Evaluation of Peripheral Visual Performance When Using Incandescent and LED Miner Cap Lamps

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Abstract—**Illumination plays a critical role in an underground miner's safety because miners depend most heavily on visual cues to recognize hazards. Mobile mining machinery, located in the miner's peripheral field of view ($\pm 10^\circ$ to about $\pm 60^\circ$ off-axis), may pose potential pinning and striking hazards. The main objective of this research was to determine if there were peripheral visual performance improvements for the detection of moving objects when using cool-white light-emitting diode (LED) cap lamps as compared to incandescent (INC) light bulbs commonly used in miner cap lamps. The cap lamp variable of interest is the spectral power distribution. The illuminances were normalized by a diffusion filter. The second objective was to determine if age is a factor for the peripheral visual performance. This is important because the workforce is aging—the average miner age is about 43 years old. Thirty subjects participated in the study, ten subjects each in the age groups of younger (18–25 years), middle (40–50 years), and older (51+ years). Visual performance was quantified by the subjects' speed and accuracy of response to detect the rotation of high-contrast (white) circular targets located 3.83 m away at -20°, 40°, and 50° off-axis. The speed of detection and the number of missed target rotations (accuracy) were measured. The prototype LED cap lamp results were best with an 11%–15% improvement compared to the INC and LED cap lamps, respectively. Age does appear to be a significant factor. For the middle and older age groups, the target movement detection time increased 75% and 60%, and the number of missed targets increased 500% and 450%, respectively, in comparison to the youngest age group. The results also suggest that target location is a significant factor. The subjects' target movement detection time for the 40° and 50° target movements increased 16% and 69%, respectively, as compared to the -20° target.**

I. Introduction

ILLUMINATION plays a critical role in an underground miner's safety since miners depend heavily on visual cues to detect hazards [1]. An example of an underground hazard where appropriate illumination is vital is that of being struck or pinned by mobile mining equipment. A Mine Safety and Health Administration (MSHA) report [2] on remote-controlled continuous mining machine accidents indicated that pinning and striking fatalities were increasing with 12 fatalities between 2000 and 2004, compared to 17 fatalities over the 15-year span between 1984 and 1999. There were 67 nonfatal striking/pinning accidents from 1999 to 2004. Typically, a miner's cap lamp is the primary and most important source of light for detecting machine movement [3], which is often located in the miner's peripheral field of view ($\pm 10^\circ$ to about $\pm 60^\circ$ off-axis). It can be very difficult for miners to detect moving machinery because the underground mining environment is noisy and can mask the audible cues given by approaching machinery; thus, it is critical that miners are able to detect motion in their peripheral field of view if they are to avoid pinning and striking hazards.

Peripheral visual performance is affected by many factors that include the object size, reflectance, contrast, viewing distance, location off-axis, and lighting conditions. Other factors include a person's age and how the human eye changes as a person ages. The retina of the human eye plays a critical role in vision [4]. The retina contains photoreceptors that convert light to electrical impulses that travel through the optic nerve to the brain. There are two types of visual photoreceptors: rods and cones. The rods are sensitive to light and dominate our night vision; the cones are sensitive to color and dominate our daytime vision. The rods also play a more dominant role in vision as light levels decrease, particularly when the lighting is between daylight and night. This twilight-type illumination, known as mesopic, is prevalent in underground mines. Rods assume additional importance under such lighting conditions as they are particularly sensitive to detecting motion in the peripheral field of view.

Previous miner cap lamp lighting research investigated visual performance with respect to peripheral motion detection. Visual performance was defined as the speed and accuracy of detecting the rotation of cylinders (targets) located at $\pm 60^\circ$ and 7.66 m from the human subject. The research approach was to determine the relationship between visual performance and cylinder luminance. The results indicated that the peripheral visual performance improved 58% when target luminance was increased from 0.0018 to 0.15 fL [5].

The main objective of the National Institute for Occupational Safety and Health (NIOSH) research presented in this paper was to determine if there were visual performance improvements for the detection of moving objects in the peripheral field of view when using cool-white light-emitting diode (LED) cap lamps as compared to incandescent (INC) light bulbs commonly used in miner cap lamps. The second objective was to determine if age is a factor for peripheral visual performance given that there is an aging workforce. This is important to

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consider because of the aging U.S. coal mine workforce that has an average age of about 43 years. The research approach differs from prior work that increased luminance to improve visual performance. Our approach was to determine if peripheral visual performance could be improved by using a LED lamp with a visible spectrum containing more short-wavelength light. Recent research has indicated that, at low-light (mesopic) conditions, such as found in nighttime driving and underground mining, an increased short-wavelength spectral content can improve visual performance [6]. LEDs with a visible spectrum containing more of the short-wavelength light can enable considerable improvement in peripheral visual performance at mesopic conditions for automotive applications [7]. Recent NIOSH mining research findings indicated that, in comparison to INC lighting for cap lamps, cool-white LEDs with a visible spectrum containing more of the short-wavelengths, which can be characterized by the spectral power distribution (SPD), can enable visual performance improvements with respect to slip/trip/fall hazard detection, where the majority of the hazards are located in the peripheral field of view at $\pm 10^\circ$ and $\pm 20^\circ$ off-axis [8].

A. Terminology

Luminous Flux: It is the time flow rate of light energy that is similar in concept to horsepower or British thermal unit per hour. The lumen is the unit of luminous flux used by the Illuminating Engineering Society of North America (IESNA) and in the International System of Units (SI) [9].

Illuminance: It is the measure of the density of luminous flux striking a surface. The IESNA units are footcandle (equivalent to lumen per square foot) and lux (equivalent to lumen per square meter); the SI system only uses lux [9].

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 [9]. For achromatic scenes, luminance is correlated with a person's perception of brightness. The most common IESNA and SI unit for luminance is candela per square meter.

Luminance Contrast: It is the relationship between the luminance of an object and its immediate background [10].

SPD: It is the radiant power emitted at each wavelength in the visible region of light (between 360 and 770 nm).

II. Methods

A. Experimental Design

A $3 \times 3 \times 3$ (age group, light source, target location) split-split plot design was used in this study. The subjects represented the whole plots, and the whole-plot treatment was the Age Group. There were three Age Group categories: Group A (18–25 years old); Group B (40–50 years old); and Group C (51+ years old). The light source was the split-plot treatment and also had three levels consisting of the following: a commercial LED cap lamp, a commercial INC cap lamp, and a prototype LED cap lamp. Circular targets were positioned at three angles from the focal point of the subject: -20°, 40°, and 50° (Fig. 1). The angle of the target location was the split-split plot treatment.

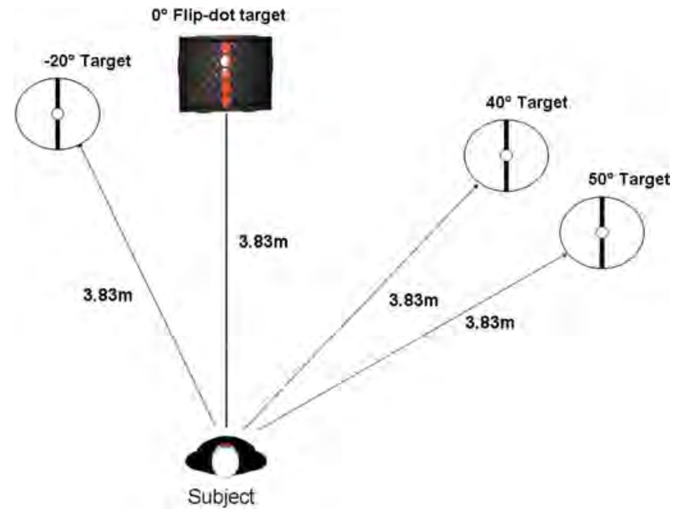

Fig. 1. Experimental layout.

Two primary dependent measures were used to examine the effects of the independent measures listed previously. These dependent measures were the following:

1) detection time (in milliseconds) to detect target movement;
2) number of target movements missed. A missed target is defined when the detection time exceeds 4.2 s. Thus, this variable was dichotomous—a trial with a missed target was recorded as "1," whereas a trial with no missed target was recorded as "0."

Analysis of variance (ANOVA) was used to determine the significance of the main effects and interactions. The use of ANOVA to evaluate dichotomous variables in this study is in accordance with the recommendations given by D'Agostino [11]. Specifically, an arcsine transformation was applied to the proportion of trials, where missed values were obtained and an ANOVA was run using the transformed values. The alpha level for all tests was set at 0.05. Multiplicative Sidak *post hoc* tests were used to determine the differences between conditions following a significant omnibus test.

B. Subjects

Thirty subjects participated in the study, ten subjects each in the age groups of A = younger (18–25 years), B = middle (40–50 years), and C = older (51+ years). NIOSH personnel from the Pittsburgh Research Laboratory (PRL) were the subjects. Only the subjects that passed the vision tests for distance visual acuity, contrast sensitivity, color vision deficiency, and peripheral vision were accepted for the study. Miners were not used because of potential expectancy biases that could confound the empirical data. Expectancy biases are particularly challenging for lighting research because the variable of the study (visible light) is usually observable to the subjects. Miners could easily detect that the light (particularly the color) from the LED-based cap lamps is very different from the camp lamp light they use on a daily basis.

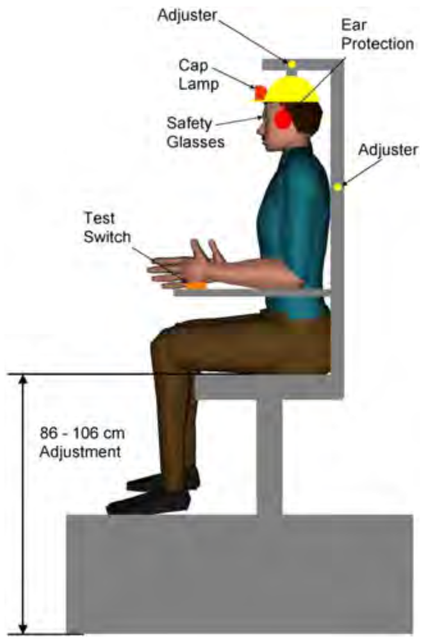

Fig. 2. Observation station used for the human subject testing.

Twenty-four male and six female subjects participated. The mean ages were 22.6, 47.3, and 57.6 years, respectively. The overall mean age was 42.5 years; the mean age of a U.S. coal miner is 43 years. The subjects' peripheral vision eye test scores were of prime interest given the study's focus. For the youngest to oldest age groups, the mean scores were 179°, 176°, and 174.4°, respectively.

The protocol for this study was approved by the NIOSH Human Subject 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

1) MIL: The testing was conducted at the Mine Illumination Laboratory (MIL) of NIOSH PRL. The MIL is a simulated underground coal mine environment that is equipped with various test equipment, data acquisition and control (dac) 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 a color and reflectivity of 10% which is similar to that of a coal mine. The experimental layout is depicted in Fig. 1.

2) Observation Station: The observation station (Fig. 2) 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 [12]. The station was required to allow the 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 the test subjects. The height of the miner's helmet with cap lamp and earphones 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.

3) Peripheral Motion Apparatus: The peripheral motion apparatus was designed to perform the dac throughout the experiment. Controlled by a dedicated laptop, the system consisted of both hardware and software elements which directly interacted with the human subjects being tested. The system's main components were the BS2sx microcontroller, dac software, high-contrast (white) circular targets connected to dc-powered motors, and a central flip-dot matrix target.

The system's input was controlled using a computer mouse. A depressed mouse button would signal the microcontroller to begin the test. The microcontroller activated a flip-dot matrix, located at 0°, as long as the mouse button was depressed. This target was used for a visual tracking task that was designed to draw the subject's focus and fix their eye orientation to the center while the subject's peripheral vision was being tested.

The control system then accessed a preloaded version of software that was installed into the microcontroller. The preloaded software was one of four different software versions compiled to vary the sequence in which the three circular targets, located at $-20°$, 40°, and 50°, were activated. Each version varied the sequence in which each target was activated a total of four times per test. This resulted in a cycle that included 12 target activations. In addition to varied sequences, the software also varied the initial time delay prior to each target being activated. Implementing time delays of 3 and 5 s created another variable used to ensure randomization and prevent learned behavior from impacting the validity of the results. The targets were circular in shape and had a diameter of 120 mm. Each target was painted a solid flat white color and had a single black line intersecting the center to produce a desired contrast of 0.90, where contrast is equal to $(L_1 - L_2)/L_1$, where L_1 and L_2 are the respective luminances of the background and target. The circular targets were activated to rotate when the microcontroller supplied the required voltage to power dc motors on which the circular targets were mounted. Although the dc motors emitted noise that could have confounded the results, the implementation of ear protection and background noise, which simulated mining equipment in operation, eliminated a subject's ability to use the auditory cues to identify circular target motion.

The data acquisition of the peripheral motion detection experiment focused around a time-stamped Excel spreadsheet macro which recorded the cap lamp used, the software version used, the target location sequence, and the peripheral motion detection reaction time. The reaction time was measured from the time the circular target was initially activated to the time the subject released the depressed mouse button, signifying peripheral motion detection. A reaction time of 4.2 s or longer would be recorded as a missed target, and the next target in the sequence would be initiated.

4) 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 INC bulb as the primary light source. This served as the reference. The second was an MSHA-approved cap lamp with a single phosphor-white

TABLE I
CAP LAMP ELECTRICAL AND PHOTOMETRIC DATA

Cap Lamp	Electrical Characteristics			Photometric Characteristics	
	Supply voltage (Vdc)	*Supply current (amps)*	*Supply power (watts)*	*Peak wavelength (nm)*	*Correlated color temperature (K)*
Incandescent	6.1	0. 63	3.84	780	2880
LED	6.1	0.42	2.56	448	5855
Prototype LED	12.0	0.113	1.36	444	6844

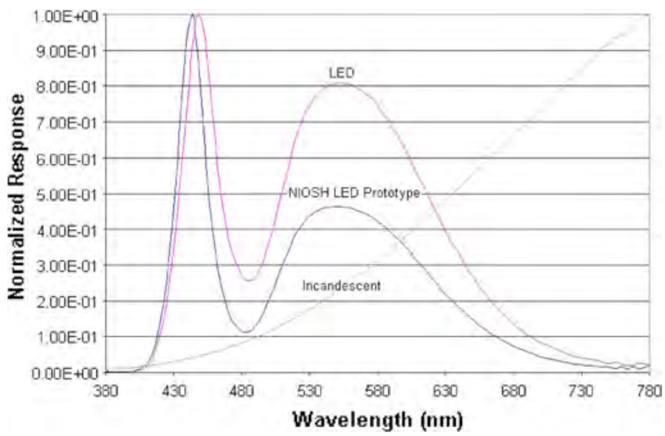

Fig. 3. SPDs for each cap lamp as normalized at their maximum values. The diffusion filters, used to normalize target illuminance, were on each cap lamp.

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 photometric requirements specified by MSHA [13]. 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. 3 depicts 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 INC 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. The LED cap lamp has more of the longer (red) wavelengths than the prototype LED due to manufacturing differences. Manufacturers can add secondary phosphors or dopants in order to have higher emission in the long wavelength range.

5) Illuminance Distributions: The illuminance levels were measured at each object location 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 average illuminance at the 40° circular target was about 48% greater with the INC cap lamp as compared to that of the LED cap lamp. Therefore, a

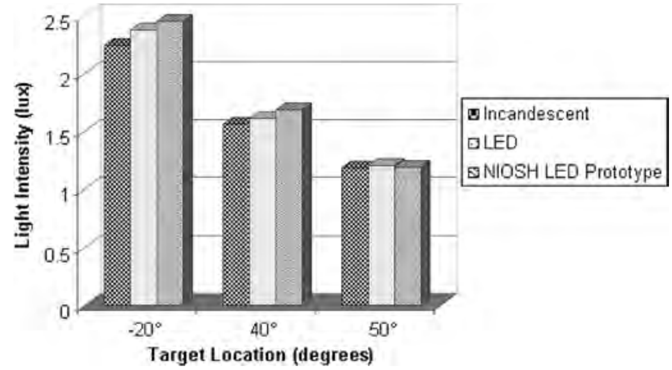

Fig. 4. Average target illuminance from each cap lamp when applying a diffusion filter to the cap lamps.

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. Fig. 4 depicts the illuminance distributions for all circular target locations when using the various cap lamps with diffusion filters. Note that the average illuminance at the 40° circular target is 3.1% less with the INC cap lamp as compared to that of the LED cap lamp.

D. Procedure

Each subject was given a minimum of 15 min to adapt to the darkened environment of MIL. Next, a subject was 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 rigidly mounted to maintain cap lamp position. Eye protection was provided similar to that worn underground. The subjects were also requested to wear hearing protection to avoid possible auditory cues which could affect the outcomes. Additionally, underground mining sounds were played during the test to further negate possible auditory cues. Once the subjects were positioned and the equipment was properly adjusted, the test procedures were explained to the subjects. Two practice (warm-up) sessions were initially conducted to help the subjects learn how to conduct the tests and to become familiar and comfortable with the test apparatus; this provided an opportunity for the subjects to ask questions on any aspect of the test they did not completely understand.

The procedure was for the subject to keep their eyes focused on the center flip-dot matrix target in front of them during this entire experiment. This target consisted of a column of continuously flipping dots that the subjects were to watch as an aid to keeping their vision focused on the center of the test area. The subjects were instructed to use a computer mouse to indicate when they saw the rotation of a 12-cm disk located at −20°, 40°, and 50° in their peripheral field of view. Holding down the left mouse button started the test. The indication of the subject noticing the rotating disk was recorded when the mouse button was released. The time difference between when a disk started to rotate and the time the mouse button was released was recorded by a custom control program. The test would resume when the mouse button was held down again. The subjects were given 4.2 s to notice the change; if they did not see the change

TABLE II
ANOVA SUMMARY FOR THE DETECTION TIME

Source	SS	df	MS	F	p
A (Age Group)	4.504E+07	2	2.252E+07	5.38	0.0108
S/A (WP error)	1.129E+08	27	4183958		
B (Cap Lamp)	4077240	2	2038620	4.62	0.0141
AB	3154770	4	788693	1.79	0.1449
*B*S/A*(SP Error)	2.384E+07	54	441403		
C (Angle)	4.715E+07	2	2.358E+07	60.14	0.0000
AC	1340666	4	335167	0.86	0.4925
BC	1451497	4	362874	0.93	0.4506
ABC	1222055	8	152751	0.39	0.9249
*BC*S/A* (SSP Error)	6.037E+08	154	391991		

Multiplicative Sidak pairwise comparisons for Detection Time by Age Group, Angle, and Caplamp. Conditions containing the same letter are not significantly different from one another. The unit of measure is milliseconds.

Age Group:	Younger	Older	Middle
	1292.3	2068.6	2260.3
	A	AB	B
Angle:	- 20°	40°	50°
	1460.4	1692.5	2468.3
	A	B	C
Cap lamp:	Commercial LED	Incandescent	Prototype LED
	2007.6	1911.0	1702.6
	A	A	B

in less than 4.2 s, the center flip-dot target stopped changing, indicating that they had missed detecting one of the circular targets, at which point they were required to release and then press down the mouse button to reset and proceed with the experiment.

The experiment consisted of five tests for each subject. The first two were warm-up tests followed by an opportunity for the subjects to clarify any portions of the procedure they did not understand. The test was then repeated for each of the three cap lamps: the INC and the two LED cap lamps. Each test consisted of a cycle of 12 random activations of the rotating disks in different portions of the subject's peripheral vision. The experiment was then repeated with the second and third cap lamp following the same procedures. The order that the rotating disks were activated and the order in which the cap lamps were tested were randomized to avoid any sequencing effects in the data. For each age category, 50% were tested with one sequence of lamps and activations and the other 50% with an alternative sequence.

III. RESULTS

A split-split plot ANOVA was used to evaluate whether there were significant differences for the independent variables. Table II summarizes the ANOVA results for the detection time. Note that the values of F near 1.0 indicate no effect for an independent variable, whereas higher values indicate a significant effect. The following sections detail the results for both dependent measures.

A. Detection Time

All three main effects were found to significantly affect detection time, whereas no interactive effects were detected (Table II). As can be seen in the table, Age Group had a significant effect on detection time $(F_{2,27} = 5.38,\ p < 0.05)$. The *post hoc* tests indicated that the subjects in Group A (younger subjects) had detection times that were significantly faster than the subjects in Group B. Differences in the detection time between the two older age groups were not significantly different.

The use of the prototype LED resulted in significantly faster detection times than the commercial LED $(F_{2,54} = 4.62,\ p < 0.05)$. On the average, the *post hoc* tests indicated that the prototype LED resulted in 11% and 15% faster detection times than the INC and commercial LED, respectively. No statistically significant difference in performance was found between the INC and commercial LED light sources.

The angle of the flip-dot targets had a sizable impact on the time to detect the stimulus $(F_{2,154} = 60.14,\ p < 0.001)$. The further from the center line of the subject's line of sight, the greater the time the subject took to detect the stimulus. The 40° target resulted in about 16% increase in detection time compared to the -20° target, whereas the 50° target had a 76% increase in detection time. All three conditions were significantly different from one another according to the *post hoc* tests.

B. Missed Targets

The results of the ANOVA on the arcsine-transformed data regarding missed targets indicated a significant interaction between Age Group and Target Degree $(F_{4,8} = 6.49,\ p < 0.05)$. This interaction is depicted in Fig. 5 (nontransformed data), where the frequency of the missed targets is greatest for the 50° target, typically followed by the 40° and -20° targets with the exception of Group A, where the -20° target condition had a slightly higher number of misses. Group B had the greatest number of missed targets followed by a slightly lower amount for Group C and a greatly reduced number of misses for Group A.

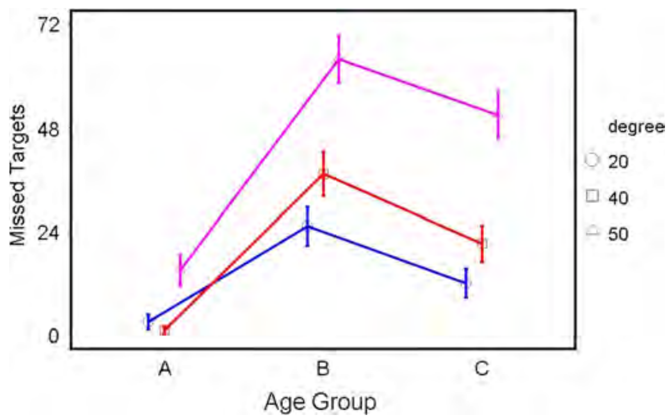

Fig. 5. Occcurence of missed targets for each age group (A = younger, B = middle, and C = older) and for each target position ($-20°$, $40°$, and $50°$). The error bars represent the standard error of the mean.

IV. Discussion

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. The prototype LED cap lamp results were best with an 11%–15% improvement compared to the INC and LED cap lamps, respectively. Note the SPD differences (Fig. 3) among the three cap lamps. The prototype LED cap lamp's visible spectrum contains more of the shorter wavelengths. The differences between the LED cap lamps are particularly notable at 555 nm, where the commercially available LED cap lamp has a much greater proportion of longer wavelengths in comparison to the prototype LED cap lamp. These results do not conclusively establish the superiority of LEDs for cap lamps, but they do suggest that LEDs with more of the shorter wavelengths, such as found with the prototype LED cap lamp, may offer improved peripheral motion detection. These results appear to be similar to the results of recent research, indicating that, at mesopic conditions, a short-wavelength spectral content can improve visual performance [6]–[8].

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 detecting objects in the peripheral visual field. This benefit, however, may be more important for middle-aged and older workers, whose ability to detect peripheral motion is compromised as the result of the aging process. However, it may be noted that, even with the improvement in peripheral vision with the prototype LED cap lamp, the toll associated with the aging process is often much greater. Nonetheless, the improved performance in peripheral vision provided by the prototype LED may help to at least partially ameliorate the decline associated with age.

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 toward 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 or allowing quicker estimation of the speed and direction with which a machine is moving.

There have been relatively few studies on the impact of age on motion detection and motion perception, but, for all age groups, people misjudge the speed of large objects which appear to be moving more slowly than their actual speed [14]. In the current study, the youngest age group had quicker response time compared to the older age groups, but, surprisingly, the older age group performed somewhat better than the middle-aged group. While the difference was not statistically significant in terms of detection time, it is nonetheless unusual for an older age group to outperform a younger age group in any measure of visual performance. The reason that the older subject would average quicker response times is not clear, but it could be that the older subjects generally had better than average visual capabilities and the middle-aged subjects were below average for their age group. Thus, it is quite conceivable that the relatively small sample of older subjects tested in this study may not have been fully representative of the visual capabilities of the older population as a whole. Interestingly, the older age group also tended to outperform the middle-aged group in terms of having fewer missed targets. The age-related results indicate how important the age factor is given that Groups B and C had detection times that were 75% and 60% more than Group A's detection time. It appears that the cap lamp SPD is an important factor to consider for the peripheral visual performance of older miners given that the prototype LED resulted in an 11% and 15% faster detection times than the INC and commercial LED.

The angle at which the targets were located also had a significant impact on detection time, with each angle being significantly different from the others. The increase in detection time from $-20°$ off-axis to $40°$ off-axis was approximately 16%. However, the increase in detection delay between $-20°$ and $50°$ was approximately 76%. Furthermore, the $50°$ target condition saw a tremendous increase in the number of missed targets compared to the $40°$ target condition. It is clear that even relatively small angular differences can make a tremendous difference in peripheral vision, as targets are positioned further off-axis. The number of missed targets generally followed this trend but was also dependent on the age group. We reason that the physiology of the human eye and the target illuminance were instrumental in accounting for the decreasing peripheral visual performance as the target angle increased. First, the greatest density of rods occurs between $\pm 10°$ and $\pm 30°$ from the retina's center [4]; therefore, it would be expected that the $-20°$ target would be detected the fastest as long as the target illuminances at $40°$ and $50°$ were not significantly greater. Peripheral visual performance will increase as the target illumination increases and all other factors are held constant. With respect to the $-20°$ target, the mean target illuminance decreased about 33% and 48% for the $40°$ and $50°$ targets, respectively. It is very important to note that the target illuminances are not typical of actual cap lamps because a neutral density diffusion filter was used to normalize the target illuminances. For instance, the INC cap lamp's actual target illuminance decreased about 46% and 58% for the $40°$ and $50°$ targets, respectively, with respect to the $-20°$ target; therefore, the peripheral visual performances would be poorer than those measured during this research. Commercially available miner cap lamps, be they INC or LED, typically exhibit a highly intense centralized beam with a total angle of about 2°–6° and a relatively dim surround or penumbra. This centralized beam would be very useful for viewing distant objects or for conducting fine detail work tasks that require high illuminance. However, this lighting distribution is not conducive for detecting moving machinery located in the peripheral field of view. We anticipate that this lighting distribution will result in other detrimental effects such as pronounced transient adaptation effects as the miner looks at a very brightly illuminated object in the center beam to an object illuminated by much less light [5]. These issues, however, are beyond the scope of this paper.

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