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AN OVERVIEW OF NIOSH MINE ILLUMINATION RESEARCH: PAST, PRESENT, AND FUTURE

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ABSTRACT

Illumination is essential for mine safety because miners depend most heavily on visual cues to detect hazards associated with slips/trips/falls and powered haulage. The National Institute for Occupational Safety and Health (NIOSH) is conducting mine illumination research to improve miner safety by enhancing a miner's ability to see mine hazards. Thus far, 16 papers have been published covering diverse topics such as cap lamps, machine-mounted lighting, glare, lighting maintenance, and light-emitting diode (LED) technology issues. NIOSH has also developed an LED cap lamp, LED area lighting, and a Visual Warning System (VWS). This paper provides an overview of the improvements from NIOSH-developed lighting that include: 94% faster trip hazard detection with the NIOSH LED cap lamp; 79% faster peripheral motion detection to detect pinning/striking hazards; no increase in glare; 71% faster machine movement hazard detection with the VWS. Current research is described concerning an LED cap lamp for metal/nonmetal miners, illumination for refuge alternative deployment and inspection, and whether lighting could be used to improve miner escape and rescue in smoke. Lastly, future possibilities of using lighting to improve miner safety are described.

INTRODUCTION

For as long as underground mining has been performed, illumination has been essential to both safety and to the ability of the miners to perform their work. This is especially easy to understand given that 80% of perception is visual (Yarbus, 1967). Open flames were used from the earliest days of mining. Carbide lamps were developed in the 19th century and were used well into the 20th century. During the early 1900s the new technology of electric lighting began making its way into underground mines in the United States. Safety was the primary driver of electric lighting given the pervasive occurrences of explosions caused by mine gas ignition. During 1917, the incandescent (INC) Edison cap lamp was approved by the U.S. Bureau of Mines (Clark and Ilsley, 1917) which had a rich history of mine illumination research that dates to 1910 (Sammarco and Carr, 2010a). The new electric cap lamps gained acceptance and eventually replaced the older lighting technologies. Today, the newest lighting technology is the light-emitting diode (LED), and it is poised to revolutionize mine illumination. High-brightness LEDs are achieving up to 149 lm/W in comparison to about 15 lm/W for an INC bulb. LEDs are robust because they do not have a glass envelope or a filament that can break, and they can provide useful light in excess of 50,000 hours of operation as compared to about 1,000 to 3,000 hours for an INC bulb. The longer life and robustness of LED lighting systems can potentially reduce the frequency of mining injuries associated with maintenance, repair, and the catastrophic lamp failures occurring during operation (Yenchek and Sammarco, 2010). LED cap lamps have been compared to INC cap lamps to better understand the technology and to ensure proper application of LEDs for mining; specifically, the performance of LED and INC cap lamps were compared in terms of correlated color temperature, color rendering, light output, electric power, ambient temperature and air flow, and light source aging (Sammarco et al., 2009d). The results indicate the superiority of LEDs compared to INC light sources used in cap lamps.

In general, lighting can influence the performance of people in the industrial workplace by way of ten mechanisms that include visual performance, visual comfort, visual ambience, interpersonal relationships, job satisfaction, and problem solving (Juslén and Tenner, 2005). For the mining industry, miners depend most heavily on visual cues to see hazards associated with falls of ground, slips/trips/falls (STFs), moving machinery, and other hazards (Cornelius et al., 1998). These hazards pose substantial risks to miners. Mine Safety and Health Administration (MSHA) accident data for 2007-2011 indicate that slips, trips, and falls (STFs) are the second leading accident class (18.9%, n=2,301) of nonfatal lost-time injuries at underground mining work locations (MSHA, 2007-2011). For this period, STFs resulted in 141,960 total days lost from work. Pinning and struck-by accidents also occur frequently. An MSHA report (Colley et al., 2006) on remote-controlled continuous mining machine (CMM) accidents indicated that pinning and striking fatalities were increasing, with 12 fatalities between 2000 and 2004 compared to 17 fatalities between 1984 and 1999. Another MSHA report (Dransite and Huntley, 2011) indicated that 33 fatalities involving a CMM occurred from 1984 to March of 2011.

Age is an important factor in relation to a miner's ability to see mine hazards. With increased age can come decreased visual abilities, particularly in the low light conditions of a mine, thus making it more difficult to see mine hazards. NIOSH human subject testing of visual performance has indicated that age is a significant factor given the visual environment of a mine and the associated lighting from cap lamps and machinery (Sammarco et al., 2009a, 2009b, 2009c, 2010b; Reyes et al., 2009, 2011). A national survey of the mining workforce indicated that the average miner age is 43.3 years (McWilliams et al., 2012). As the mining workforce ages, the need for effective underground lighting becomes even more important for miner safety. Vision deteriorates with age. Physiological changes include reduced light to the retina because of reduced pupil size that reduces the field of view, a yellowing of the eye lens which reduces light to the retina, reduction in the amount of rod photoreceptors that play a dominant role in vision as light levels decrease, and more sensitivity to glare (Harvard Health Letter, 2006). Crouch (1982) reported that 78% of the miners interviewed complained or questioned the lighting systems relative to discomfort and disability glare, veiling reflections, and afterimages. From the study results, Crouch estimated that miners working within the existing illuminated coal mining face environments could experience as much as a 40% or more loss of visibility from glare. Finally, cap lamp research for a simulated coal mining visual environment indicated about a 50% increase in discomfort glare for subjects over 50 years old as compared to a group of younger subjects with a mean age of 22.6 years (Sammarco et al., 2009a).

This paper presents a summary of NIOSH mine illumination safety research for machine-mounted lighting, LED cap lamps, and lighting effects on the physical body. It also presents current research on an LED cap lamp for metal/nonmetal miners, illumination for refuge alternative deployment and inspection, and whether lighting could be used to improve miner escape and rescue in smoke. The results presented in this paper were from controlled human subject testing in the NIOSH mine illumination laboratory unless otherwise stated. Age was a factor in this research as well, so the following age categories were established: young (18-25 yrs.), middle (40-50 yrs.), and older (51+ years). The age group from 26 to 39 years was not used because there are generally minimal changes in vision for those ages (Blanco et al., 2005). Volunteers that had radial keratotomy, monocular vision, glaucoma, or macular degeneration were excluded. Only the volunteers that passed vision tests for distance visual acuity of 20/40 or better, contrast sensitivity of 1.72 to 1.92 values of log contrast sensitivity, the absence of color vision deficiency, and peripheral vision of at least 80˚ for each eye were accepted for the studies.

MACHINE-MOUNTED LED LIGHTING

Area lights

Underground lighting installed on mobile machinery is used to illuminate work areas for the machine operators. Headlights are used to improve visibility in the direction of travel, while flood-type lights provide illumination around the machine periphery. A continuous mining machine (CMM) is one example where flood-type lighting is installed on each side of the machine. This area lighting can help miners see moving machinery and STF hazards. Increasing the light output can improve the ability to see these hazards.

NIOSH researchers conducted a comparative study of visual performance using INC, fluorescent, and LED lighting technologies to create area lighting combinations (Figure 1) (Reyes et al., 2009). Visual performance was quantified for the detection of movement in the peripheral field of view and the identification of tripping hazards. Measurements were made of the speed and the accuracy of detecting these hazards. Additionally, the effects of age on visual performance were investigated. Overall, the results indicate that age played a significant factor in visual performance as the young age group produced average detection times that were as much as 27% and 18% faster than the middle and older age groups for the peripheral motion and tripping hazard studies, respectively. Lastly, the results indicated that lighting conditions also played a significant factor in visual performance. The lighting combination of 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 for the other lighting conditions, and trip hazard detection improved between 6% and 7%.

Figure 1. A CMM with standard lighting (top) compared to with NIOSH LED lighting (bottom).

Visual warning system

The VWS was conceived as a safety intervention to reduce struck-by or pinning accidents involving moving machinery such as a CMM. The VWS visually alerts miners that the machine is about to move and it indicates the type of machine movement such as forward or reverse, turn right or left, pivot right or left, and conveyor swing right or left. It can be a stand-alone system or be used to provide visual warnings for a proximity warning system.

The VWS luminaires were strategically placed about the machine's perimeter (Figures 2 and 3). The VWS identifies the impending machine movement based on the machine control inputs and selects the appropriate luminaires for the machine areas that could pose a struck-by or pinning hazard. Next, it activates the red warning lights in those hazardous machine areas to improve machine visibility and indicate the type of machine movement.

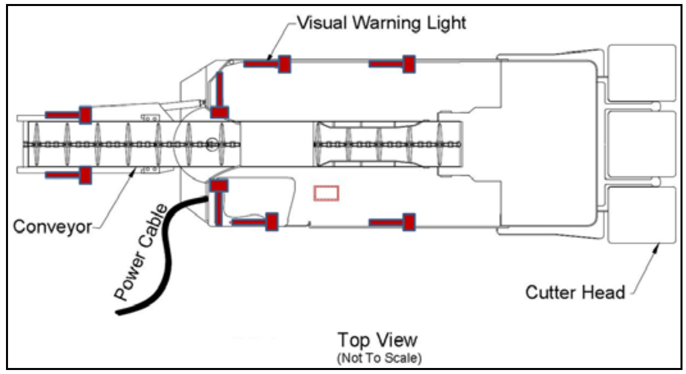

Figure 1. The VWS has LED-based lights placed at the machine perimeter. Shown is the VWS laboratory version used for human subject testing. The VWS field version uses four light units.

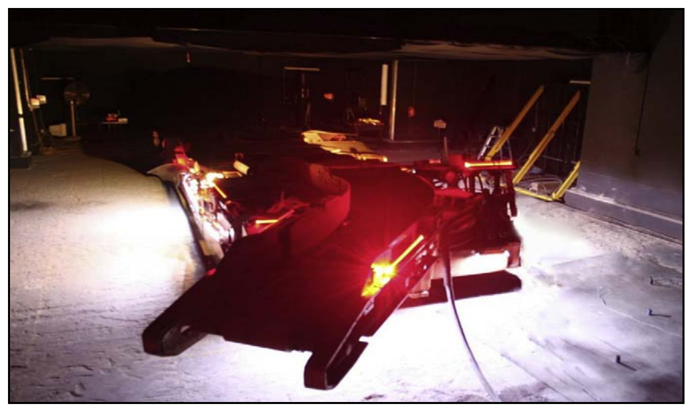

Figure 3. The visual warning system installed on a CMM. The red warning light indicates that the conveyor is going to swing to the right.

Human subject testing was conducted using the VWS. The improvements in machine movement detection when using the VWS were dramatic (Sammarco et al., 2012). For instance, for forward and reverse CMM movements, the average detection time for the no-lighting condition was 1.96 s while the average for the flash VWS mode was 0.49 s.

This distance traveled is significant especially when considering the confined spaces of a mine. The most dramatic time difference results were with the machine pivots, where the average detection time for the no-lighting condition was 2.23 s, while the average for the dynamic VWS mode was 0.47 s. During this 1.76-s difference, the CMM would pivot 5.63º given the pivot rate of 3.2º/s. To give context to the importance of these results, our analysis of the 33 fatalities documented by MSHA (Dransite and Huntley, 2011) indicated that 30 fatalities involved machine forward, reverse, or pivot movements.

CAP LAMP LIGHTING

NIOSH conducted LED cap lamp research in two phases, where the first phased focused on enhancing the color of light to improve visual performance, especially for older workers. The second research phase focused on the lighting distribution such that floor and moving machinery hazards received more light to improve visibility.

Phase I: Light color

In general, as a person's age increases less light reaches the retina. One method to address this is to increase illumination; however, this has the negative effects of increasing glare and decreasing the availability of battery power for battery-powered lighting such as cap lamps. Our approach to address age-related issues was to manipulate the visible light color spectrum of a cap lamp so that the light is perceived brighter although the luminous flux is the same as measured by mesopic photometry. At low-light (mesopic) ambient conditions found in underground mining, an increased short-wavelength spectral content can improve visual performance because the eye is more sensitive to short wavelengths of visible light. Prior research findings indicated that visible light having more short-wavelength energy enables improved detection of off-axis objects when the visual environment is mesopic (He et al., 1997; Van Derlofske et al., 2005; Bullough and Rea, 2000). NIOSH developed an LED cap lamp that used cool-white LEDs that emit more of the short wavelengths of light as compared to warm-white LEDs or INC lights. Cool-white LEDs have more short-wavelength energy thus giving the appearance of bluish-white light versus traditional warm-white INC bulbs that emit a yellowish light and have more longer-wavelength energy. There are categories of white available for LEDs such as warm-white, neutral-white, daylight, and cool-white.

The results of a comparative study using an INC cap lamp, a commercially-available LED cap lamp, and a NIOSH prototype LED cap lamp indicated significant improvements for older subjects when using the NIOSH prototype LED cap lamp. Moving hazard detection improved 15.0%, trip hazard detection improved 23.7%, and discomfort glare was reduced 45.0% (Sammarco et al., 2009c, 2010b).

Phase II: Light distribution

The lighting distribution from cap lamps has traditionally been provided by a single, primary light source along with a circular optical reflector to direct light to a circular spot ranging from about 6˚ to 10˚ as depicted by Figure 4 (left photo). This is very similar to a flashlight—a design approach unchanged since the 1914 Edison cap lamp. This spot beam provides a tunnel vision visual environment that limits peripheral vision given that it provides very little illumination of the floor or mine ribs. To address this issue, NIOSH developed a prototype LED cap lamp having a radically different beam distribution as depicted in Figure 4 (right photo). This cap lamp has multiple, phosphor-white LEDs as the primary light source along with secondary total internal reflection 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 STF 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 the required photometric requirements (CFR, 2005). The cap lamp beam distribution and intensity are software controlled. This enables the flexibility of matching the cap lamp lighting to the task at hand which varies considerably. For instance, the visual needs vary between a roof bolt operator and a mechanic. Currently, cap lamps have a "one size fits all approach" where an intense, tight spot beam is provided regardless of the visual task.

NIOSH researchers conducted the investigation by comparing two commercially-available LED cap lamps and a NIOSH prototype LED cap lamp at varying power settings. The cap lamps had similar spectral power distributions; thus, the visible light color was not a factor for the visual performance of hazard detection. Visual performance was quantified by measuring times of detection for finding rotating targets in the peripheral field of view, which is important for detecting moving machinery hazards and trip and fall hazard objects on the floor.

Results show that the NIOSH prototype LED cap lamp improved the ability to perceive objects in the visual field by improving peripheral motion detection times by as much as 79.5% and up to 94% faster trip hazard detection, no increase in discomfort glare, and using up to 50% less power compared to commercially available LED cap lamps (Reyes et al., 2011) (Sammarco et al., 2011).

LIGHTING AND THE PHYSICAL BODY

Balance

Lighting can influence the performance of people in the industrial workplace by way of ten mechanisms that include visual performance, visual comfort, visual ambience, interpersonal relationships, job satisfaction, and problem solving (Juslén and Tenner, 2005). Poor lighting and reduced visual feedback decreases detection of STF hazards and has also been shown to decrease postural stability, increasing one's risks for falls (Brooke-Wavell et al., 2002). Therefore, an initial investigation involving human subjects was conducted to determine if cap lamp lighting significantly influences measures of static postural stability (displacement and velocity of center of pressure).

Figure 4. Illumination from a traditional LED cap lap (left) and from the NIOSH LED cap lamp (right).

Subjects were tested for balance in addition to visual screening tests. Only subjects who passed balance and visual screening tests were accepted for the study. The balance screening tests consisted of horizontal gaze nystagmus, walk and turn, one-leg stand, and Romberg tests (Khasnis and Gokula, 2003; Tharp et al., 1981). First, baseline balance measurements were collected given the lighting conditions found in a laboratory environment. The data were collected as a subject stood on a force plate (ACCUGAIT, Advanced Mechanical Technology, Inc., Watertown, MA). Next, testing was conducted in the NIOSH Safety Research Coal Mine (SRCM). A force plate was embedded into the mine floor flush with the walking surface of the mine. From the force plate, an un-obstructed view of 287.7 m (944 ft) could be seen down an entry that had a nominal width of 3.2 m (10.5 ft). All mine light sources were turned off during testing with the only light source coming from the cap lamp being tested. Three cap lamps were used. Two of them were commercially available and used a single phosphor-white LED as the primary light source, along with an optical reflector to direct the light to a circular spot beam ranging from about 6˚ to 8˚. The NIOSH LED cap lamp was the third cap lamp.

Results of this investigation showed no statistically significant differences in the balance measures of interest among three LED cap lamps tested. However, balance was shown to significantly decline ($p < 0.05$) when tested in the SRCM compared to the laboratory baseline testing condition. A significant limitation of this initial investigation concerned the nominal entry width of 3.2 m (10.5 ft), which is about half the width of entries commonly encountered in contemporary room-and-pillar coal mines in the U.S., where the width is typically about 6.1 m (20 ft). The SRCM dates back to 1910, when the majority of the mining was conducted by older mining techniques that used drills, cutting bars, and explosives to mine the coal. The mine wall illumination depends on the distance from the light source to the mine wall, where the illumination varies according to the inverse square law. Thus the wall illumination in a typical room-and-pillar coal mine would decrease by a factor of four given a mine width of 6.4 m (21 ft). This would reduce the illumination to below that provided, for instance, by a full moon on a clear night. It is unknown if this reduced illumination would negatively affect the usefulness of the wall as a visual frame of reference thus affecting the balance measures of interest. Previous research has found that restricting peripheral vision (through wearing personal protective eyewear) is likely to affect balance negatively, and this may be comparable to walking in an area with dimly illuminated walls (Wade et al., 2004). Additional research is needed to address this potential issue.

Head tilt and walking speed

The primary objective of this research was to determine if the light beam distribution from the NIOSH LED cap lamp affected average walking speed or head pitch. We inferred that as floor illumination increased, walking speed would increase and head pitch would decrease — i.e., the better that miners can see the floor, the faster they can walk and the less they need to pitch their heads down to illuminate the floor with their cap lamps. Less head pitch down can enable a better forward field-of-view so that miners can see hazards in front of them.

A pilot experiment was conducted at an underground mine site and was followed by a more in-depth testing in a laboratory that limited or eliminated several environmental factors present in the field study. Two types of LED cap lamps were used: a corded LED cap lamp and the NIOSH LED cap lamp developed during phase II research. Each subject wore an instrumented hardhat fitted with a 6-axis, wireless inertial measurement unit that transmitted data to a laptop computer. All test subjects were instructed to walk a path marked with green reflective floor tags placed approximately half a meter apart. While following the path on the floor, subjects were also to locate seven wall-mounted targets distributed along the path.

The field test results indicated a 2º decrease in head tilt when using the NIOSH LED cap lamp. While this improvement appears small, it translates to a significant extension of 0.46 m (18.1 in) for the line-of-sight intersection with the floor, while laboratory test data indicated about 5.4º decrease in head tilt when using the NIOSH LED cap lamp (Patts et al., 2012). This translated to a line-of-sight intersection with the floor of about 0.97 m (38.2 in) as depicted by Figure 5. The line-of-sight was determined from computer simulations. The actual eye fixation points are unknown but could be measured by using eye tracking instrumentation.

Field test data indicated no difference in walking speed; however, laboratory data indicated a small but statistically significant increase in walking speed when using the NIOSH LED cap lamp.

Because the field environment was an actual production coal mine, the conditions were less than ideal and difficult to control (e.g., variable roof height, excessive water, and dust on the floor). Roof height was a major issue given that the roof undulated significantly, causing some of the taller miners to occasionally stoop or bend their head to the side in order to avoid hitting their head. Thus the head pitch and walking speed data were affected by these conditions. Overall, we inferred from the data that NIOSH LED cap lamp light distribution more positively affects head tilt and walking speed by providing better illumination.

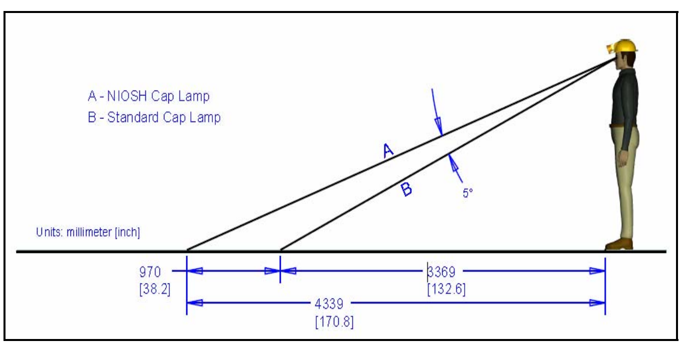

Figure 2. Laboratory data line-of-sight comparison between the NIOSH LED cap lamp (sight line A) and the Standard cap lamp (sight line B) for a 50th percentile male. The horizontal sight line range increases 0.97 m (38.2 in) when using the NIOSH LED cap lamp. Distance units are meters [inches].

CURRENT AND FUTURE RESEARCH

Metal/nonmetal LED cap lamp

The latest research addresses the unique needs for metal/nonmetal mining where the visual environment and visual tasks are different compared to coal mining; hence, an LED cap lamp for metal/nonmetal miners is being developed. The cap lamp builds upon the knowledge gained during NIOSH research phases I and II as well as feedback obtained during various metal/nonmetal mine field trips. The cap lamp is a hybrid that combines the multi-beam distribution with an intense spot beam (Figure 6) useful for distance viewing such as needed for inspecting a stope or a limestone roof that could be 9.2 m (30 ft) or more high.

Figure 3. Comparison of spot beam intensity between a cordless LED cap lamp (left) and the NIOSH metal/nonmetal LED cap lamp (right).

Self-escape and rescue lighting

Underground miners use various visual cues to help them escape from a smoke-filled mine, and these same visual cues are used during rescue. The Code of Federal Regulations (CFR) Title 30 Parts 75.380 and 75.381 require that there be at least two separate and distinct travelable passageways as escape ways that are clearly marked to show route and direction of travel to the surface (CFR, 2010). The color, size, and spacing of the escape way markers are not specified so they vary significantly among mines. Typically, primary and secondary escape ways are marked with reflective ceiling tags of various colors. Miners also look for mine rail tracks as a visual cue for escape and rescue. To date, there has not been mine illumination research to scientifically determine the visibility of escape cues in smoke conditions; thus, the purpose of this research was to determine which color ceiling tag (red, blue, and green colors) is easest to see in a smoke environment using different cap lamps (LED and INC) and different color lasers (red, blue, and green). Also, the same cap lamps and lasers were used to detect a rail track section. Three cap lamps were used: an INC, a commercially-available LED, and the phase II research NIOSH LED cap lamp. Class IIIa laser diode light sources were used separately to illuminate the tags and rail. All lasers were low power (< 5 mW output) and had the following peak wavelengths: green = 532 nanometers (nm), red = 650 nm, and blue = 405 nm.

Human subject testing was conducted at the NIOSH Mine Illumination Laboratory (MIL) in Pittsburgh. Because age is a factor in illumination research, the subjects were grouped into three age categories. The MIL contains a smoke chamber and the associated test apparatuses to conduct mine illumination research in a simulated, smoke-filled environment. The smoke chamber was sealed from the outside air to contain the simulated smoke. It was also constructed to isolate the human subjects, and the researchers conducting the testing, from the smoke during the testing; thus, the human subjects were in a fresh air environment with no direct contact of their eyes with the smoke which could have caused eye irritation. A transparent window located at one end of the chamber (right side of Figure 7) enabled the subject to see into the smoke-filled chamber. Test apparatus located inside of the smoke chamber included red, blue, and green ceiling tags on a continuous chain loop mounted to the ceiling and a moving section of track on the floor. The ceiling tags and track travel towards the human subjects in the smoke to mimic the person walking (0.91 m/sec (3 ft/sec)) through a mine. Theatrical smoke was used to simulate smoke from a mine fire. Smoke density was controlled via a closed-loop control system that used an optical density sensor.

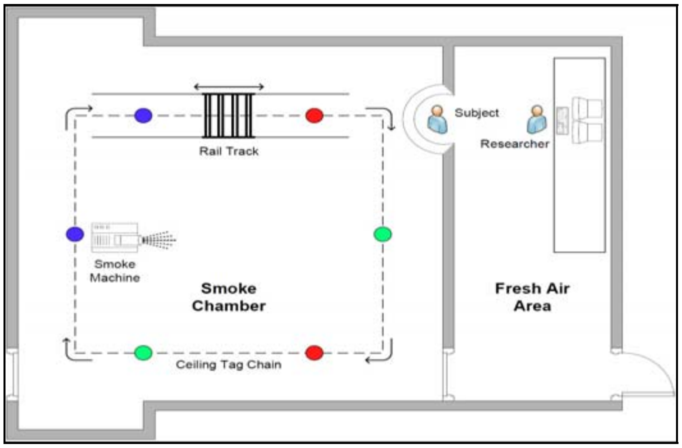

Figure 4. Floor plan of the Mine Illumination Laboratory smoke chamber.

Subjects were instructed to stand at the clear window of the smoke chamber (Figure 7) and place their chin on a chin rest so as to enable a consistent field of view among the subjects. One subject at a time was tested. Each subject used a handheld, pushbutton device to start and stop the tests. The subjects depressed the pushbutton to start the test and released it when they detected a target (ceiling tag or rail track) approaching them in the smoke. The data acquisition system of the test apparatus then measured and recorded the detection distance between the subject and the detected object. This detection distance was used to determine visual performance where the greater distances indicated better visual performance.

Results of this study indicate rather complex relationships among the cap lamps and lasers used in smoke conditions, the type of target being detected, and the age group performing the tasks. However, while several interactions were present for many of the comparisons tested, a number of important findings can be gleaned from this study. Cap lamps were superior to lasers in all circumstances of ceiling tag detection with the exception of when using the green laser. The INC cap lamp worked best in the simulated smoke compared to the LED cap lamps for the youngest subjects when detecting the rail track; however, this benefit was not observed for the two older age groups. The INC cap lamp's color-corrected temperature is indicative of a warm-white light which will result in better color rendition that could have been apparent to only the youngest subjects. The green laser was the best color for detecting the ceiling tags and rail track compared to the red and blue lasers. The green ceiling tags were the easiest color to detect, followed by red then blue. On average, the track was easier for the subjects to detect than the ceiling tags, where the average detection distances were 2.50 m (98.48 in) and 1.88 m (73.90 in), respectively.

While several important findings emerged from this research, several limitations existed. The theatrical smoke used for the testing was a white-colored smoke which could differ from the smoke generated by some mine fires. Further, variations in the smoke due to density, particulate size, reflectivity, and color would differ from actual mine fires. Secondly, the three ceiling tag colors were selected because they are commonly used in mines. Twelve tag colors are available, so it is unknown if another color may prove to be better than green.

The potential impacts of this research could lead to new cap lamp designs and a standardization of ceiling tag colors that are the most visible in smoke. These impacts could improve miner safety and the knowledge gained could potentially cross over to benefit others such as firefighters. More research is needed given the importance and complex scientific nature of this research.

Refuge alternatives

All underground coal mines are required to provide refuge alternatives within a particular distance of the working face and at additional locations outby the faces. It is required by CFR Title 30 Part 75.1506, "Refuge Alternatives," that "At all times, the site and area around the refuge alternative shall be kept clear of machinery, materials, and obstructions that could interfere with the deployment or use of the refuge alternative [and that] The operator shall protect the refuge alternative and contents from damage during transportations, installation, and storage" (CFR, 2010). Therefore, the deployment, use, and maintenance of refuge alternatives must be addressed.

Visual inspection is used to detect and recognize hazards and conditions that could damage the refuge alternative. A miner's cap lamp is used for illumination during visual inspection; however, the cap lamp is ill-suited for the required visual tasks given the intense spot beam provided. Wide area lighting would better suit the visual inspection of the site and area around the refuge alternative. This inspection occurs on a regular basis as well as during placement. Thus NIOSH researchers are investigating auxiliary lighting that can illuminate large areas such as the mine roof. Figure 8 depicts the roof illumination for a 6.1-m-wide (20-ft-wide) entry as provided by a prototype LED area light. The prototype LED area light requires about 4 watts of power and occupies a space of 101.6 mm x 76.2 mm x 101.6 mm (4 in x 3 in x 4 in), thus enabling portability.

Figure 5. Illumination provided by prototype LED area light for visual inspection of refuge alternative sites. The illumination can also be directed to illuminate the floor area. The distance to the person pictured is about 9.1m (30 ft).

Gait study

Our prior research concerning balance was conducted because it factors into one's risks for falls (Sammarco et al., 2012). Balance was measured under static conditions with the test subjects standing still while looking down a narrow entry in the SRCM. The research results merited further investigation; therefore, we are conducting a gait study to explore the measures of a person's dynamic stability in an actual underground mine. Dynamic stability will be measured through kinematic variables including head angle and trunk acceleration during walking down a coal mine entry that is nominally 6.1 m (20 ft) wide. This width will enable us to overcome the limitations of having a narrow entry. We expect that the new dynamic stability data will enable greater insights into one's risks for falls, and this new gait study will overcome the narrow entry limitation of our prior research.

Eye-tracking study

Our prior research on head tilt and walking speed determined line-of-sight via computer simulations. We have recently acquired eye tracking instrumentation that enables accurate determination of the eye fixation points during various test conditions. Therefore we are conducting an eye tracking study to determine how the cap lamp lighting distribution affects where a person looks. The eye tracking instrumentation will be used as subjects detect trip hazards located on the floor in their forward field of view much like the prior research that was conducted for trip hazard detection (Sammarco and Lutz, 2011;

Sammarco et al., 2010b). Two types of LED cap lamps will be used: the NIOSH LED cap lamp developed under phase II research and the new metal/nonmetal LED cap lamp developed by NIOSH. Thus, in addition to collecting eye tracking data, we will be able to better evaluate the visual performance afforded by the new metal/nonmetal cap lamp for trip object detection.

Potential future research

Our research has focused on improving illumination to enhance a miner's visual response to hazards, particularly STF and struck-by/pinning hazards. This research is unique in that it addressed an underlying factor to accidents—namely, a miner's ability to see and avoid mining hazards. Our more recent illumination research moves beyond the visual response to a physical response to illumination in terms of head tilt, static balance, gait, and eye position all of which have underlying factors for STF and struck-by/pinning accidents. One potential new area of research concerns the biological response to illumination. This presents another novel approach to improving miner safety, especially for those involved in rotating shifts, night shifts, and extended work hours. Shift work is commonly encountered in coal and metal mines. A recent mining survey indicated that 56.1% of underground coal mines operate two shifts per day for production workers with an average of 46.9 hours worked per week; 74.2 % of underground metal mines operate two shifts per day for production workers with an average of 40.0 hours worked per week (McWilliams et al., 2012).

Shift work disrupts the sleep/wake cycle, specifically the human circadian system, which can result in poorer quality and shorter duration of sleep (Fischer et al., 1997; Roach et al. 2003). This can lead to impairments in alertness and cognitive performance in terms of reaction time and decision making (Dorrian and Dinges, 2005; Harrison and Horne, 2000). In general there can be associated safety risks to shift work and night shift workers (Akerstedt et al., 1994; Dinges, 1995). A mining study that focused on accidents involving equipment operation found that accidents occurring during night shift were significantly more severe than on the other two shifts, suggesting work performance during night hours as being relatively impaired, perhaps due to lowered levels of cognitive performance (Wagner, 1988). Hence, a potential new research area would address the use of short wave light to shift the human circadian system and improve cognitive performance, which could enable a reduction of shift work accidents.

CONCLUDING REMARKS

Improving the safety of miners through better illumination was and continues to be the main goal of NIOSH illumination research. Our specific aims were to reduce STFs and struck-by/pinning accidents in mining as well as reducing glare and addressing the visual needs of an aging workforce. Our approach was two-fold: use scientific methods for designing and conducting human subject tests that enabled quantification of the effects of improved illumination; secondly, develop lighting that could improve a miner's visual performance for hazard detection as compared to commercially available lighting for the mining industry. The results of the visual performance comparisons among various 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. It is apparent that LED technology, if properly used, has the potential to improve safety by improving visual performance with respect to detecting mine hazards. It is also apparent that LED technology has other benefits such as longer life and robustness that can potentially reduce maintenance costs and the frequency of mining injuries associated with maintenance, repair, and catastrophic lamp failures occurring during operation. The results of the machine-mounted lighting testing indicated significant visual performance improvements for detecting hazards when using the VWS and LED area lighting.

Our research indicates that lighting affects more than visual performance; it can affect physical body movements and positions that could enable better hazard recognition and potentially improve balance to decrease the likelihood of a fall. We continue to explore these areas in our current research concerning eye tracking and gait. Our current research is also addressing visual detection in smoke conditions and improved visual inspection for refuge alternatives.

Illumination is essential to mine safety, and it can affect a large variety of safety areas as evidenced by the diversity of our mine illumination research. Much has been learned and much advancement in mine illumination has been realized; however, there remain many more opportunities to improve miner safety by enhancing a miner's visual, physical, and biological responses to light, and more opportunities for improvement will continue given the rapid pace of LED technology developments.

DISCLAIMERS

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