Comparative evaluation of Light Emitting Diode cap lamps with an emphasis on visual performance in mesopic lighting conditions

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***Abstract*—Conducted at the Office of Mine Safety and Health Research laboratory of the National Institute for Occupational Safety and Health (NIOSH), this experiment is part of ongoing mine illumination research designed to explore the benefits of solid state lighting technologies when applied to the underground mining industry. This experiment involves the comparative evaluation of cap lamps with similar spectral power distributions, focusing on the electrical and battery discharge characteristics, with a secondary objective being exploring the benefits gained through alternative light beam distributions. NIOSH researchers conducted the investigation by comparing three commercially available LED cap lamps and a NIOSH prototype cap lamp at varying power settings. Visual performance for the detection of hazards was quantified by recording times of detection for finding rotating targets in the peripheral field of view and objects representing trip and fall hazards on the ground. Results show that the NIOSH prototype improved the ability to perceive objects in the visual field by improving peripheral motion detection times by as much as 79.5%, and ground hazard detection times by as much as 194.1%.**

***Index Terms*—mine illumination; visual performance; machine lighting; mine safety.**

I. Introduction

Researchers at the National Institute for Occupational Safety and Health (NIOSH) are investigating different lighting technologies with the objective of improving mine safety by improving visual performance and reducing glare. The scope is machine-mounted, auxiliary, and cap lamp luminaries for underground coal and metal/nonmetal mining. Recent NIOSH research has focused on the spectral characteristics of light from miner cap lamps to improve safety. The results indicate significant gains in visual performance that could reduce pinning/striking accidents [1], glare-induced accidents [2] and slip/trip/fall (STF) accidents [3]. NIOSH researchers also conducted an empirical study of visual performance for detection of trip hazards and peripheral motion detection given various types of machine-mounted area lighting. The lighting technologies were incandescent, fluorescent, and LEDs [4]. The results indicated that lighting combinations that consisted of auxiliary LED area lights significantly improved visual performance for the detection of hazards found in the peripheral field of view, as well as those found on the ground.

Two limitations of cap lamp research are that no visual performance evaluations have been done to investigate battery discharge and decreasing light output as the light source ages. The driver circuit for an LED is an important factor in determining battery discharge. Also, LEDs require current regulation to maintain their light output. Passive regulation circuits, such as those using a resistor, do not regulate current and therefore result in a decrease in light output as the battery discharges. The significance of this decrease in light output in terms of visual performance is unknown. In addition to battery discharge, light source aging also plays a significant role. LEDs do not typically fail catastrophically as do incandescent light sources; rather, they gradually decrease in light output over time. Because this time can span a period of over 50,000 hours, it can be difficult to determine when the LED will no longer enable sufficient visual performance for safety and so should be replaced. LED life is defined by lumen maintenance that is typically reported as the operating time (L) in hours, which corresponds to a set reduction in the initial light output. For general lighting, the useful life (lumen maintenance) is denoted by L_{70}, which corresponds to a 30% reduction of the initial light output; this is the approximate threshold considered to be acceptable by most of the occupants within a space [5]. Note that L_{70} denotes a general threshold for detecting light reduction and is not related to human visual performance required for safety; thus, it is not known if L_{70} is an acceptable threshold with respect to visual performance.

Lastly, cap lamp research has not addressed the issue of light distribution. Traditionally, the cap lamp beam has been a narrowly focused spot of approximately 6° to 8°. This spot pattern does not afford much light on the mine floor, nor does it provide much light on moving mining machinery. This tight spot pattern does lend itself to viewing distant objects.

Providing more light to the floor and moving machinery could increase visual performance for the detection of related hazards. One research study, conducted to assess a subject's ability to detect trip hazard objects on the floor of an illuminated chamber, found that detection ability improved as illuminance increased [6].

The research objectives of the present study were to determine how visual performance was affected by: (1) battery discharge given differing LED driver circuit topologies; (2) alternative beam patterns compared to a tightly focused spot beam pattern; (3) the lumen maintenance benchmark L_{70}.

II. METHODS

A. LED cap lamps

Four types of LED cap lamps were used. Each cap lamp was new and powered at levels for a fully charged battery. Cap lamps 1 through 3 used a single phosphor-white LED as the primary light source, along with an optical reflector to direct the light to a circular spot ranging from approximately 6° to 8°. Cap lamps 1 through 3 are commercially available and were approved by the Mine Safety and Health Administration (MSHA). The fourth cap lamp was a laboratory prototype developed by NIOSH. The cap lamps were selected based on the research objectives concerning visual performance.

For each cap lamp, the electrical and photometric characteristics are listed in Table I. Each cap lamp was energized from a regulated power supply to eliminate voltage fluctuations as a cap lamp battery discharged. The power supply voltage and current was set to represent fully charged batteries for cap lamps 1a, 2, and 3. Cap lamps 1b, 4a, 4b, and 4c represent discharge rates and benchmark testing as explained in the text.

TABLE I
CAP LAMP ELECTRICAL AND PHOTOMETRIC DATA

Cap lamp	Electrical characteristics			Photometric characteristics	
	Supply voltage (Vdc)	Supply current (milli-amps)	Supply power (watts)	Peak wavelength (nm)	Correlated color temp. (K)
1a	4.10	684	2.80	452	7728
1b	3.87	592	2.29	452	7664
2	4.07	769	3.13	448	6546
3	3.95	530	2.09	456	6216
4a	2.99	585	1.75	448	6138
4b	2.96	450	1.33	448	6087
4c	2.75	320	0.88	448	6029

1. Battery discharge given differing LED driver circuits

Cap lamp 1 uses a passive, current-limiting resistor for the LED driver circuitry. The advantages of this driver are that it is simple, inexpensive, and it is relatively easy to obtain intrinsic safety because no inductors and capacitors are used. However, the disadvantage is that it does not maintain constant current, so the LED light output will decrease as the battery discharges. Cap lamps 2 and 3 used a constant-current driver. The main advantage is that a constant current is maintained so that the LED light output is relatively constant as the battery discharges. However, the disadvantages are that this type of circuit is more complex and costly. It can also be more difficult to achieve intrinsic safety if inductors and capacitors are used, and circuit board dimensions become a factor because more components are necessary.

Within the initial 30 minutes of operation, cap lamps 1 and 2 exhibited relatively sharp light output drops. At 12 hours, cap lamp 1 light output decreased to slightly less than 80% of its initial output (Fig.1); however, cap lamp 2 decreased to about 95% of its initial output (Fig. 2). Cap lamp 3 also used a constant current driver and exhibited a light output decrease very similar to that of cap lamp 2.

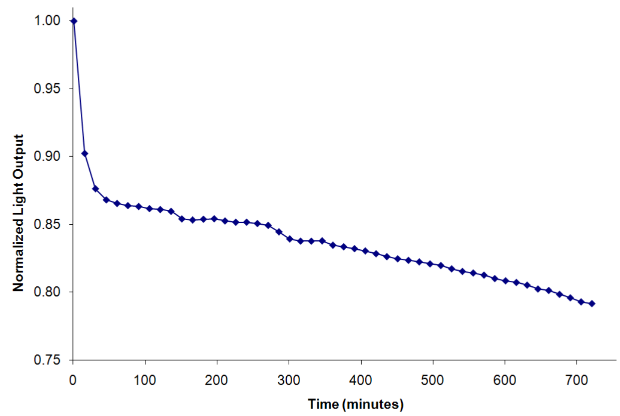

Fig. 1. Normalized light output at 25 °C as a function of battery discharge time for cap lamp 1, which uses a resistor for current limiting [7].

The discharge point of interest was 8 hours. For cap lamp 1, the datum of interest were (a) the fully charged battery point and (b) the eight-hour discharge point. For cap lamps 2 and 3, the eight-hour discharge point was not of interest because the light output only decreased about 5%.

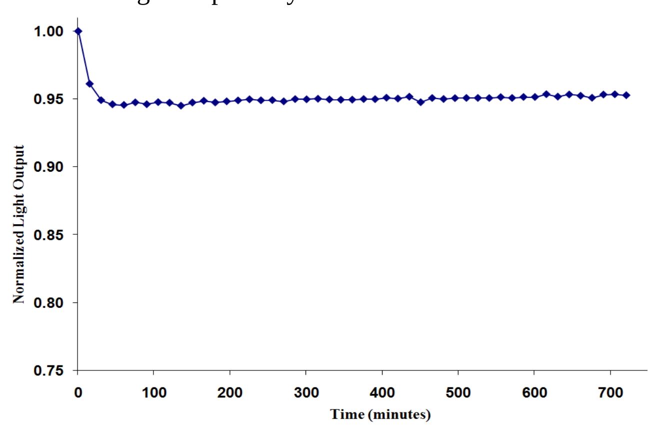

Fig. 2. Normalized light output at 25 °C as a function of battery discharge time for cap lamp 2, which uses a constant-current regulator [7].

2. Beam distribution

This NIOSH prototype uses multiple phosphor-white LEDs as the primary light source along with secondary optics to direct and distribute the light to specific hazardous areas in the mine. The intent is to provide more illumination for miners in order to facilitate detection of slip/trip/fall hazards located on the mine floor, as well as the detection of moving machinery hazards associated with pinning/striking accidents. The NIOSH prototype LED cap lamp meets MSHA photometric requirements [8]. Fig. 3 depicts a simulation of the beam distribution for cap lamp 4.

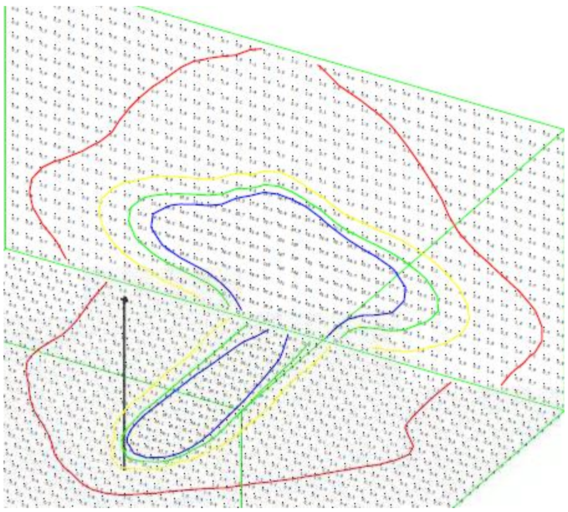

Fig. 3. Beam pattern isolux simulation of cap lamp 4. The minimum threshold values for the isolux lines are: red (the outermost line) ≥1 lux; yellow ≥5 lux; green ≥ 10 lux; blue (the innermost line) ≥15 lux [6].

The actual beam distributions for cap lamps 1 and 3 are shown by Fig.4. The beam distribution from cap lamp 2 was virtually identical to that of cap lamp 1.

Fig. 4. Cap lamp beam distribution as projected onto a black wall located 1.83 m from the cap lamps. Cap lamp 1 (left) and cap lamp 3 (right).

3. Lumen maintenance benchmark L_{70}

Three power level conditions (a, b, and c) were established utilizing cap lamp 4. Condition c represented a 30% light output decrease as compared to condition b, while condition b represented a 30% light output decrease compared to condition a. Note that the change in current among the conditions is not linear because LED light output is not a linear function of current due to a condition called LED droop, where the efficiency of the LED decreases as current increases.

B. Setting

The testing was conducted at the Mine Illumination Laboratory (MIL) at the NIOSH facility in Pittsburgh, PA. 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 488 cm wide by 213 cm high and is coated with a rough-textured material that has a dark color and spectral reflectivity of about 5%, which is typical for coal.

C. Subjects

NIOSH personnel at the Pittsburgh facility were recruited to be subjects. Miners were not used as subjects because of potential expectancy biases that could confound empirical data. None of the subjects were specifically involved with this cap lamp research, and most of the subjects were not familiar with miner cap lamps or they had used them infrequently. Only the subjects that passed vision tests for distance visual acuity, contrast sensitivity, and peripheral vision were accepted for the study. Subjects that had radial keratotomy, monocular vision, glaucoma, or macular degeneration were excluded. Subjects signed an informed consent form and were instructed about their right to withdraw freely from the research at any time without penalty. The protocol was approved by the NIOSH Human Subject Review Board.

Thirteen subjects participated: 11 male and two female. While gender was not a variable in this study, the gender percentage distribution was representative of the U.S. miner population. Two age categories were established given that age is a factor for visual performance in general and as established by prior mine illumination research [1], [2], [3], [4]. The younger age group was from 40 to 50 years of age. The older age group was over 50 years old. The average subject age was 54 yrs.

III. EXPERIMENTAL LAYOUT AND APPARATUS

A. Peripheral Motion Detection

1.0 Experimental Layout

The experimental layout for this study is depicted in Fig. 5. The system consisted of three components operated by a microcontroller-based data acquisition and control system. The hardware consisted of a flip-dot matrix, three circular targets connected to dc-powered motors, and a mouse used as the trigger for the experiment. The subjects controlled the system's input and initiated the test sequence through an electrical signal sent to the microcontroller when the mouse button was depressed. The microcontroller's software was programmed to activate the flip-dot matrix as well as control the sequence and duration of the circular target's rotations. The flip-dot matrix served as a visual target to draw the subject's focus and fix the subject's eye orientation to the center. The panel was located in the subject's forward field of view (0°) to ensure that each subject used peripheral vision to detect the motion of the circular targets.

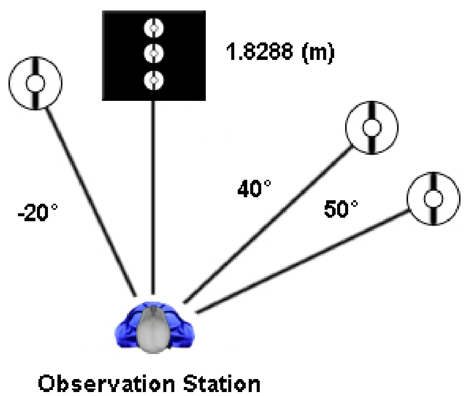

Fig. 5. Experimental layout for Experiment 1: Peripheral Motion Detection.

The control system accessed different software versions compiled to vary the circular target activation sequences. The targets measured 120 millimeters (mm) in diameter and were painted white with a single black line across the center. The circular targets, positioned at -20°, 40°, and 50° off-axis, were rotated by dc motors mounted on tripods. Audible cues emitted from the dc motors were masked by using ear protection and playing the sounds of mining equipment in operation in the background. This eliminated the subject's ability to use the cues to identify the active target, thus confounding the data being recorded. The data acquisition process consisted of a time-stamped spreadsheet macro that recorded all the pertinent data, such as the lighting mode, the software version, the target activation sequence, and the subject's reaction time in detecting movement.

2.0 Illuminance Measurements

Illuminance measurements were recorded for each of the light sources to investigate the light distribution designs and compare light output at a given location. The averages, recorded in Table II, were calculated from three spot checks recorded on the circular targets and on the flip dot matrix located at 0° off-axis.

TABLE II
AVERAGE PERIPHERAL MOTION TARGET LLUMINANCES (LUX)

Cap lamp	Target locations			
	-20°	0°	40°	50°
1a	1.45	25.77	1.11	1.00
1b	1.35	24.66	1.02	.92
2	1.51	30.45	.88	1.04
3	3.58	281.33	1.52	.87
4a	34.82	197.07	3.66	.96
4b	27.86	139.53	2.83	.75
4c	20.16	113.70	2.13	.55

3.0 Experimental Design

Covariates for the peripheral motion target detection portion of the study were the angle of the targets (-20°, 40°, and 50°) and cap lamp conditions. Seven cap lamp conditions were tested using four separate cap lamps. These included cap lamps 1 and 2 from manufacturer A, cap lamp 3 from manufacturer B, and a NIOSH prototype, cap lamp 4. Of the two cap lamps tested from manufacturer A, one was tested in a fully charged state (cap lamp 1a), and one in a state equivalent to an 8-hour discharge of the battery (cap lamp 1b). Cap lamp 2 from manufacturer A was tested fully charged, as was cap lamp 3 from manufacturer B. The NIOSH prototype cap lamp was tested at three power settings [minimum (c), middle (b), and maximum (a)] that were determined for testing the L_{70} benchmark.

Mixed effects Cox regression models with shared frailties (using coxme routine in R statistical software) were developed to assess the main effects of target angle and cap lamp conditions on time to detection of the targets. Trials where the target was not located in 4.2 seconds were treated as censored observations. Cox regression model development was guided by the Akaike Information Criterion (AIC). At each step of model development, variables were entered according to what resulted in the lowest AIC. Z statistics were used to assess significant effects of individual cap lamps, using the discharged cap lamp 1b as a referent. Each variable was tested to evaluate the proportional hazards assumption. Kaplan-Meier estimates of the survival functions for detection of the targets for each cap lamp conditions were assessed at each target angle.

4.0 Results

Table III provides the results of the Cox regression analysis for the peripheral motion study. Target angle was the factor with the greatest influence on detection time, followed by cap lamp conditions. For cap lamp conditions, only the NIOSH prototype cap lamps performed significantly better in terms of target detection compared to the referent cap lamp ($p < 0.01$).

TABLE III
COX REGRESSION ANALYSIS RESULTS

VARIABLE		beta	SE	Z	df	P	Exp(beta)
Target Angle		-1.337	0.055	-24.52	1	.000	.262
Cap lamp conditions	2	-.135	.143	.885	1	.347	.874
	4a	.486	.139	3.50	1	.001	1.581
	4b	.785	.139	5.67	1	.001	2.194
	4c	.601	.139	4.33	1	.000	1.823
	3	.218	.141	1.55	1	.12	1.243
	1a	-.0487	.142	-.33	1	.74	.954

A total of 415 censored observations (i.e., undetected targets) were made, comprising 31% of all trials. Of these, 289 observations were associated with the 50 degree target, 93 censored observations were associated with the 40 degree target, and 33 censored observations were associated with detection of the -20 degree target.

Results indicate that the NIOSH prototype performance was best for the middle power setting (46% improvement), followed by the maximum power setting (43% improvement), and the minimum power setting (35% improvement), compared to the referent conditions. Table IV provides the median detection times and 95% confidence intervals for each of the cap lamp conditions. Increasing target angle led to longer target detection times and an increased number of censored observations (missed targets).

TABLE IV
MEDIAN DETECTION TIMES AND 95% CONFIDENCE INTERVAL BOUNDS FOR CAP LAMP CONDITIONS

Cap lamp	Median detection time (s)	Lower 95% CI bound	Upper 95% CI bound
4b	1.500	1.034	1.965
4a	1.590	1.291	1.889
4c	1.800	1.533	2.067
1a	2.125	2.088	3.111
1b	2.350	1.664	3.036
3	2.600	1.606	2.994
2	2.775	2.195	3.355

B. Trip and Fall Hazard Detection

1.0 Experimental Layout

The general layout for this study is depicted in Fig. 6. A motorized curtain was installed and hung from the ceiling to prevent the subject from observing the location where the researcher set the objects.

The objects for trip detection tests were made from sections of PVC electrical conduit. Each object was 6.4 cm long with a 3.3-cm outer diameter and 2.2-cm inner 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 (5%) very similar to an object that was coated with the material typically found on a coal mine floor. Battery powered infrared LEDs were installed inside the objects to aid in the post-process video data analyses.

Three location distances were established. The near-field (0.762 meters (m)) is about the distance a person can see with peripheral vision while looking straight ahead. The middle-field (1.8288 m) is about the distance of two strides for the average male. The far-field (3.6576 m) is a common visual attention location for a walking person.

An electrical timer controlled the motorized curtain, automatically opening and closing it for ten-second intervals. To aid in the post-processing, LEDs were installed to indicate the curtain's state. A red LED indicated that the curtain was closed and a green LED indicated it was open. The sessions were video recorded and then analyzed frame by frame to determine the response time of the subjects.

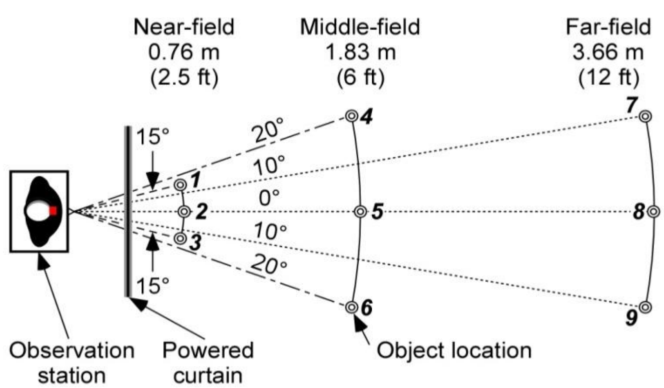

Fig. 6. The plan view of the trip hazard detection testing layout.

2.0 Illuminance Measurements

Illuminance plays a significant role in visual performance where visual performance improves as illuminace increases. The illuminances for each of the trip object locations were recorded in Table V for the various cap lamp conditions.

TABLE V
TRIP HAZARD ILLUMINANCE (LUX) MEASUREMENTS BY OBJECT LOCATIONS 1THRU 9 OF FIG. 6

Cap lamp	Object location								
	1	2	3	4	5	6	7	8	9
1a	1.18	1.24	1.20	.68	1.44	1.47	.72	23.31	2.47
1b	1.09	1.15	1.10	.62	1.37	1.45	.74	22.25	2.32
2	1.14	1.16	1.15	.76	1.49	1.44	.76	40.6	1.10
3	.86	.78	.84	.98	1.15	1.03	3.23	28.4	2.05
4a	3.18	9.43	1.91	4.11	32.1	3.24	7.83	34.6	5.87
4b	2.45	7.35	1.52	3.30	24.95	2.46	6.18	27.11	4.55
4c	2.10	5.38	1.17	2.45	18.45	1.88	5.27	24.4	4.18

TABLE VI
COX REGRESSION ANALYSIS RESULTS

VARIABLE		Beta	SE	Z	df	P	Exp(beta)
Near-field		1.254	.098	12.87	1	.000	3.507
Far-field		-.402	.669	-4.26	1	.000	.669
Cap lamp conditions	2	.384	.138	2.77	1	.006	1.468
	4a	1.182	.145	8.17	1	.000	3.262
	4b	1.378	.143	9.61	1	.000	3.967
	4c	-.031	.144	-0.21	1	.830	.970
	3	.106	.141	0.75	1	.450	1.112
	1a	1.036	.142	7.31	1	.000	2.818
Age Group		-.635	.319	-1.99	1	.047	.530

3.0 Experimental Design

Covariates for slip/trip/fall (STF) object detection consisted of cap lamp conditions (the same seven conditions as for the peripheral motion study discussed above), proximity of the field (near, middle, and far), and age group (younger and older). As with the peripheral motion study, the discharged cap lamp 1b served as the referent condition for cap lamp condition. The referent condition for field proximity was the middle field. Mixed effects Cox regression models with shared frailties (coxme routine from R statistical software) were developed to assess the effects of field proximity, cap lamp conditions, and age group on time to detection of trip hazard targets. Trials where the target was not located within 10 seconds were treated as censored observations. Cox regression model development was guided by the Akaike Information Criterion (AIC). At each step of model development, variables were entered according to what resulted in the lowest AIC. Z statistics were used to assess significant effects of individual cap lamps, using the discharged cap lamp of manufacturer A as a referent.

4.0 Results

Table VI provides the results of the Cox regression analysis for the slip/trip/fall study. Field proximity was the factor with the greatest influence on detection time, followed by cap lamp conditions, and then age group. Coefficients for the field proximity variable indicate that objects in the near field were detected much more rapidly than those in the middle field, and those in the far field were detected more slowly than were middle-field objects. Several cap lamp conditions were found to improve STF object detection compared to the referent cap lamp ($p < 0.01$). The top three, in order of largest improvement to lowest, were the NIOSH prototype 4b (18% decrease in detection time), and NIOSH prototype cap lamp 4c (16% decrease in detection time), and Manufacturer A cap lamp 1 (13% decrease in detection time). The older age group was found to exhibit slower detection times compared to the younger age group ($p < 0.047$). Table VII provides the median detection times and 95% confidence intervals for each of the cap lamp conditions for STF object detection.

TABLE VII
MEDIAN DETECTION TIMES AND 95% CONFIDENCE INTERVAL BOUNDS FOR CAP LAMP CONDITIONS

Cap lamp	Median detection time (s)	Lower 95% CI bound	Upper 95% CI bound
4b	3.345	3.127	3.563
4c	3.430	3.303	3.557
1a	3.530	2.947	4.113
2	4.065	3.283	4.847
3	4.080	3.191	4.969
4a	4.131	3.135	5.127
1b	4.365	3.855	4.875

IV. Discussion

The results indicated that visual performance was not significantly affected by battery discharge given differing LED driver circuit topologies of a simple resistive LED driver circuit and a constant current LED driver circuitry. However, it is important to note that, due to the experiment's limitations, this statement is not intended to imply that constant current LED driver circuitry is unnecessary. A resistive drive circuit is more likely to enable thermal runaway conditions, which could result in catastrophic failure of the LED. Secondly, the light output decrease at 8 hours from using a resistive drive circuit is visually noticeable, and some miners may find this objectionable.

The results also indicated that the alternative beam patterned distribution of the NIOSH prototype cap lamp 4b enabled the best (lowest) average detection time for trip hazard detection and peripheral motion detection visual performance. Cap lamp 4b required 1.33 watts, which was much lower than cap lamps 1, 2, and 3. However, this result does not take into account the efficiency of an LED driver circuit because cap lamp 4 did not possess one; therefore the LEDs were directly connected to a current-regulated power supply. The other cap lamps did have LED driver circuits connected to a power supply. If cap lamp 4b were connected to an LED driver circuit that had an efficiency of 85%, the total power required would be approximately 1.56 watts, which is significantly lower than the power required by cap lamps 1, 2, and 3.

These same results indicated that L_{70} is an acceptable benchmark for lumen maintenance given that the visual performance difference for conditions a, b, and c of cap lamp 4 was not significant. There is, however, a significant benefit from the determination of this benchmark in that it highlights a major difference between LED and incandescent lighting. Because LED cap lamps decay over time, whereas traditionally used incandescent cap lamps inevitably fail, LED cap lamps afford an added benefit in terms of safety and maintenance-related issues associated with bulb replacement.

The research results imply that age is a significant factor in visual performance among the different age groups, as was shown in prior NIOSH research [1], [2], [3]. Also, there was a large difference in visual performance between the two age groups, thus highlighting the importance of considering this factor given an aging workforce. While these results were expected, there was a limitation on the strength of the study attributed to the small sample size.

A second limitation was that the testing was conducted in a laboratory environment that closely emulated an underground coal mine, but it did not include factors such as wet floor conditions or airborne dust. Additionally, the subjects were stationary, and each person's viewpoint and eye height from the floor was fixed by seating them in the observation station. This test situation reduced the likelihood of confounding data and the tripping risks associated with subjects walking in a dark area, but it did not emulate walking activities.

Given the laboratory setting test results and the production of field-worthy cap lamps, the next step in the development process is identifying mine companies with which to form a collaborative agreement to investigate how they will perform in real-life conditions using miners in an underground mine environment.

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Disclaimers

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 the National Institute for Occupational Safety and Health.

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