Evaluation of Visual Performance When Using Incandescent, Fluorescent, and LED Machine Lights in Mesopic Conditions

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Abstract—**This experiment investigated the effects of different machine-mounted area lighting technologies on visual performance in a simulated underground mine environment. The primary objective was to conduct a comparative evaluation of the lighting technologies based on the visual performance of 36 human subjects in a simulated underground mine environment. Incandescent (Incand), fluorescent (Fluor), and light-emitting diode (LED) technologies were used to create four lighting combinations. Visual performance was quantified for the detection of movement in the peripheral field of view and the identification of ground hazards. Measurements were made of the speed (response time measured in milliseconds), the accuracy (the number of targets and objects missed), and the subjective discomfort rating of the glare experienced for each lighting combination. A secondary objective explored the effects of aging on visual performance. The results indicate that lighting combinations which consisted of 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. They furthermore indicate that age plays a significant role in visual performance.**

Index Terms—**Machine lighting, mine illumination, mine safety, visual performance.**

I. Introduction

THE Illuminating Engineering Society of North America reports that the coal mine face is the most difficult lighting environment in the world [1]. Given the limitations of illumination produced by a miner's cap lamp, identifying potential hazards in a working area can often prove extremely difficult. Reduced levels of light around mining machinery can impair a miner's ability to judge the speed or direction of a machine. Coupled with the fact that machines such as continuous miners have deceptively quick rates of travel, a miner is exposed to extreme conditions in which illumination plays a critical role in their ability to perform their jobs safely. According to the Mine Safety and Health Administration (MSHA), a total of 144 fatal accidents were attributed to moving mining machinery and were reported in underground coal mines from 2001 to 2007. Twenty-five of those were attributed to accidents that involved continuous miners. MSHA also reports that 11% of lost-time injuries reported from 2002 to 2006 were attributed to those caused by machinery. In addition to pinning and striking accidents, the second highest cause of lost-time injuries is slip or fall of a person. MSHA records indicate that slip or fall of person lost-time injuries account for 17.4% of the reported cases from 2002 to 2006. Increasing light levels around the perimeter of machines may potentially improve visual recognition of these hazards and, consequently, reduce the number of injuries and fatalities in the mining industry. However, when increasing light levels, glare becomes a significant aspect to consider as it may negatively affect a miner's vision and ability to detect hazards. Accordingly, mine illumination systems must be properly designed to limit the effects of glare in order to efficiently illuminate an area and improve safety.

The main objective of The National Institute for Occupational Safety and Health (NIOSH) research outlined in this paper was to explore the existence of visual performance improvements through the implementation of different machine-mounted lighting systems. The visual performance of 36 human subjects was evaluated and compared for four different lighting conditions that consisted of incandescent lights alone, a combination of incandescent and light-emitting diode (LED) lights, fluorescent lights alone, and a combination of fluorescent and LED lights. A secondary objective was to determine the role of aging on visual performance and the benefits of using one lighting mode over another. Physiological changes that occur as a person ages include reduced pupil size, cloudier lenses, and reduction in the amount of photoreceptors that play a dominant role in low-level lighting, all have a significant impact on visual performance as light levels decrease. Because the physiology of the human eye is such that visual performance degrades as a person ages, implementation of lighting systems that can account for that degradation is critical.

II. Methodology

A. Overview

Pursuant to the ethics guidelines established by the human subject review board, subjects were first informed about their rights and were given a detailed description of what each experiment would consist of. Subjects were given 15 min to allow for their vision to adapt to the darkened environment in which the experiment was going to be administered. Each subject was seated on the observation station (Fig. 1) before

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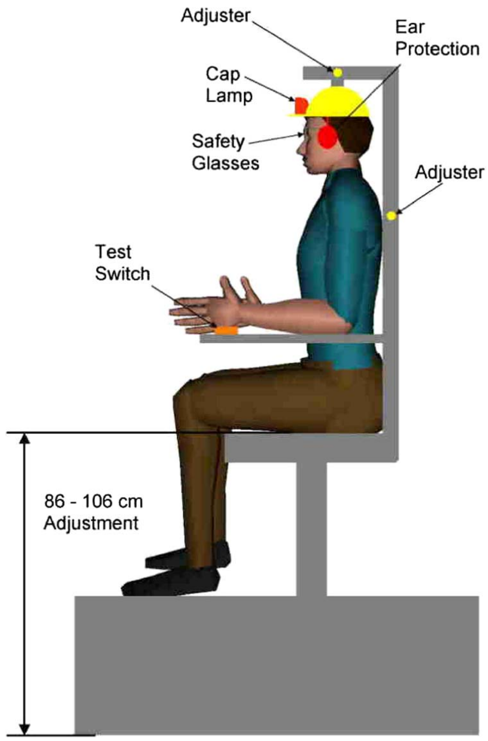

Fig. 1. Observation station.

proper adjustments were made to ensure that each subject had the same eye height from the floor. Ear protection was then adjusted, as needed, depending on the experiment being administered. Eye protection was provided to each subject to further simulate proper personal protective equipment worn in underground mine environments. Various measures were implemented in each study to prevent learned behavior from impacting validity of results. This was done by the introduction of varied sequences and counterbalancing of tests that varied between subjects. Each study consisted of a practice session to allow the subjects to familiarize themselves with the different control systems and procedures. After the completion of the practice session, each subject was asked if there were any questions, and they were addressed prior to commencing the actual test.

This experiment consisted of three different studies designed to evaluate machine-mounted area lighting technologies. The first study was designed to quantify a subject's visual performance in detecting movement in their peripheral field of view. This is important for avoiding pinning and striking accidents. The second study was designed to quantify a subject's visual performance in detecting trip hazards located in their forward field of view. The third study was designed to obtain a subjective discomfort rating of the light sources used, as observed from two different points of view. The reaction times in detecting each hazard and the accuracy in which targets and objects were identified was recorded and documented as outlined in this paper.

B. Setting

1) HPRM: The experiment was conducted at the NIOSH Office of Mine Safety and Health Research laboratory in the Human Performance Research Mine (HPRM). The HPRM measures 21.25 m by 8.45 m and has a roof height of 4.67 m. The dimensions were selected to provide space consideration for large pieces of mining machinery and the data acquisition and control (DAC) systems required to conduct ongoing research efforts at NIOSH. The interior of the facility was painted a flat black color to closely match the color and reflectivity found in an underground mine setting. Proper labeling of exits and escape ways was among the safety precautions implemented to create an environment suitable for human subject testing.

2) Observation Station: NIOSH personnel designed and constructed the observation station, depicted in Fig. 1, to ensure that each subject was tested from a fixed position. This was developed in efforts to create a method of observation that was consistent for each of the 36 subjects tested, thus eliminating the possibility of confounding data due to variations in the subjects' point of view. This also allowed subjects to complete multiple studies, while remaining seated, to prevent being exposed to unnecessary risks in having to walk through a darkened facility to go from one study to the next.

Electronic actuators were installed to raise and lower the seat, as much as 20 cm, for the purpose of adjusting each subject's eye to a height of 165.1 cm. This height is equivalent to the 50th percentile standing male [2].

Subjects were required to wear a rigidly mounted hardhat to accommodate for variations in torso heights and to maintain a consistent head and cap lamp position. The helmet was equipped with ear protection that each subject was required to wear during testing. The observation station and all of its components were painted flat black to minimize any distractions or reflection of any light during the testing phase.

C. Light Sources

Area lights were installed on a continuous miner and were used to create four different lighting modes. These lighting modes were made up of a single light source or a combination of two lighting technologies that consisted of incandescent, fluorescent, or LED lights. While testing occurred on one side of the machine, lights were installed on both sides to closely simulate normal operation. The following four modes were used in each of the three studies.

1) Incandescent and LED Machine Lights: This lighting mode consisted of the incandescent area lights commonly installed on continuous miners with the addition of LED strips installed around the perimeter of the machine. The locations of these LED area lights is depicted by the rectangular bars on both sides and the rear of the continuous miner as shown in Fig. 2.

2) Incandescent Machine Lights Alone: Incandescent lighting mode consisted of the area lights commonly installed on continuous miners. The location of these lights is depicted by the rectangular shapes around the middle of the machine in Fig. 2.

3) Fluorescent Machine Lights Alone: Fluorescent lighting mode consisted of area lights installed on some continuous miners. These lights consist of two fluorescent bulbs encased in

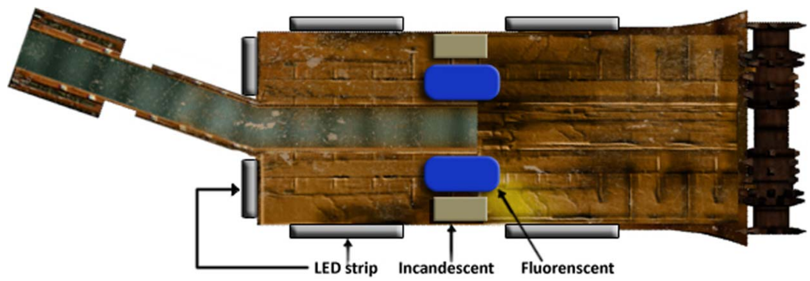

Fig. 2. Light source locations.

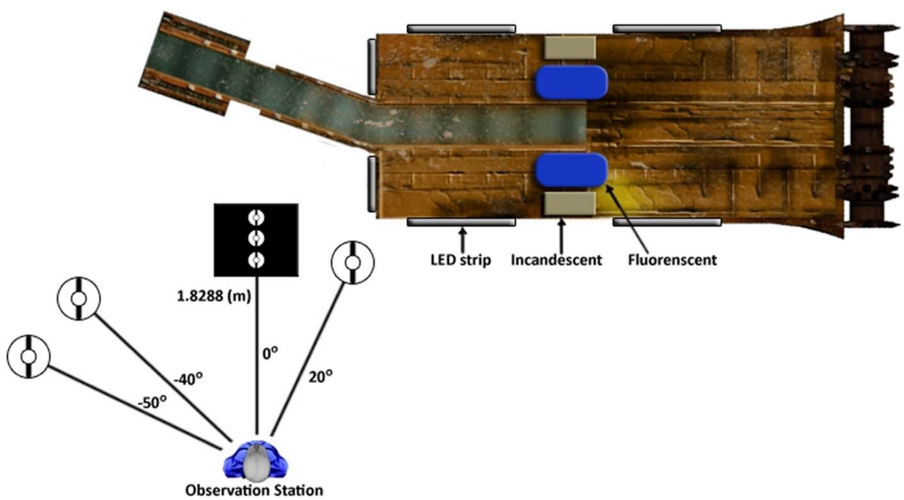

Fig. 3. Experimental layout for Study 1: peripheral motion detection (figure not to scale).

a hardened steel frame. The location of these lights is depicted by the octagonal shapes around the middle of the machine in Fig. 2.

4) Fluorescent and LED Machine Lights: This lighting mode consisted of the fluorescent area lights previously mentioned for lighting mode 3 with the addition of the LED strips installed around the perimeter of the machine. The locations of these LED area lights are depicted by the rectangular bars on both sides and the rear of the continuous miner as shown in Fig. 2.

D. Subjects

A total of 36 subjects were recruited from NIOSH personnel. Twenty-six males and ten females were selected based on their vision screening examination results performed by the NIOSH medical staff. Each subject underwent extensive screening for distance visual acuity, contrast sensitivity, color vision deficiency, and peripheral vision capabilities. Because one of the objectives of this experiment was to explore the visual performance, with respect to aging, three age groups were designated to accommodate age groups representative of the mining industry. Twelve subjects were recruited for each of the age groups: Group A was for subjects ages 18–25, group B was for subjects ages 40–50, and group C was for subjects 51 and above. The average age of the subjects tested was 42 years which was closely representative of the average age for a miner in the United States, which is approximately 43 years of age [3].

III. Experiment

A. Peripheral Motion Detection Study

1) Experimental Layout: The experimental layout for this study is depicted in Fig. 3. The system used for this study consisted of four major components operated by a DAC system. The main components of the DAC were a microcontroller, a flip-dot matrix, three circular targets connected to dc-powered motors, and a mouse. The system's input was controlled by each subject in the form of an electrical signal sent to the microcontroller when the mouse button was depressed. A depressed mouse button initiated the test sequence. The microcontroller was programmed with software developed to activate the flip-dot matrix, as well as control the sequence and duration of the circular target's rotation. This flip-dot matrix was used as a visual target to draw the subject's focus and fix their eye orientation to the center. This panel was located in the subject's forward field of view, at 0°, to ensure that each subject used their peripheral vision to detect the motion of the circular targets as opposed to 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 activated. The targets measured a total of 120 mm in diameter and were painted white with a single black line across the center. The circular targets, positioned at -50°, -40°, and 20° 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

TABLE I
AVERAGE TARGET ILLUMINANCE IN LUX

Target Position (degrees)	Incandescent & LED	Incandescent	Fluorescent	Fluorescent & LED
20	2.89	2.62	2.76	3.00
-40	1.96	1.50	2.11	2.58
-50	2.30	1.26	2.57	3.69

the noise by using ear protection and playing sounds of mining equipment in operation in the background. 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, which recorded all the pertinent data such as the lighting mode used, the software version used, the sequence in which the targets were rotated, and the subject's reaction time in detecting movement.

2) Illuminance Measurements: Illuminance measurements were recorded for the three circular targets as illuminated by each of the four lighting modes. The lights were left on for 10 min prior to taking light measurements to allow each light source to stabilize. For each target, three spot measurements were made using the Konica Minolta T-10 Illuminance Meter. The meter's sensor was attached flat against the circular target in each of three positions: top, middle, and bottom. The average illuminance measurements are recorded in Table I.

3) Procedures: This study consisted of five different trials, one of which was a practice session. Subjects were given instruction on the operations of the test apparatus before the practice session was initiated. The subjects were instructed to keep their eyes focused on the flip-dot matrix target in front of them during the duration of the study. They were handed a computer mouse and were briefed on its operation. Holding down the left mouse button initiated 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 the time elapsed from the time the circular target was initially activated to the time the subject released the depressed mouse button. A reaction time of 4.2 s or above would be recorded as a missed target. The remaining four trials were the actual test which consisted of the variation of the four lighting modes.

4) Result: Peripheral motion data were examined using a split–split plot design, with subjects as the replication factor, AGEGROUP as the main plot factor, LIGHTING was the split plot factor, and ANGLE was the split–split plot factor. The initial analysis of variance of the time to the detection of the stimulus was performed, but the plot of residuals versus fitted values was found to have a nonlinear trend; thus, the analysis reported employed a natural log transformation of the original time data. This transformation resulted in greatly improved behavior of the residuals. Alpha levels were set at 0.05.

Analysis using the log-transformed data demonstrated significant main effects due to AGEGROUP ($F_{2,22} = 5.19, p < 0.05$) and ANGLE ($F_{2,264} = 224.19, p < 0.001$). None of the other factors were found to be statistically significant; however, a trend was observed for both LIGHTING ($F_{3,99} = 2.20, p = 0.09$) and the AGE*LIGHTING interaction ($F_{6,99} = 1.98, p = 0.08$). Fig. 4 displays the effect of AGEGROUP on detection time using retransformed (i.e., original scale) data. The Dunn–Sidak multiple comparison test for the AGEGROUP effect indicated that only the young and older age groups differed significantly from one another ($p < 0.05$). The same post hoc test was used for the ANGLE effect, and results showed that detection time was significantly different for each angle studied, as depicted by Fig. 5.

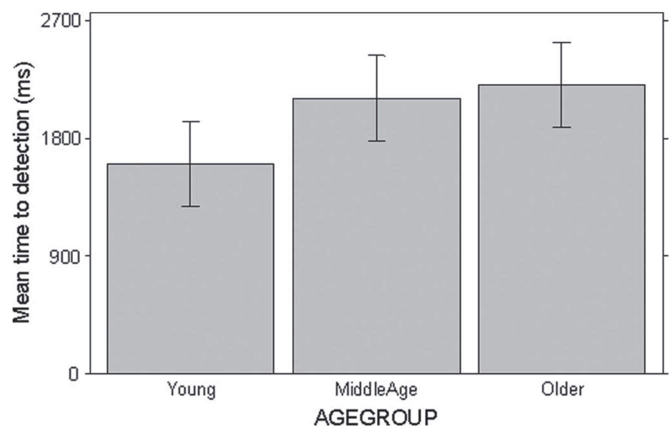

Fig. 4. Effects of age group on time.

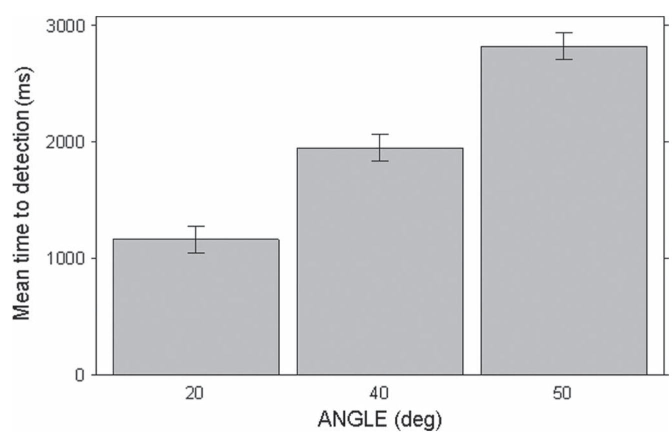

Fig. 5. Stimulus detection by target angle.

B. Trip and Fall Study

1) Experimental Layout: The general layout for this study is depicted by Fig. 6. A motorized curtain was installed 0.91 m in front of the observation station to prevent the subject from gaining an advantage of knowing the location of the objects while the researcher set the different pattern locations on the ground. Two location distances were established for this

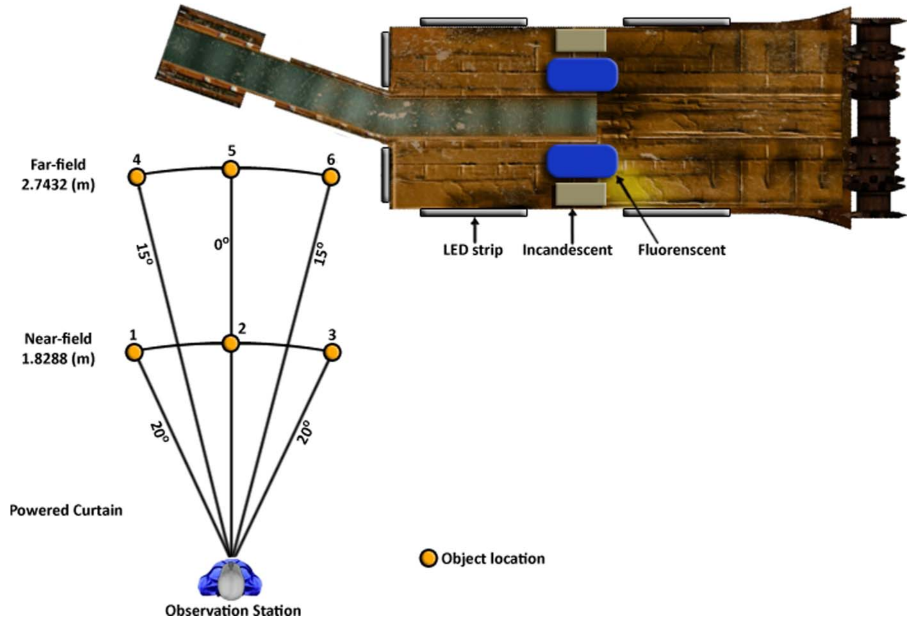

Fig. 6. Experimental layout for Study 2: trip and fall hazard detection (figure not to scale).

TABLE II
TRIP AND FALL OBJECT ILLUMINANCES IN LUX

	Incandescent & LED	Incandescent	Fluorescent	Fluorescent & LED
Object 1	2.93	0.87	0.85	2.41
Object 2	4.81	1.04	1.12	5.14
Object 3	5.76	0.86	0.94	5.82
Object 4	1.72	0.84	0.88	1.59
Object 5	1.93	0.87	1.04	2.03
Object 6	1.6	0.75	0.96	1.78

experiment: near field 1.8288 m, about the distance of two strides for the average male, and far field 2.7432 m which is a more common visual attention location for a walking person. Each object was 6.4 cm long with a 3.3-cm outer diameter. The objects were painted a dark color such that they would have a very low contrast (−0.11–0.09) and a reflectivity very similar to that of objects found in an underground mining environment. Because the objects were hard to detect, NIOSH personnel designed the objects to house battery-powered infrared LEDs to illuminate themselves when observed through a video camera's night mode but still remain difficult to detect by the subject's eyes.

The electrically powered curtain was connected to a timer circuit programmed to open and shut the curtain after 10 s. The 10-s span was visually displayed using a red LED, for curtain closed, and a green LED, for curtain opened. Each sequence was video recorded and postprocessed to determine the amount of time it took to find each object. The timing was calculated as the time elapsed from the instant the timer circuit switched from a red LED to a green LED to the instant the subject identified and pointed at each target with a laser pointer. A total of 11 object pattern location combinations were used in which the number of objects varied from two to four and the locations of the objects varied from near field to far field and to a combination of both.

2) Illuminance Measurements: Light intensity measurements were recorded for each of the six possible object locations as illuminated by each of the four lighting modes. The lights were left on for 10 min prior to taking light measurements to allow each light source to stabilize. The intensity measurements were made using the Konica Minolta T-10 Illuminance Meter. A single spot check was performed on each object by placing the meter's sensor flat against the cylinder while facing the observation station. The average illuminance measurements are recorded in Table II.

3) 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. A video camera was pointed at the ground which included a shot of the timer circuit. The purpose for this positioning was to identify the instant the timer circuit started, signified by the illumination of a green LED, to the instant the subject identified and pointed at a particular object on the ground. 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 automatically closed after 10 s, and the next object pattern combination was prepared. Each lighting mode trial consisted of four different

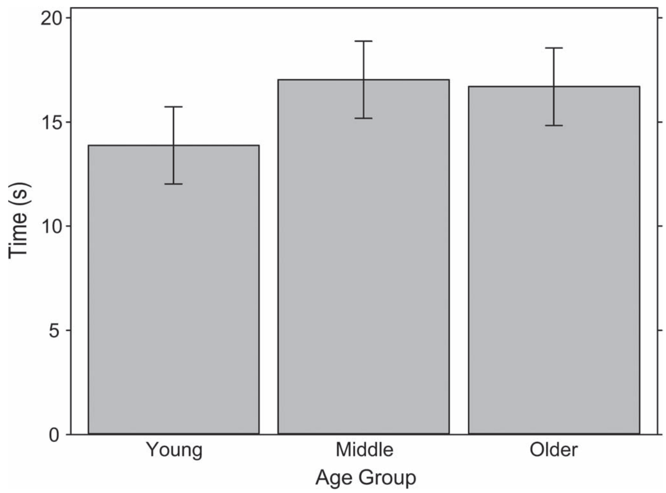

Fig. 7. Effects of age group on time.

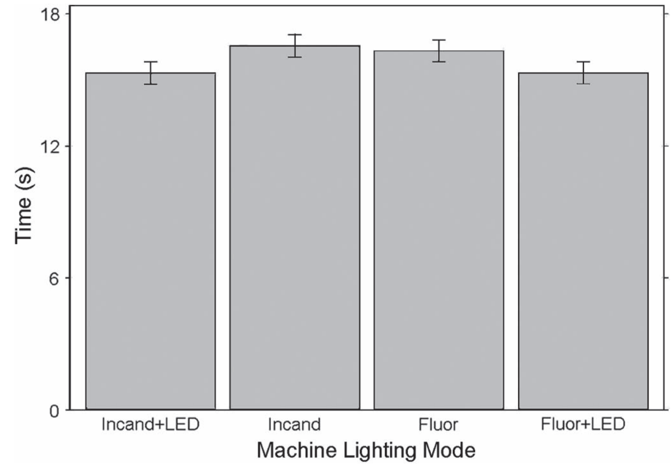

Fig. 8. Effects of lighting mode on time.

object patterns. The time to find each object and the time to complete all four trials for a given lighting condition were recorded. NIOSH personnel used video editing software to identify specific frames in which the subjects identified the objects and the corresponding time stamps associated with each object.

4) Results: Independent variables for this experiment consisted of AGEGROUP (three levels) and LIGHTING conditions (four levels). The three levels of AGEGROUP were young (ages 18–25), middle age (ages 40–50), and older (ages 51 and older). Twelve subjects were recruited for each age group for a total of 36 subjects. The four lighting conditions were as follows: 1) incandescent and LED machine lights; 2) incandescent machine lights alone; 3) fluorescent machine lights alone; and 4) fluorescent and LED machine lights. In addition, the subject wore a hardhat fitted with an incandescent cap lamp for all trials. The dependent variable was the total time (in seconds) it took for the subject to locate all objects on the floor in front of them.

A split-plot experimental design was used to analyze the data. Subjects were treated as the replication (whole-plot) variable, with AGEGROUP as the whole-plot factor and LIGHTING (randomized on a within subjects basis) constituted the split-plot factor. Alpha levels were set at 0.05.

Detection time of the floor objects was found to be significantly affected by the main effects of both AGEGROUP and LIGHTING. The interaction of AGEGROUP and LIGHTING was not significant ($F_{6,99} = 0.54, p > 0.05$). The sections as follows provide additional detail regarding the significant main effects.

a) Age group: Fig. 7 illustrates the influence of AGEGROUP on the time required to locate the floor objects. Age group was a significant factor in the ANOVA ($F_{2,22} = 3.48, p < 0.05$). A post hoc Dunn–Sidak pairwise comparison test indicated a significant difference between the young age group and the two older age groups in terms of the time taken to detect objects, with younger subjects detecting objects approximately 3 s faster than the older age groups on average. No differences in detection times were present between the middle age and older age groups ($p > 0.05$).

b) Lighting conditions: Differences in lighting also influenced the time to detect floor objects ($F_{3,99} = 6.92, p < 0.001$). Fig. 8 provides the detection time of the floor objects under each of the four lighting conditions. Dunn–Sidak post hoc analysis indicated that the two lighting conditions that consisted of LED lighting as the auxiliary source (the incandescent and LED and the fluorescent and LED conditions) resulted in detection times that were significantly faster (by approximately 1 s) than times achieved with the other two lighting modes (incandescent machine lights and fluorescent lights alone). There was no significant difference in detection time between these pairs of lighting conditions ($p > 0.05$).

C. Discomfort Glare Study

1) Experimental Layout: The experimental layout for the glare experiment is depicted in Fig. 9. The De Boers scale was used to obtain a subjective rating on the degree of discomfort experienced by subjects when exposed to the glare produced by each lighting mode. The De Boer's scale is a nine-point subjective scale where a rating of one was considered "unbearable" and a rating of nine was considered "just noticeable." This scale was printed and mounted onto the machine where the subject would be asked to focus their attention to. Two positions were selected for this study based on the positions that a continuous miner operator would generally stand during normal operations. Position #1 was toward the rear corner of the machine at a distance of 1.2192 m. Position #2 was located diagonally of the rear corner of the machine at a distance of 2.7262 m.

2) Procedures: The subjects were instructed to stand at Position #1 which was notably marked to ensure that each subject had the same point of view. They were warned not to look directly at the light sources to prevent impairing their vision prior to starting the study. They were instead instructed to look directly at the De Boer scale where the ratings were listed. Each of the lighting modes was then turned on, giving ample time for the light sources to stabilize prior to asking the subjects to rate the discomfort glare experienced. After going through the four different lighting modes, the subjects were then walked to Position #2 where the process was repeated. NIOSH personnel noted the rating and recorded any comments made.

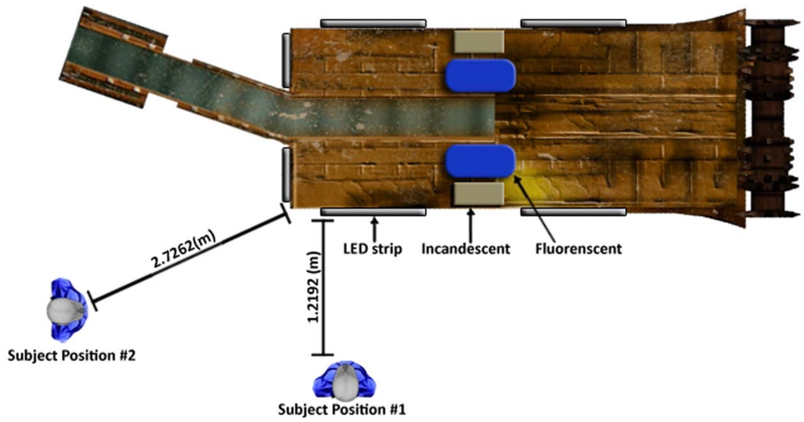

Fig. 9. Experimental layout for Study 3: discomfort glare (figure not to scale).

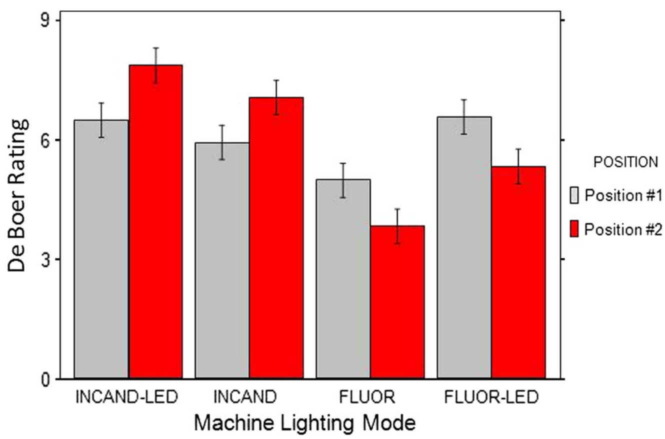

Fig. 10. Glare ratings by lighting and position.

3) Results: Subjective discomfort glare ratings were obtained using the De Boer scale (reference). A split–split plot experimental design was again employed, using subjects as the replication factor, AGEGROUP as the main plot factor, LIGHTING as the split plot factor, and POSITION as the split–split plot factor. It was assumed for the purposes of the analysis that the De Boer rating values represented equal gradations on the scale [4]. The interval difference between two discomfort glare ordinal ranks was considered to be of the same order of magnitude. Accordingly, the use of parametric techniques to perform the analysis can be employed [5]. Alpha levels were set at 0.05.

The ANOVA indicated the presence of an interaction between LIGHTING and POSITION $(F_{3,132} = 22.19, p < 0.001)$. This interaction is depicted in Fig. 10 as follows. As can be seen from this figure, glare ratings were higher for the incandescent lighting condition when positioned behind the machine, while glare rating for lighting conditions involving fluorescent lights were higher when positioned next to the machine. Fluorescent lighting conditions were generally associated with lower ratings of glare than incandescent conditions, and conditions using LEDs tended to have slightly greater glare ratings.

IV. Discussion

Overall, the results have indicated that age played a significant factor in visual performance as the younger age group produced average detection times that were as much as 27% and 18% faster than the older age group for the peripheral motion and tripping hazard studies, respectively. The results for both studies further indicated that lighting conditions also played a significant factor in visual performance. The lighting condition which consisted of both fluorescent and LED lights resulted in the fastest detection times for the peripheral motion study where the average detection times were between 12% and 14% faster than the other lighting conditions. The combination of fluorescent and LED lights provides more of the shorter wavelengths of visible light than any of the other lighting conditions. Prior NIOSH research indicated that lighting characterized by having more of the short wavelengths of visible light improved visual performance for peripheral motion detection [6]. This combination also provided the greatest average target illumination (Table I). Thus, the superior peripheral motion detection visual performance is likely to be the result of a combination of increased illuminance and having more of the short wavelengths of visible light. The lighting condition which consisted of incandescent and LED lights resulted in the fastest detection times for the tripping hazard study where detection times were between 6% and 7% faster than lighting conditions that did not include LED lights. However, the difference in average detection times between the lighting combination of incandescent and LED lights and the combination of fluorescent and LED lights was not statistically significant in the tripping hazard study. A given lighting combination did not consistently give greater target illuminances in this study as was the case for the peripheral motion detection study. The lighting combination of incandescent and LED lights and the combination of fluorescent and LED lights did provide much more target illumination compared to using only the incandescent or fluorescent area lights. Thus, the superior trip detection visual performance is likely to be the result of increased illuminance and having more of the short wavelengths of visible light.

The results of the comparative analysis conducted between lighting modes that consisted of LED lighting and those that did not provide important data for improving the design of lighting systems to improve mine illumination and, consequently, improve a miner's ability to perform their job safely. By increasing light levels, a miner can more easily detect moving hazards in his peripheral and forward fields of view and ultimately reduce his exposure to risks associated with pinning and striking and trip and fall injuries.

The implications of this paper focus on the concept that using LED lighting as an auxiliary source to increase illumination is noteworthy. As the past NIOSH research has shown, the use of spectral power distributions having more of the short wavelengths of visible light, as afforded by the use of cool white LED cap lamps, can improve visual performance in mesopic conditions [6]. It is with these benefits in mind that the research described in this paper indicates that the use of LED lights, as an auxiliary source of area lighting, would improve the visual performance of miners working around the perimeter of a machine. Future design considerations for lighting systems can be influenced by this concept, but there are caveats to be noted. Perhaps, more important than increasing illuminance levels around the machine is the lighting technology used, the location of the light sources, and the direction in which the light is emitted. The results from the discomfort glare study indicate that the fluorescent machine lights generally had De Boer ratings associated with higher levels of discomfort glare. This may be attributed to elevated illuminance levels that the light source was producing. The results also indicated that lighting conditions that consisted of LED machine lights had De Boer ratings associated with the least amount of discomfort glare, when experienced from position #1. While these results were expected, they did not hold true for all LED lighting combinations, when viewed from position #2. The results indicate that the incandescent lights alone resulted in lower levels of discomfort glare when compared to the fluorescent and LED lighting combination. This may be attributed to the way in which the light was being directed as the fluorescent light was mounted in such a way that emitted light back toward the area where the continuous miner operator would normally be standing (position #2). An important consideration in designing machine-mounted lights is the application of optics and shields to direct the light where needed, rather than emit it in every direction, to reduce glare. This is particularly important with light sources that are capable of producing illuminances that can impair a miner's vision enough to drastically reduce their ability to perform their job safely.

Another consideration is that of maintenance. Because this particular experiment only explored the use of LED lights as auxiliary lights, it is not within the scope of this paper to declare that LED area lights will produce vast improvements on visual performance in favor of other lighting technologies. However, past research exploring the power consumption and durability of LED lights, which generally translate to lower maintenance requirements, affords NIOSH personnel the ability to make the recommendation to consider the design and implementation of lighting systems using LED technologies. All things considered, the benefits of using LED area lights as auxiliary sources in existing lighting systems can result in improved illumination methods underground and increase mine safety and health.

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