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Do light-emitting diode cap lamps enable improvements in miner safety?

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Introduction

An underground mine is a dynamic environment that consists of confined spaces, low reflectivity surfaces, low visual contrast and numerous glare sources. These factors ultimately pose significant impediments to a miner's ability to perform his or her job safely. Typically, a miner's cap lamp is the primary and most important source of light for detecting hazards posed in the form of falls of ground, machinery-related pinning and striking incidents, and slipping and tripping hazards. Accordingly, illumination plays a critical role in an underground miner's safety because miners depend, most heavily, on visual cues to detect these potential hazards (Cornelius et al., 1998). It can often prove difficult for miners to detect such hazards because objects associated with slip, trip and fall hazards are typically of very low contrast and reflectivity, and extremely noisy mining environments can mask audible cues given by approaching machinery. Glare is another factor to consider, as it can impede a miner's ability to identify hazards and perform his or her job safely. Accordingly, proper design of mine illumination systems emerges as a critical factor to consider for miner safety.

The main objective of the NIOSH research presented in this paper was to examine whether visual performance improvements might be obtained through the manipulation of a cap lamp's spectral content distribution. Specifically, the subjects' visual performance was compared when using cool-white light-emitting diode (LED) technologies that have a higher concentration of short-wavelength energy versus traditional warm-white incandescent bulbs that emit a "yellowish" light due to the higher concentration of longer-wavelength energy. Recent nighttime driving and underground mining research has indicated that in low-light (mesopic) conditions, increased short-wavelength spectral content can improve visual performance (Van Derlofske and Bullough, 2003; Van Derlofske et al., 2005; Sammarco and Lutz, 2007; Sammarco et al., 2008a, 2008b). A secondary objective was to determine the role of aging on visual performance in mesopic conditions with respect to these lighting technologies. The physiology of the human eye is such that visual performance degrades as a person ages. These physiological changes include reduced pupil size, cloudier lenses and reduction in the amount of rod photoreceptors that play a dominant role in vision for low-light conditions may all have a significant impact on visual performance as light levels decrease. This emerged as another critical factor to consider during these studies due to the age of U.S. coal mine workforce, which currently averages approximately 43 years.

This paper summarizes the results of three experiments designed to investigate these factors. Experiments 1 and 2 were designed to examine the ability to detect peripheral motion and slip, trip and fall hazards, respectively, using an LED cap lamp as compared with the more commonly used incandescent cap lamp. Experiment 3 was designed to evaluate discomfort and disability glare produced by LED and incandescent cap lamps.

Abstract

Proper illumination is critical to a miner's ability to detect hazards in underground mines. Moving hazards are often located in the miner's peripheral field-of-view, while slip/trip/fall hazards are often located in the forward field-of-view. The objective of the research described in this paper was to determine if light-emitting diodes (LEDs) improve visual performance as compared to traditional incandescent (INC) cap lamps. The research presented focuses on comparative studies of a National Institute for Occupational Safety and Health (NIOSH) prototype LED, a commercial LED and an INC camp lamp. Thirty subjects participated in these studies, with ten subjects in each of the following age groups: 18 to 25 years, 40 to 50 years and 51+ years old. Visual performance was quantified by the subjects' speed and accuracy in detecting hazards, while visual performance for disability glare was quantified by the use of contrast sensitivity tests. Results suggest that LEDs with a visible spectrum containing a higher concentration of the shorter wavelengths can enable visual performance improvements with respect to disability glare, the detection of moving hazards in the peripheral field-of-view and the detection of floor hazards in the forward field-of-view. The NIOSH prototype LED cap lamp provided the best visual performance improvements for the older age groups in every test.

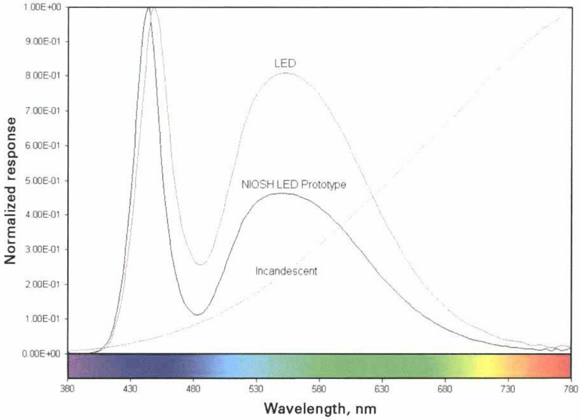
Table 1

Cap lamp electrical and photometric data.

	Electrical characteristics			Photometric characteristics	
Camp lamp	Supply voltage, Vdc	Supply current, amps	Supply power, watts	Peak wavelength, nm	Correlated color temp., K
INC	6.1	0.63	3.84	780	2,880
Commercial LED	6.1	0.42	2.56	448	5,855
Prototype LED	12.0	0.113	1.36	444	6,844

FIGURE 1

Spectral power distributions (SPDs) for cap lamps used.



General methodology

Subjects. The same human subjects, 24 male and six female, participated in all three experiments. Subjects were recruited from NIOSH personnel at the Pittsburgh Research Laboratory (PRL). None were specifically involved with the cap lamp research. Most of the subjects were not familiar with miner cap lamps, or they had used them infrequently. The decision not to use miners as subjects was due to possible expectancy biases that could confound the empirical data. For example, miners might determine that the blue-white light from an LED cap lamp is very different from the yellowish light of an incandescent cap lamp; thus, a negative bias could exist because they are not accustomed to the LED light color, or a positive bias could exist if the person perceives something new as better.

Age was an independent variable for each experiment. Three age groups, each consisting of ten subjects, were established: Group A = 18 to 25 years of age, Group B = 40 to 50 years of age; and Group C = 51 years of age; and over. The average age of the participants was 42.5 years, which is representative of the average U.S. coal miner's age of 43 years. Screening of subjects included extensive vision testing for distance visual acuity, contrast sensitivity, color vision deficiency and peripheral vision. Screening was followed by a detailed description of the experiments to be conducted as well as a consent form that informed subjects about their right to withdraw freely from the research at any time without penalty.

Cap lamps. The experiments were designed to compare three cap lamps that served as the independent variables for each study. The first cap lamp was a Mine Safety and Health Administration (MSHA)-approved cap lamp designed to use a single incandescent bulb as the primary light source. This was selected as the experiments' referent light source. The second cap lamp was a commercial, MSHA-approved, cap lamp designed to use 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 was designed to use two phosphor-white LEDs as the primary light source. The electrical data recorded for each cap lamp is listed in Table 1. Additionally, each cap lamp was characterized with respect to its spectral power distribution (SPD), depicted in Fig. 1. Because initial illuminance distribution measurements revealed significant variations in the light output, the application of diffusion filters was necessary to normalize the light output for each cap lamp. For example, preliminary measurements indicated that the illuminance of certain objects was 42% greater with the prototype LED cap lamp than with the incandescent cap lamp. Controlling the illuminance distributions throughout the experiments ensured that the lighting research was contained to the spectral content of the cap lamps rather than a combination of several underlying factors that would confound the data. The diffusion filters successfully maintained a more uniform illuminance distribution among cap lamps.

Mine illumination laboratory. Experiments were conducted at the Mine Illumination Laboratory (MIL) located at NIOSH Pittsburgh Research Laboratory. Measuring 4.88 m (16 ft) wide by 2.13 m (7 ft) high, this simulated underground coal mine environment is fully equipped with data acquisition and control systems, with networked computers and with safety equipment and signage essential to accommodate human subject testing. MIL was designed to match the texture, color and reflectivity of surfaces commonly found in underground coal mines.

Observation station. It was important to have each subject be at a fixed, known coordinate with respect to each test apparatus and to have each subject's position fixed so that their point of view was the same regardless of their body size. This eliminated data confounding from variations in the subjects' point of view. Hence, NIOSH personnel designed and constructed an observation station (Fig. 2) to enable each subject to be tested at an eye height of 1.651 m (65 in.). This eye height, with reference to the floor, was based on the 50th percentile standing male (USDOT, FAA, 2003). Controlled using electric actuators, the seat was designed to rise 200 mm (7.9 in.) from the lowest position to its highest to accommodate testing of subjects ranging from the 5th percentile female to the 95th percentile male.

The height of the miner's helmet was independently adjustable from the seat height to accommodate varying torso lengths, which ranged from 686 to 848 mm (27.0 to 33.4 in.). A swivel was incorporated into the station to allow the seat to rotate 360°, thus enabling the subject to face multiple test apparatuses without leaving the observation station. This feature reduced the overall testing time enabling the researchers to minimize subject fatigue and boredom, limiting the subject's exposure to potential trip or fall hazards if they were to travel to and be seated on a separate observation station for each test. The observation station and all of its components were painted flat black to eliminate any reflection of light and to prevent distractions during testing.

General procedures. Each subject was given a minimum of 15 minutes to adapt to the darkened environment of the MIL. Next, a subject was seated on the observation station and adjustments were made such that each person had the same eye height of 1.651 m (65 in.) from the floor. While seated, the subjects wore a hardhat rigidly mounted to the observation station to help maintain a consistent head and cap lamp position. Eye protection was provided similar to that worn underground. The subjects were provided hearing protection to avoid possible auditory cues that could affect outcomes. Additionally, a sound track of underground mining operations was played during the tests to negate possible auditory cues and to help create a more realistic environment. Once the subjects were positioned and the equipment properly adjusted, the test procedures were explained to the subjects. Warm-up (practice) sessions were initially conducted to help subjects learn how to conduct the tests and to become familiar and comfortable with the test apparatus and procedures.

FIGURE 2

The observation station used for all experiments.

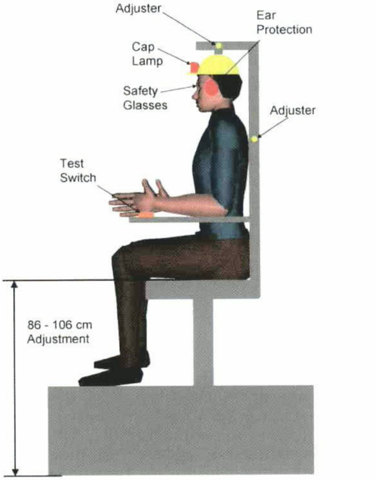
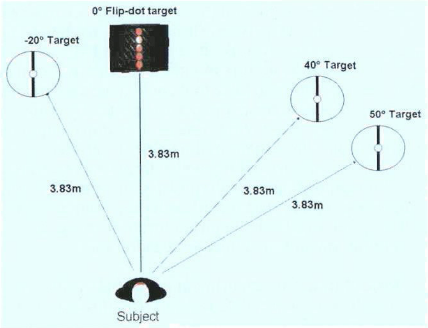


FIGURE 3

Experimental layout for Experiment 1: Peripheral motion detection (figure not to scale).



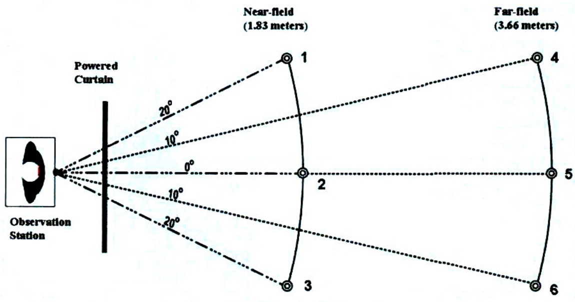
Experiment 1: Peripheral motion detection

Experimental design. A 3 x 3 x 3 (age group x light source x target location) split-split plot design was used in this study (Kirk, 1995). Subjects represented whole-plots, and the whole-plot factor was age group. There were three age group categories: Group A = 18 to 25 years old; Group B = 40 to 50 years old; Group C = 51+ years old. The light source was the split-plot factorial and also had three levels consisting of: a commercial LED cap lamp, a commercial incandescent cap lamp and a prototype LED cap lamp. High contrast, white circular targets were positioned at -20°, 40° and 50° (Fig. 3) off axis. The angle of the target location was the split-split plot factorial. Two primary dependent measures were used to examine the effects of the independent measures listed above. The two primary dependent measures were detection time, i.e., time to detect target movement, measured in milliseconds (ms), and number of target movements missed.

Apparatus. The peripheral motion apparatus was designed and built by NIOSH to perform the data acquisition and control (DAC) throughout the experiment. The system's main components were a microcontroller,

FIGURE 4

Experimental layout for Experiment 2: Floor hazard detection (figure not to scale).



a flip-dot matrix target, DAC software and high-contrast (white) circular targets connected to dc-powered motors. The system's input, controlled by the subjects being tested, was a computer mouse. Subjects would depress the mouse button causing an electrical signal to the microcontroller to initiate the test. The microcontroller then activated a flip-dot matrix, located at zero degrees, which served as a visual tracking target. The purpose of this visual tracking target was to draw a subject's focus and fix their eye orientation to the center. In doing so, the subject would be forced to use their peripheral vision to detect motion rather than using direct line of sight.

The control system accessed one of four different software versions compiled to vary the sequence in which the three circular targets were sequentially activated. The circular targets, positioned at -20°, 40° and 50° off-axis, were rotated by dc motors mounted on tripods. Because the dc motors emitted noise that could have confounded the results, it was necessary to mask the noise by using ear protection and background sounds of mining equipment in operation. This eliminated a subject's ability to use the auditory cues to identify which target was activated. The data acquisition process consisted of a time-stamped spreadsheet macro that recorded the cap lamp used, the software version used, the target location sequence and the peripheral motion detection reaction time.

Procedures. This experiment consisted of five trials, two of which were practice sessions. The three other trials consisted of experimental trials where the type of cap lamp was varied. Subjects were encouraged to ask questions if any part of the instructions were unclear. The subjects were then instructed to keep their eyes focused on the center flip-dot matrix target in front of them during this entire experiment. They were handed a computer mouse and were briefed on the operation of the mouse. Holding down the left mouse button started the test. The subjects were to release the depressed mouse button to indicate when they saw a circular target rotate. Reaction time was measured as time the circular target was initially activated to the time the subject released the depressed mouse button. A reaction time of 4.2 seconds or above would be recorded as a missed target. In addition to varied sequences, randomization in time delays and counterbalancing of tests were implemented to prevent learned behavior from impacting validity of results.

Results and discussion. A split-split plot analysis of variance (ANOVA) was used to evaluate whether there were significant differences for the independent variables. All three main effects (age group, angle and cap lamp) significantly affected detection time; no interactive effects were detected. Age group had a significant effect on detection time ($F_{2,27} = 5.38$, $p < 0.05$). Group A (younger subjects) had significantly faster detection times than Group B subjects. Detection time differences were not statistically significant between Groups B and C. The target angle significantly affected detection time ($F_{2,154} = 60.14$, $p < 0.001$). The 40° target resulted in about a 16% increase in detection time compared to the -20° target, while the 50° target had a 76% increase in detection time. The prototype LED enabled significantly faster detection times than the commercial LED ($F_{2,54} = 4.62$, $p < 0.05$). On average, post hoc tests indicated that the prototype LED resulted in 11% and 15% faster detection times than the INC and commercial LED cap lamps, respectively. No statistically significant difference in performance was found between the INC and commercial LED cap lamps. The prototype LED cap lamp's visible spectrum contains more of the shorter wavelengths than the commercial LED cap lamp. The differences between the LED cap lamps are especially notable at 555 nm, where the commercial LED cap lamp has a much greater proportion of longer wavelengths in comparison to the prototype LED cap lamp. The lack of an interaction between age and light source indicates that the prototype LED cap lamp provides similar benefits to all age groups in terms of improving the ability to detect moving objects in the peripheral visual field. This benefit, however, may be more important for middle-aged and older workers.

Experiment 2: Floor hazard detection

Experimental design. A within-subjects design was employed in this study. Presentation of cap lamps were randomly assigned to subjects and a restricted randomization was used for stimulus order presentation within cap lamps. The independent variables were the four object patterns: near field, far field and two combinations of near field and far field. The dependent variables, quantifying visual performance, remained the same as Experiment 1.

Experimental layout. The general layout is depicted by Fig. 4. A motorized curtain was installed 0.91 m (3.0 ft) in front of the observation station to prevent the subject from gaining an advantage in finding the objects while the researcher switched object location patterns. This curtain was connected to a microcontroller programmed to control the curtain and time the duration of each test. Two location categories were established for this experiment:

near-field at 1.83 m (6.0 ft), about the distance of two strides for the average male, and far-field at 3.66 m (12.0 ft). The far-field location is a more common visual attention location for a walking person, and it is a location of higher illuminance given the cap lamp mounting on the miner's helmet. Table 2 lists the near field and far-field illuminances. Each object was 64 mm (2.5 in.) long with a 33 mm (1.3 in.) outer diameter. The objects were painted a dark color such that they would have a very low contrast (-0.11 to 0.09) and a reflectivity very similar to an object that was coated with the material on a mine floor. Four object location patterns were presented to each subject: two objects in the far and near field; two objects in near field; two objects in the far field and two objects in the far and near field.

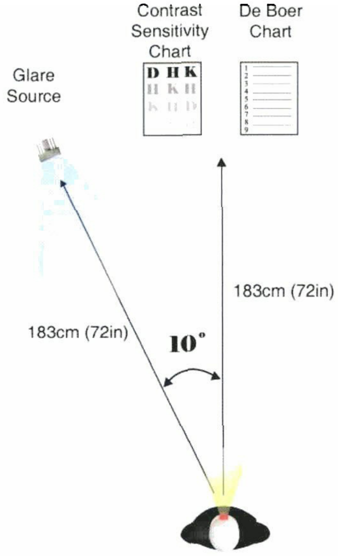
Table 2

Near and far-field illuminances.

	Incandescent	Commercial LED	Prototype LED
Average near-field illuminance (lux)	1.28	1.17	1.17
Average far-field illuminance (lux)	1.27	1.49	1.26
Overall average illuminance (lux)	1.28	1.34	1.22

FIGURE 5

Experimental layout for Experiment 3: Discomfort and disability glare (figure not to scale).



Procedures. The procedure was to close the black, electrically-powered curtain and arrange objects according to the corresponding object patterns selected for each subject. The subjects were instructed to point at each object using a laser pointer and count it out loud. When the subject was ready, the curtain was opened and the PC-based data-acquisition system started recording time. Two researchers determined that an object was detected the instant the subject pointed the laser pointer at the target and confirmed it audibly by counting. The curtain was closed after a ten second period and the Excel spreadsheet macro recorded the time for which the last object was accounted for or the ten-second period had expired.

Results and discussion. Results of the Cox regression forward selection process indicated that object pattern was the most influential factor in terms of detection time, followed by the type of cap lamp used and then the age group. No significant interactions were detected and the proportional hazards assumption was met in all cases. In the comparison of cap lamp effects, both LED cap lamps (prototype and commercial LED) led to more rapid detection of objects compared to the traditional INC cap lamp ($p < 0.001$). Comparisons of cap lamp performance demonstrate the clear superiority of the LED cap lamps for the current task. Compared to the incandescent cap lamp, currently standard in the mining industry, the LED cap lamps resulted in detection times that were, on average, more than 1.5 seconds faster. The prototype LED cap lamp resulted in 23.7% faster detection times than the INC cap lamp and 21.9% faster detections times than the commercial LED cap lamp. The mean detection time and standard error for the INC cap lamp was 7.447 sec. 0.5999 SE. The prototype LED resulted in slightly faster detection time than the commercial LED cap lamp; however, the difference was not statistically significantly.

Experiment 3: Discomfort and disability glare

Experimental design. A 3 x 3 (age group x cap lamp) split-plot factorial design was used. The age group represented the whole-plot factor and light source represented the split-plot factor. The interaction of age group and light source was part of the split-plot analysis. The dependent variables were the subjective discomfort glare ratings (qualitative, De Boer scale 1 through 9) and the contrast sensitivity score for disability glare. The presentation order for cap lamps was counterbalanced, where replication 1 was the baseline presentation order and replication 2 was the reversed presentation order.

Apparatus. The experimental layout for the glare experiment (Fig. 5) was set up to seat each subject facing toward the two charts used throughout the experiment. The De Boers scale and the Mars letter contrast sensitivity chart were both used to investigate the degree of discomfort and disability experienced by subjects when exposed to the glare produced by each cap lamp. These charts were located at zero degrees, at a height equal to that of the subject's eye height. The cap lamps were positioned 1.83 m (72 in.) away from the test subject at an angle of -10° off axis. The cap lamps were pointed directly at the subject to simulate glare from another miner's cap lamp.

Procedures. This experiment consisted of two parts. The first part was designed to obtain a subjective rating of discomfort for each of the three cap lamps used. Subjects were instructed to focus their attention to a rating scale located directly in front of them while a glare source was adjusted. Using the De Boer scale, which is a commonly accepted method for measuring discomfort glare, the subjects were asked to rate the glare source located 10° off-axis. The De Boer's scale is a nine-point subjective scale, where a rating of 1 is considered "unbearable" and a rating of 9 was considered "just noticeable." The rating given by each subject is recorded using a customized software database.

After the completion of the discomfort test, the disability test was administered. This test was designed to determine the degree to which the glare sources would impair a person's vision. The Mars letter contrast sensitivity chart was used to measure visual performance with respect to contrast sensitivity. Visual performance was quantified by a subject's ability to correctly identify letters of varying contrast while a glare source was directed towards the subject's eyes. The test would conclude when the subject missed two consecutive letters, at which point the contrast sensitivity was calculated.

Results and discussion. ANOVA was used to evaluate whether there were significant differences for the contrast sensitivity tests and the De Boer ratings, respectively. De Boer ratings were treated as an interval variable, as distances between various measurements on the scale were considered meaningful. Parametric statistical tests (such as F tests) may be applied to De Boer ratings, an approach that was utilized, for example, in a study on disability glare by the Federal Highway Administration (Porter et al., 1995). Results indicated a significant interaction was present between age group and cap lamp for contrast sensitivity. Additional statistical analysis indicated that the prototype LED cap lamp resulted in significantly better contrast sensitivity scores in the older age group compared to the other cap lamps, whereas the youngest age group showed no difference in contrast sensitivity between any of the cap lamps ($FS_{4,108} = 10.091$, $p < 0.05$). The commercial LED and incandescent cap lamp indicated no statistically significant difference in contrast sensitivity across age groups ($FS_{2,108} = 1.10$, $p > 0.05$). The qualitative De Boer ratings of discomfort glare were affected by age group ($F_{2,45} = 9.41$, $p < 0.001$) but not by the cap lamp. Analysis of the mean De Boer ratings for each cap lamp suggests that ratings were highest (a higher rating means less discomfort glare) for the prototype LED than for the other cap lamp; however, this qualitative assessment did not achieve statistical significance among the cap lamps. It is apparent from the findings of this study that spectral content of light from the LED cap lamps do not appear to increase discomfort glare, and that only the prototype LED cap lamp has the potential to significantly improve safety by reducing disability glare, especially among older workers who are most susceptible to glare and its effects. For older workers, there was a 45% improvement in contrast sensitivity compared to the other light sources studied. Contrast sensitivity is an important aspect of visual performance especially in underground coal mines that are typically a low-contrast environment. Additionally, it is a critical factor for many work tasks, so implementation of the prototype cap lamp design could provide a major benefit for the aging mining population with respect to disability glare.

General discussion

Given the conditions of this study, the results suggest that LEDs with more of the shorter wavelengths, such as found with the prototype LED cap lamp, may offer improved peripheral motion detection, floor hazard detection and reduce disability glare for older workers. These results appear to be similar to results of recent research indicating that, at mesopic conditions, a short-wavelength spectral content can improve visual performance. Note that the prototype LED cap lamp had the shortest wavelengths, and it enabled the best results in all three experiments. The commercial LED cap lamp did not perform as well as the prototype LED cap lamp for Experiment 1: peripheral motion detection. Thus, the results suggest that not all LED caps lamps, given the conditions of this study, will enable significant visual performance improvements.

The results of the visual performance comparisons between LED and INC 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. Such a benefit could prove to be very important for the health and safety of the underground miner. For example, a reduced capability in peripheral motion detection or perception could make it difficult for miners to detect moving machinery or could cause them to misjudge the speed that a machine is moving towards them. Any improvement in the ability to perceive objects moving in the periphery will convey an advantage in terms of being able to avoid contact with moving machinery.

Lastly, this study was limited to new cap lamps that functioned at optimal performance. A larger and more detailed study is needed to determine the effects of the real-world conditions of light source aging and battery discharge over a typical mine shift. The authors' previous research has indicated that there are significant differences between INC and LED cap lamps for real-world conditions and that LEDs have significant advantages (Sammarco et al., 2008b). Specifically, the light output of a new INC cap lamp with a nickel-hydride battery decreased about 35% after 8 hours, while a new LED cap lamp with the same battery had a light output decrease of about 3%. After aging the INC and LED, the light outputs decreased an additional 35% and 3%, respectively. Additionally, changes in spectral power distributions of the INC and LED camp lamps were evaluated for a 10-hour battery discharge. The LED had very little spectral shift, while the INC had a substantial shift to less of the shorter wavelengths. Generally, visual performance increases with increasing light, and it increases when the light contains more of the shorter wavelengths; thus, it is reasonable to expect that the visual performance improvements, enabled by LEDs, would be even greater under real-world conditions. ■

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Disclaimer

The findings and conclusions in this report have not been formally disseminated by the National Institute for Occupational Safety and Health and should not be construed to represent any agency determination or policy.

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