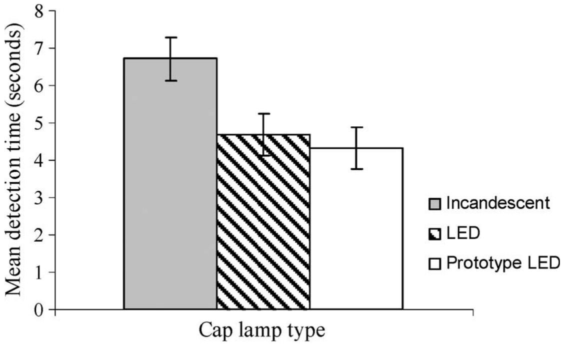

Fig. 6. Bonferroni *post hoc* results for the mean detection time for each cap lamp.

Two main effects were considered significant ($p < 0.05$): the cap lamps and the object patterns. A Bonferroni *post hoc* analysis was conducted at $\alpha = 0.05$ level for the significant main effects. Fig. 6 shows the Bonferroni *post hoc* results for the cap lamps, and Fig. 7 shows the results for the object patterns. The y-error bars above and below the means indicate the standard error.

The mean detection time of 6.7 s was the longest when subjects used the incandescent cap lamp. This time was 55.3% greater than that when subjects used the prototype LED cap lamp. This difference was statistically significant; however, no significant differences existed in a pairwise comparison between the LED and prototype LED cap lamps. There was a difference between the incandescent and LED cap lamps; however, it did not approach statistical significance ($p < 0.05$).

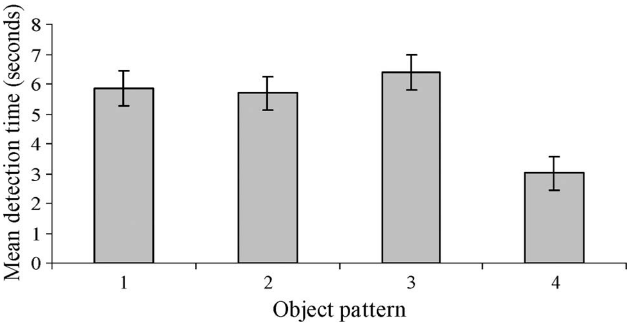

Fig. 7. Bonferroni *post hoc* results for the mean detection time for each object location pattern.

A significant difference existed among object patterns. The mean detection time was 6.4 s for object pattern 1. This time was 113.3% slower than the mean detection time for object pattern 4, which consisted of two objects in the far field. The means for object patterns 1, 2, and 3 were found not to be statistically different.

No significant ($p < 0.05$) interaction existed between the cap lamp and object pattern factors.

IV. DISCUSSION

Our research objective was to determine if LED technology could be used to improve visual performance with respect to slip/trip/fall hazard detection. The missed object and detection time data seem to support that the higher content of shorter wavelengths as found with cool white LEDs could offer significant visual performance improvements.

In terms of missed objects, the LED-based cap lamps had no missed-object occurrences; however, the incandescent cap lamp had three occurrences, all of which were object location 2 (on axis). It is particularly significant given that these misses occurred in the near field. The distance between the subject and the near-field object was only about two to three walking strides away; thus, this object location poses the highest safety risk of all locations. It is noted that the on-axis object location is particularly challenging given foveal vision limitations in low light. The object illuminance does not seem to be a factor because the illuminance from the LED cap lamp was 11% less and the prototype LED cap lamp illuminance was 8% less than the illuminance from the incandescent cap lamp. The other on-axis location was in the far field at object location 5. No objects at this location were missed for the incandescent cap lamp. This far-field location is a more common visual attention location for a walking person, and this could be one reason why objects at this location were not missed; however, it is noted that the incandescent cap lamp illuminance was 14% higher at this location.

The object detection time data also support that LED technology is likely to enable significant improvements in visual performance. The mean detection time when using the incandescent cap lamp was 55.3% greater than that of the prototype LED cap lamp and 43.5% greater than that of the LED cap lamp. The prototype LED cap lamp's mean detection time was faster than that of the LED cap lamp, but these differences did not have statistical significance given the data from nine subjects. The LED cap lamp SPD (Fig. 4) had proportionately more longer wavelengths, resulting in a "warm white" light compared to that of the prototype LED which is a "cool white" light with proportionately more shorter wavelengths. A larger and more detailed study is needed to explore visual performance with regard to warm white and cool white LEDs.

The visual performance testing was conducted in terms of on-axis and peripheral visual tasks for objects located in the near field and far field. The visual task consisted of multiple components that included visual search of the forward field of view, near-field detection, far-field detection, and the combined near- and far-field detection. Therefore, the visual performance was an aggregate of all visual task components. A more detailed study is needed to determine the on-axis and peripheral visual performances separately.

It is important to note that all cap lamps were powered by laboratory-grade power supplies so that the cap lamp power remained constant. The power levels were set to that of a fully charged battery; this is a best case scenario. The SPD of the incandescent cap lamp would significantly shift to longer wavelengths (reds and yellows) as the battery power decreased during the mine shift, while the SPDs of the LED-based cap lamps would be largely unchanged; hence, we would anticipate a greater decline in visual performance for the incandescent cap lamp in comparison to the LED cap lamps.

The results of the visual performance comparisons between LED and incandescent cap lamps provide important data for improving the design of future cap lamps and should positively affect the safety of employees in the underground mining industry. It is apparent that LED technology has the potential to improve safety by improving visual performance with respect to detecting slip, trip, and fall hazards.

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Mention of any company or product does not constitute endorsement by NIOSH. The findings and conclusions in this report are those of the authors and do not necessarily represent the views of NIOSH.

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