Evaluation of glare for incandescent and LED miner cap lamps in mesopic conditions

J. SAMMARCO, A. MAYTON, T. LUTZ AND S. GALLAGHER

J. Sammarco, A. Mayton, T. Lutz and **S. Gallagher** are senior research scientist, lead research scientist, lead research scientist and senior research scientist, respectively, with the Pittsburgh Research Laboratory, National Institute for Occupational Safety and Health (NIOSH), Pittsburgh, PA.

Introduction

The Illuminating Engineering Society of North America (IESNA) cites the working face of an underground coal mine as the most difficult environment in the world to illuminate (Rea, 1993). It is a dynamic environment that includes dust, confined spaces, low reflective surfaces, low visual contrasts and glare. Lighting is critical to miners who depend heavily on visual cues to spot fall of ground, potential machinery-related pinning and striking incidents, and slipping and tripping hazards (Cornelius et al., 1998).

Glare can be defined as the sensation from an uncomfortably or painfully bright light within a person's visual field. Glare occurs from too much light and extremes that produce too broad a range of light levels compared to those for which the eyes are adapted. The effects of glare on workers include discomfort glare (annoying or painful sensation), disability glare (reduction of visibility), recovery or re-adaptation (visual performance returning to initial state) and photobiological (optical radiation effects on living systems). To assess visual performance, one must consider distinct parameters associated with the glare produced, the environment and the observer. The aspects of glare that affect visual performance include illuminance at the eye, angle of the glare source, luminance and size, spectral power distribution (SPD) and the duration of exposure. Additionally, visual performance is impacted by environmental and observer parameters, which include ambient conditions; complexity of the lighting environment; difficulty of location with light sources; and the observers, age and visual health (Rea, 2000; Van Derlofske and Bullough, 2006).

Glare studies have been done in the past with underground coal miners (Crouch, 1982; Guth, 1982). From a study of discomfort glare with underground coal miners, Guth (1982) noted that miners are less sensitive to discomfort glare than office workers. The evaluation procedure used had been developed for interior lighting conditions (IES, 1973). Concerning disability glare, Crouch (1982) reported in a joint study by Bituminous Coal Research Inc. and the Illuminating Engineering Research Institute that 78% of miners interviewed complained or questioned the lighting systems relative to discomfort and disability glare, veiling reflections and after-images. 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. Trotter (1982) listed ten methods to reduce glare. Most of these methods resulted in decreasing the luminance at the observer's eye or increasing the background luminance with respect to the task luminance.

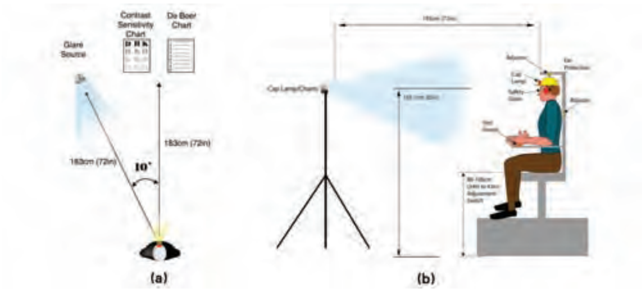
A number of nonmining studies have investigated glare. Most studied glare relative to various aspects of automobile headlamps while driving. For instance, Van Derlofske (2004) and Bullough (2002; 2003) concluded

Abstract

The U.S. National Institute for Occupational Safety and Health (NIOSH) is conducting mine illumination research to determine if light-emitting diode (LED) cap lamps can improve safety by reducing glare. Glare can impede a miner's ability to see hazards and to safely perform their work. Another objective is to determine if a person's age is a factor. This is important because the workforce is aging — the average miner is now about 43 years old. Three cap lamps were used to evaluate glare: an incandescent cap lamp, a commercially available LED cap lamp and a NIOSH prototype LED cap lamp. Thirty NIOSH personnel from the Pittsburgh Research Laboratory (PRL) served as test subjects. Three age groups were established with ten subjects in each group. Testing was conducted in the Mine Illumination Laboratory (MIL) of NIOSH PRL. The results indicate no statistically significant difference in discomfort glare among the incandescent and LED cap lamps. However, an analysis of variance for disability glare indicates that the LED cap lamps were superior for the older subjects. Disability glare scores for the oldest subject group improved 53.8% when using the NIOSH prototype LED cap lamp compared to the incandescent cap lamp and 36.5% compared to the commercial LED cap lamp. It appears that, given the conditions of this study, LED cap lamps will not increase discomfort glare and can enable significant improvements in disability glare for older workers. It is also evident that not all LEDs are created equal. The disability glare improved the best for older workers when they used the NIOSH prototype LED cap lamp, which has a different spectral power distribution (SPD) (more short wavelength energy) than the commercial LED cap lamp. Therefore, for disability glare, the results suggest that the SPD is an important factor to consider in cap lamp design.

FIGURE 1

Experimental layout: (a) plan view and (b) side view. (Figures not to scale.)



that the light source spectrum, as measured by the spectral power distribution (SPD), played a significant role in causing discomfort glare but did not play a significant role for disability glare. Two studies (Collins and Brown, 1989; Scheiber, 1994) investigated glare recovery according to age. Scheiber (1994) noted that the recovery time for older compared to younger subjects increased by a factor of three.

Three situations indicate the need for new research addressing cap lamp glare. First, a miner's cap lamp is typically the primary and most important source of light (Trotter and Kopeschny, 1997). However, cap lamps are often a source of discomfort or disability glare, which can impact both safety and task performance. Secondly, as stated above, age is a factor for glare. This is important to consider because the aging U.S. mine workforce has an average age of about 43 years. Thirdly, light emitting diodes (LEDs) are being used in new cap lamp designs. LEDs are an emerging technology for mine illumination and there is no prior research that addresses the safety of LEDs with respect to glare. Therefore, the primary objective of this study was to determine if new LED-based cap lamp technology has an impact on discomfort or disability glare for subjects in three distinct age groups. The authors' approach was to focus on the spectral content of light, as measured by the SPD, because this can influence glare and because LEDs can have drastically different SPDs compared to the incandescent lights traditionally used in cap lamps, even though both types of lighting can provide the same luminance.

Terminology

The following terms are based on Whitehead and Bockosh (1992):

- Correlated color temperature (CCT): The phrase used to describe the temperature at which a Planckian black body radiator and an illumination source's appear to match (usually specified in Kelvin (K)).
- Illuminance: The measure of the density of luminous flux striking a surface. The IESNA and the International System of Units (SI) units are footcandle (fc) and lux (lx), where lumen (lm) is the unit of luminous flux and lx = lm/m^2 and fc = lm/ft^2.
- 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. Luminance is closely correlated with a person's perception of brightness. The IESNA and SI unit is candela (cd)/m^2.
- Luminous flux: The time flow rate of light energy similar in concept to horsepower or Btu per hour. The lumen (lm) is the unit of luminous flux used by the IESNA and the SI.
- Spectral power distribution (SPD): The radiant power emitted at different wavelengths in the visible light spectrum. For most practical purposes, it includes the range from 380 to 780 nanometers (nm).

Methods

Experimental design. A 3 x 3 (age group x glare source) split-plot factorial design was used, and two replications of each light source condition were performed for each subject. Age group represented the whole-plot factor and light source represented the split-plot factor. The interaction of age group and light source was part of the split-plot analysis. An analysis of variance (ANOVA) was used to evaluate whether there were significant differences for the independent variables.

The primary independent variables were:

- Age categories: Group A = 18 to 25 years old, Group B = 40 to 50 years old and Group C = 50+ years old; and
- Glare sources: LED cap lamp, incadescent cap lamp and a NIOSH prototype LED cap lamp.

The dependent variables were:

Table 1

Cap lamp electrical and photometric data.

	Electrical characteristics		Photometric characteristics		
Cap lamp	**Supply voltage, Vdc**	**Supply current, amps**	**Supply power, watts**	**Peak wavelength, nm**	**Correlated color temperature, K**
Incandescent	6.1	0. 63	3.84	780	2,880
LED	6.1	0.42	2.56	448	5,855
Prototype LED	12.0	0.113	1.36	444	6,844

- Subjective discomfort glare ratings: Qualitative using a de Boer scale 1 through 9; and
- Contrast sensitivity score: Quantitative using a Mars Contrast Sensitivity test score.

The presentation order for cap lamps was counterbalanced where rep 1 was the baseline presentation order and rep 2 was the reversed presentation order.

The glare sources were treated as a within-subjects variable with each subject rating the discomfort glare based on the de Boers scale, which is a commonly accepted method for measuring discomfort glare. The de Boers scale is a nine-point subjective scale including qualifiers at the odd points: 1 = unbearable, 3 = disturbing, 5 = just acceptable, 7 = satisfactory and 9 = just noticeable. The even numbers (2, 4, 6 and 8) designated a degree more or less of the odd numbered qualifiers.

Disability glare was quantified by measuring a subject's visual performance for contrast sensitivity while a given glare source was present. As glare increases, the ability to detect low contrast object decreases. Age is another factor that directly affects contrast sensitivity, as age increases the ability to detect low contrast object decreases. The Mars Letter Contrast Sensitivity test was used to measure visual performance with respect to contrast sensitivity. This is a standardized test chart that measures 23 x 35.5 cm (9.1 x 14 in.) and is printed with 48 letters that are 1.75 cm (0.7 in.) high. The letters are arranged in eight rows of decreasing contrast.

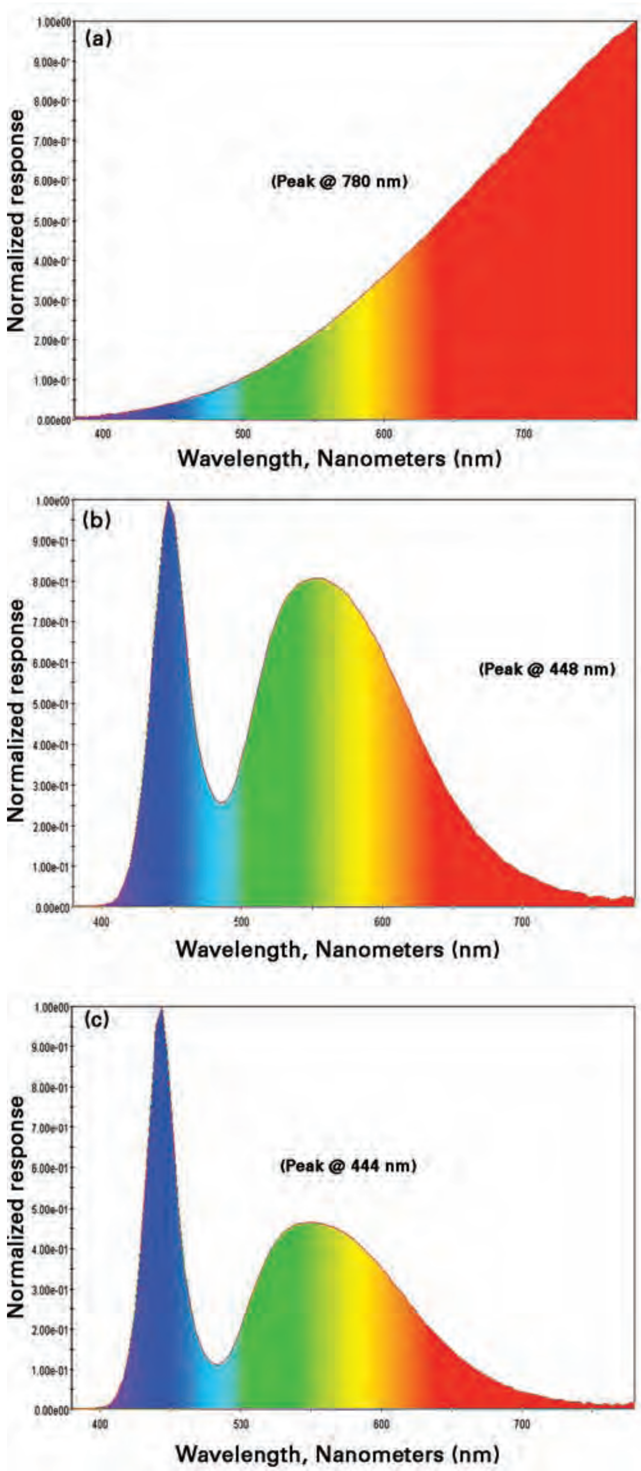
Subjects. NIOSH personnel from the Pittsburgh Research Laboratory (PRL) were the subjects. No NIOSH personnel involved with cap lamp research were used. Only the subjects that passed vision tests for distance visual acuity, contrast sensitivity, color vision deficiency and peripheral vision were accepted for the study. Most NIOSH personnel had very little if any familiarity with cap lamps so as to reduce expectancy biases. Miners were not used because of potential expectancy biases that could confound empirical data. Miners could immediately determine that the bluish-white light from an LED cap lamp is very different from the yellowish light of an incandescent cap lamp; thus, a negative bias could exist because the light is not what they are accustomed to, or a positive bias could exist if the person perceives something new as better.

Twenty-four male and six female subjects participated. There were ten subjects each in the age groups of younger (18 to 25 years), middle (40 to 50 years) and older (50+ years). The mean ages where 22.6, 47.3 and 57.6 years, respectively. The age group from 26 to 39 years was not used because there are generally minimal changes in vision for those ages. The subjects' contrast sensitivity eye test scores were of prime interest because disability glare was empirically quantified in terms of contrast sensitivity. For the youngest to oldest age groups, the mean scores were 1.748, 1.748 and 1.649, respectively, where a higher score is better. The mean value on this test for young (mean of about 20 to 25 years) and older (mean of about 55 to 60 years) subjects with normal vision is about 1.7 for both age groups. Older subjects classified as having low vision had mean scores of about 1.3 (Dougherty et al., 2005).

Subjects signed an informed consent form and were instructed about their right to withdraw freely from the research at any time without penalty. The NIOSH Human Subject Review Board approved the protocol for this study.

FIGURE 2

The spectral power distributions for each cap lamp: (a) incandescent, (b) LED and (c) NIOSH prototype LED.



Experimental layout and apparatus

Mine illumination laboratory. 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 systems, and

Table 2

ANOVA summary for contrast sensitivity.

Source	*SS*	*df*	*MS*	*F*
S (Subjects)	2.438	9	0.271	–
R (Reps)	0.024	1	0.024	0.28
A (Age Group)	5.721	2	2.861	33.66[1]
AR	0.011	2	0.006	0.07
SAR (WP error)	3.825	45	0.085	–
B (Cap Lamp)	0.319	2	0.159	12.86[2]
AB	0.188	4	0.047	3.80[3]
$B\psi_{1(A)}$	0.128	2	0.064	5.1554
$B\psi_{2(A)}$	0.060	2	0.030	2.433
$A\psi_{1(B)}$	0.053	2	0.027	2.146
$A\psi_{2(B)}$	0.156	2	0.078	6.272[4]
$A\psi_{3(B)}$	0.074	2	0.037	2.965
$\psi_{1(A)}\psi_{1(B)}$	0.049	1	0.049	3.976
$\psi_{1(A)}\psi_{2(B)}$	0.125	1	0.125	10.091[5]
$\psi_{1(A)}\psi_{3(B)}$	0.017	1	0.017	1.398
$\psi_{2(A)}\psi_{2(B)}$	0.004	1	0.004	0.316
BR	0.031	2	0.016	1.26
ABR	0.016	4	0.004	0.33
SABR (SP error)	1.339	108	0.0124	–
Total	**13.9125**	**179**		

	Treatment A coefficients				**Treatment B coefficients**		
	Young	Middle	Old		Incandescent	LED	NIOSH prototype LED
$C_{1j} =$	1	-1	0	$C_{1k} =$	-1	-1	2
$C_{2j} =$	1	0	-1	$C_{2k} =$	-1	1	0
$C_{3j} =$	0	1	-1				

[1] $F_{.05,2,45} = 3.21$ (For observed *F* test statistic: $p < 0.001$)
[2] $F_{.05,2,108} = 3.08$ (For observed *F* test statistic: $p < 0.001$)
[3] $F_{.05,4,108} = 2.45$ (For observed *F* test statistic: $p < 0.05$)
[4] $(4F_{.05,4,108})/2 = 4(2.45)/2 = 4.90$(For observed *F* test statistics: $p < 0.01$)
[5] $(4F_{.05,4,108})/1 = 4(2.45) = 9.80$ (For observed *F* test statistic: $p < 0.05$)

networked computers. The interior is 488 cm (192 in.) wide by 213 cm (84 in.) high and is coated with a rough-textured material that has a color and reflectivity similar to that of a coal mine. The experimental layout (Fig. 1) for glare testing was arranged to place the test subject in the observation station facing the test cap lamps to simulate glare from a coworkers cap lamp. The cap lamps were located 183 cm (72 in.) away from the test subject at -10 ° off axis from the charts directly in front of the test subject. The cap lamp was placed at the same height as the eye height of the test subject (165.1 cm or 65 in.). Each of the three test cap lamps was tested twice in a different order with the same contrast sensitivity chart.

Observation station. The observation station (Fig. 1 (b)) was designed to enable all human subjects to be tested at the same eye height with reference to the floor. The eye height of 165.1 cm (65 in.) is based on the 50th percentile male standing (USDOT, 2003). The station was required to allow test subjects ranging from the 5th percentile female to the 95th percentile male to be adjusted to the 165.1 cm (65 in.) eye height when in the seated position. Torso heights for the specified test subjects have a range of 68.6 cm (27 in.) to 84.8 cm (33.4 in.). The seat was designed to rise 20.3 cm (8 in.) from the lowest position to the highest to accommodate all 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 observation station uses an electric actuator for adjusting the seat height with 20.3 cm (8 in.) of travel. The helmet height is manually adjustable up to 25.4 cm (10 in.) with hand-operated clamps. The helmet adjusts fore and aft manually up to 15.2 cm (6 in.). The seat is adjustable fore and aft and has foldable arm rests. The platform includes a fixed foot rest. The platform is constructed of wood and steel and outlined with yellow reflective tape to minimize tripping when the human subjects are preparing to be tested. All of the components are a flat-black color to help eliminate any reflections or distractions during testing.

Cap lamps. Three cap lamps were used. Each cap lamp was brand new and powered at levels for a fully charged battery. The first was an MSHA-approved cap lamp using a single incandescent bulb as the primary light source. This served as the reference. The second was an MSHA-approved cap lamp with a single phosphor-white LED as the primary light source. The third cap lamp was a laboratory prototype that was jointly developed by the Lighting Research Center of Rensselaer Polytechnic Institute and NIOSH. This prototype uses two phosphor-white LEDs as the primary light source. The NIOSH prototype LED cap lamp meets the photometric requirements specified by MSHA (CFR 30, 2005). Each cap lamp had a unique beam profile such that the beam spots were of varying size and intensity; therefore, the illuminance at the subject's eye varied as follows: incandescent cap lamp was 50 lux, LED cap lamp was 100 lux and the NIOSH prototype

LED cap lamp was 70 lux. None of the cap lamps were focusable.

Each cap lamp was characterized in terms of its electrical data and its SPD. For each cap lamp, the electrical and photometric data are listed in Table 1. Each cap lamp was energized from a regulated power supply rather than a cap lamp battery to eliminate voltage fluctuations as the battery discharged. The power supply voltages for the different glare source cap lamps were set at 4, 6 and 8 V according to the specifications for the particular make and model of cap lamp. These voltages are representative of fully charged batteries.

At daytime light levels (photopic conditions), the eye's cone photoreceptors dominate vision, but as light levels decrease, the rod receptors of the eye have an increasing role in night vision. Rods have greater short-wavelength spectral sensitivity than cones. The spectral content of visible light can be characterized by the spectral power distribution (SPD). Lighting research indicates that at low-light (mesopic) conditions, where rods and cones both contribute to vision, a short-wavelength spectral content can improve visual performance. Therefore, the spectral content for each cap lamp was characterized by measuring the SPD. Figure 2 depicts the SPD for each cap lamp. The LED and NIOSH prototype LED cap lamps have a "bluish-white" color of light because the cool-white LEDs have a greater proportion of short-wavelength energy in comparison to the yellowish light of incandescent lighting commonly used for miner cap lamps. Both LED cap lamps use a cool-white type of LED characterized by a correlated color temperature (CCT) between 5,000K and 10,000K. It is important to note that there is a wide range of "white" available for LEDs. There are neutral white (CCT is typically 3,700K to 5,000K) and warm white (CCT is typically 2,600K to 3,700K). The CCT for warm-light LEDs is similar to incandescent lamps. The CCTs for each cap lamp after a five minute warm up are listed in Table 1.

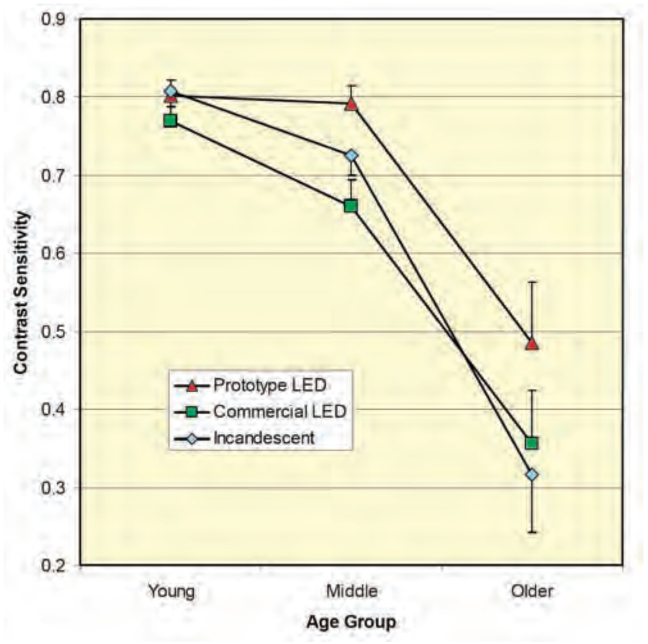
Procedure. The subjects sat in a darkened environment until their eyes adapted. Next, subjects were seated on the observation station and adjustments were made such that each person had the same eye height of 165.1 cm (65 in.) from the floor. While seated, the subjects wore a miner's hardhat with an incandescent cap lamp light illuminated for a low ambient light level. Researchers then explained the glare experiments and how they would be conducted.

Prior to the start of the glare experiments, researchers gave an overview of the experiment to the subjects, explaining that the experiment included tests for assessing subjects' responses to discomfort and disability glare. Subjects were directed to focus their eyes on a center display target at all times while seated on the observation station. Next, one of the cap lamp glare sources was turned on and given time to stabilize (warm up). The subject's response to the discomfort glare was obtained followed by their responses to the disability glare tests. Two datasets were collected for each of the three cap lamps. The cap lamp sequences were the incandescent, LED and NIOSH prototype LED for Dataset 1 and the reverse cap lamp sequence for Dataset 2.

The first test measured discomfort glare and focused on subjects providing a subjective rating of each glare source using the de Boer scale shown on the chart in front of them. While sitting in the observer's chair, subjects were asked to think about the discomfort ratings relative to the designated cap lamp as it was switched on. Subjects subsequently gave a numerical rating from 1 to 9 for the de Boer scale chart. Immediately following the discomfort glare test, the disability glare test was conducted. The Mars Letter Contrast Sensitivity test was utilized by switching out the de Boer scale target with the appropriate contrast sensitivity chart. Three charts with different lettering orders were used to minimize learning effects. Each chart had the letters C, D, H, K, N, O, R, S, V and Z in varying contrasts and sequences. The subjects were asked to read aloud the letters on the chart from left to right for each row of letters beginning at the top row and moving down the chart. Researchers explained that selections would only include the letters C, D, H, K, N, O, R, S, V and Z. When in doubt about any letter, subjects made their best guess from this set of letters. The test continued until they failed to correctly identify two consecutive letters. After completing both discomfort and disability tests, the glare source cap lamp was switched off and the subjects were asked to relax for about one minute to allow their eyes to readapt to the ambient light level provided by the incandescent cap lamp fitted to the a miner's hardhat that they were wearning.

FIGURE 3

The interaction between age group and glare source in terms of contrast sensitivity.



Test chart illuminance. Illuminance in the vertical plane was measured at the test charts for test conditions, i.e., for each cap lamp separately with ambient lighting and for ambient lighting only. Illuminance levels were produced from light reflected from the surrounding test environment including the subject and observer station. Ambient lighting conditions were produced from the cap lamp mounted to the subject's helmet. Measurements were made on the test chart at three locations (top, mid-

Table 3

ANOVA summary for de Boer ratings.

Source	***SS***	***df***	***MS***	***F***
S (subjects)	78.450	9	8.717	–
R (reps)	0.939	1	0.939	0.27
A (age group)	66.078	2	33.039	9.41[1]
AR	1.878	2	0.939	0.27
SAR (WP error)	158.050	45	3.512	–
B (cap lamp)	5.344	2	2.672	1.92
AB	11.556	4	2.889	2.07
BR	4.478	2	2.239	1.61
ABR	3.556	4	0.889	0.64
SABR (SP error)	150.400	108	1.392	
Total	**480.728**	**179**		

[1] $F_{.05,2,45} = 3.21$

Multiplicative Sidak Pairwise comparisons for deBoer ratings[2] by age group. Age groups containing the same letter are not significantly different from one another.

Age Group:	**Young**	**Middle**	**Old**
	4.47	3.77	2.98
	A	AB	B

[2]The de Boer scale is as follows: 1 = unbearable, 3 = disturbing, 5 = just acceptable, 7 = satisfactory, 9 = just noticeable.

dle and bottom). The average illuminance measured in the absence of any cap lamp glare source and for the ambient condition only was 4.76 lux. For the incandescent, LED and NIOSH prototype LED test cap lamp glare sources, the average illuminances were 6.26, 5.17 and 7.01 lux, respectively.

Results

Tables 2 and 3 summarize the ANOVA results for the contrast sensitivity tests and the de Boer ratings, respectively. These tables include degrees of freedom (df), sums of squares (SS), mean square (MS) and F-ratios (F value for the main effects and interactions). As can be seen in Table 2, a significant interaction was detected between age group and light source for contrast sensitivity. The nature of the interaction is depicted in Fig. 3.

To determine the nature and sources of the non-additivity resulting in this interaction, treatment-contrast and contrast-contrast interactions were examined (Kirk, 1995). Results of these tests are also contained in Table 2. This analysis indicated that the specific contrasts responsible for the interaction compared the NIOSH prototype LED cap lamp versus the two other cap lamps and compared age Group A with age Group C. Specifically, the NIOSH prototype LED cap lamp resulted in significantly better contrast sensitivity scores in the older age group compared to the other cap lamps, whereas the youngest age group showed no difference in contrast sensitivity between any of the cap lamps (FS 4,108 = 10.091, $p < 0.05$). Followup contrasts examining whether differences existed between the LED and incandescent cap lamp indicated no statistically significant difference in contrast sensitivity across age groups (FS 2,108 = 1.10, $p > 0.05$). A test examining differences in contrast sensitivity between the young and middle age groups indicated a decrement in performance in the middle age group (FS 2,108 = 10.97, $p < 0.05$). Figure 3 discloses an even more rapid drop in contrast sensitivity in the older age group. However, a formal test between these age groups was not possible (Kirk, 1995).

The qualitative de Boer ratings were affected by age group (F 2,45 = 9.41, $p < 0.001$) but not by light source. Post hoc Multiplicative Sidak tests indicated a significant difference in de Boer rating between young and old age groups. However, the middle age groups were not different in terms of de Boer rating from either the young or old groups. Analysis of the mean de Boer ratings for each cap lamp suggests that ratings were highest (with a higher rating meaning less discomfort glare) for the NIOSH prototype LED than for the other cap lamps. However, this qualitative assessment did not achieve statistical significance between cap lamps.

Discussion

The results of the glare comparisons between LED and incandescent cap lamps provide important data for improving the design of future cap lamps and have the potential to positively affect the safety of employees in the underground mining industry. It is apparent from the authors' findings that spectral content of light from cool-white LEDs does not appear to increase discomfort glare and it has the potential to significantly improve safety by reducing disability glare, especially among older workers (who are most susceptible to glare and its effects).

While the benefits of the NIOSH prototype LED design in contrast sensitivity were significant only when comparing youngest versus oldest age groups, it is notable that the NIOSH prototype LED also scored highest in the middle age group. In fact, contrast sensitivity for the NIOSH prototype LED was little changed between the young and middle age groups. Meanwhile, both the incandescent and the commercial LED declined in contrast scores between these age groups. This suggests the possibility of a small benefit for the NIOSH prototype design even among middle age workers, which becomes increasingly apparent in older subjects.

An interesting result from the analysis of the interaction was that the authors were able to test whether contrast sensitivity was different between the incandescent and the commercially available LED light source. No statistically significant difference was observed between these two light sources in terms of contrast sensitivity scores. Thus, the only light source that had any positive impact on contrast sensitivity was the NIOSH prototype LED and that result was age dependent. Also, age had a significant negative impact on contrast sensitivity with a slight decline seen from the young to middle age groups and a steep decline between middle and older age groups. The authors reasoned that the prototype cap lamp improved contrast sensitivity for older subjects because it provided the most short-wavelength energy, which should help older subjects. As a person ages, the eye changes such that the muscles of the iris weaken, which limits how large the pupil expands, and the lens of the eye becomes less opaque. Thus, less light reaches the retina for an older person. Secondly, an older person has fewer rod photoreceptors in the eye compared to a young person. These rods play a critical role in night vision, and they are more sensitive to short-wavelength energy. Therefore, older adults would respond better to light with a higher proportion of short-wavelength energy. High contrast and high illumination are not typical in underground mining, so age and contrast are important factors for mining.

There are other factors that could have helped the prototype LED cap lamp to have a positive impact on contrast sensitivity. The illuminance at the eye was 70 lux for the prototype LED cap lamp and 100 lux for the LED cap lamp. Contrast sensitivity would decrease as the illuminance at the eye increases, so the prototype cap lamp would have some advantage. But note that the incandescent cap lamp provided only 50 lux at the eye, yet this decrease did not improve contrast sensitivity for any age group. Secondly, contrast sensitivity would improve as the test chart illuminance increased. The prototype cap lamp provided 7.01 lux of test chart illuminance compared to 6.26 lux for the incandescent cap lamp and 5.17 lux for the LED cap lamp. Note again that no statistically significant difference was observed between the incandescent and LED cap lamp. The authors would expect that contrast sensitivity would improve for the LED cap lamp if the illuminance at the eye decreased and if test chart illuminance increased to the levels of one of the other cap lamps. However, the authors do not know if the improvement would be statistically significant.

The qualitative assessment using the de Boer discomfort glare scale provided additional confirmation of the increasing glare discomfort associated with increasing age. There was a clear linear trend in discomfort ratings indicating the increasing discomfort with age (Table 3). De Boer ratings were not significantly affected by the light source. However, mean ratings were highest for the NIOSH prototype LED followed by the incandescent and LED light sources. Again, note that discomfort glare increases as illuminance at the eye increases; the illuminances at the eye were 50 lux (incandescent cap lamp), 100 lux (LED cap lamp) and 70 lux (prototype LED cap lamp). There is the possibility to reduce discomfort glare for the LED and prototype LED cap lamps if the illuminance at the eye decreased to 50 lux. One can infer from these results that the LED-based cap lamps can provide significantly more illumination without increasing discomfort glare. This increased illumination would likely aid a miner's ability to spot hazards in their forward field of vision.

Again, the general results indicate that, given the conditions of this study, the LED-based cap lamps do not increase discomfort glare and they have the potential to decrease disability glare for older workers. These findings differ from other research concerning automotive headlamp glare, where the light source spectrum played a significant role in causing discomfort glare but did not play a significant role for disability glare (Bullough et al., 2003). The conditions of this research differed in that the illuminance at the eye for normal automotive driving was much less (0 to 10 lux) and that the glare sources included halogen and high-intensity discharge headlamps that have different spectral power distributions in comparison to the LEDs used in miner cap lamps.

Taken together, the results of this study provide evidence that the NIOSH prototype LED design has several benefits in terms of improving visual performance (especially among older workers) and may help decrease glare discomfort compared to currently available light sources. As mentioned above, the current average age of the mining population is 43 years. As a result, many mine workers could be positively impacted by implementation of the NIOSH prototype LED cap lamp design. For older workers, there was a 45% improvement in contrast sensitivity compared to the other light sources studied. Because contrast sensitivity is an important aspect of visual performance and is a critical factor for many work tasks, implementation of the prototype cap lamp design could provide a major benefit for the aging mining population.

Lastly, this study was limited to cool-white LEDs and new cap lamps that functioned at optimal performance at the power levels for a fully charged battery. A larger and more detailed study is needed to explore discomfort and disability glare with regard to warm-white and neutral-white LEDs. It would be expected that warm-white LEDs would result in glare findings similar to the incandescent cap lamp. Another study would also be needed to determine the effects of battery discharge over a typical mine shift. It would be expected that the glare findings would change because the relative light output and SPDs would change as the battery discharged.

Acknowledgments

The studies described in this paper were conducted with assistance from R. Unger, M. Reyes, and T. Dubaniweicz of NIOSH PRL. M.A. Rossi, R.N., conducted the vision testing.

Disclaimers

Mention of any company or product does not constitute endorsement by NIOSH. The findings and conclusions in this report are those of the authors and do not necessarily represent the views of the National Institute for Occupational Safety and Health.

References

Bullough J.D., et al., 2003, "An investigation of headlamp glare: Intensity, spectrum, and size," Report No. DOT HS 809 672. U.S. Department of Transportation, National Highway Traffic Safety Administration.

Bullough J.D., Fu, Z., and Van Derlofske, J., 2002, "Discomfort and disability glare from halogen and HID headlamp systems," SAE 2002 World Congress, Detroit, MI, March 4-7, SAE 2002-01-0010, 7 pp.

CFR 30 - Code of Federal Regulations, 2005, Title 30, Chapter 1- Mine Safety and Health Administration, Department of Labor, Part 19 – Electric Cap Lamps. U.S. Government Printing Office, Revised July 1.

Collins, M., and Brown, B., 1989, "Glare recovery and its relation to other clinical findings in age relate maculopathy," Clinical Vision Science, Vol. 4, No. 2, pp. 155-163.

Cornelius, K., Steiner, L., and Turin, F., 1998, "Using coal miners' experience to identify effective operating cues," 42nd Annual Meeting of the Human Factors and Ergonomics Society.

Crouch, C.L., 1982, "Disability glare studies on underground mine personnel," Proceedings of the 2nd International Mine Lighting Conference of the International Commission on Illumination (CIE), pp. 186-191.

Dougherty, B.E., Flom, R.E., and Bullimore, M.A., 2005, "An evaluation of the Mars letter contrast sensitivity test," Optometry and Visual Science, Vol. 82, No. 11, pp. 970-975.

Guth, S.K., 1982, "Discomfort glare sensitivity of underground mine personnel," Proceedings of the 2nd International Mine Lighting Conference of the International Commission on Illumination (CIE), pp. 17-21.

Illuminating Engineering Society (IES), 1973, "Outline of a standard procedure for computing visual comfort ratings for interior lighting," Committee on Recommendations of Quality and Quantity of Illumination of the IES, R00 Report No. 2 (1972), Journal of the IES.

Kirk, R.E., 2005, Experimental Design: Procedures for the Behavioral Sciences, Third Edition, Pacific Grove, CA: Brooks/Cole, 921 pp.

Rea, M.S., ed., 1993, Lighting Handbook: Reference & Application, 8th Edition, New York, NY: Illuminating Engineering Society of North America.

Scheiber, F., 1994, "Age and glare recovery time for low-contrast stimuli," Proceedings of the Human Factors and Ergonomics Society, Santa Monica, CA, Human Factors and Ergonomics Society, pp. 496-499

Trotter, D.A., 1982, The Lighting of Underground Mines, Gulf, 216 pp.

Trotter, D.A., and Kopeschny, F.V., 1997, "Cap Lamp Improvements in Canadian Mines," Applied Occupational and Environmental Hygiene,

USDOT, FAA, 2003, Human Factors Design Standard (HFDS), Report # DOT/FAA/CT-03/05 HF-STD-001.

Van Derlofske, J., and Bullough, J.D., 2006, "Balancing Visibility and Glare," National Highway Traffic Safety Workshop, MS PowerPoint presentation.

Van Derlofske, J., Bullough, J., Dee, P., Chen, J., and Akashi, Y., 2004, "Headlamp Parameters and Glare," (Report No. SAE 2004-01-1280), Society of Automotive Engineers World Congress & Exhibition 2004 (SP-1875, pp. 195-203), Warrendale, PA, Society of Automotive Engineers.

Whitehead, K., and Bockosh, G., 1992, Mining Handbook, 2nd Edition, Society for Mining, Metallurgy, and Exploration (SME), Vol. 1, Chapter 11.9.