Discomfort Glare Comparison for Various LED Cap Lamps

John J. Sammarco, *Senior Member, IEEE*, Alan G. Mayton, Timothy Lutz, and Sean Gallagher

***Abstract*—Researchers at the National Institute for Occupational Safety and Health (NIOSH) are investigating different lighting technologies with the objective of improving mine safety. This paper presents the results from an ongoing study that compares discomfort glare for different light-emitting diode (LED) cap lamps using the de Boer glare rating scale. The cap lamps tested included two commercially-available LED cap lamps and one NIOSH prototype LED cap lamp tested at three different illumination levels. Prior research indicated that the NIOSH prototype enabled much better visual performance as compared to other LED cap lamps. It uses three LEDs that produce multiple illumination areas in comparison to commercially-available cap lamps that use one LED and projects a narrow spot pattern. Across subjects and cap lamp test conditions, measured illuminances (averaged at both eyes) varied from 0.62 to 3.73 lx, whereas the de Boer glare ratings varied from 4.86 to 7.71. An analysis of variance based on 15 subjects indicated a significant difference in the discomfort glare due to cap lamps ($F_{4,52} = 18.01, p < 0.001$). *Post hoc* tests indicate that one of the commercially available cap lamps exhibited lower discomfort scores, with no statistically significant differences detected between the others. Thus, the NIOSH prototype cap lamp does not cause excessive discomfort glare yet enables better visual performance.**

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

I. Introduction

The Illuminating Engineering Society of North America cites the working face of an underground coal mine as the most difficult environment in the world to illuminate [1]. Lighting is critical to miners; they depend heavily on visual cues to spot falls of ground, slip, trip, and fall (STF) hazards, and pinning and striking hazards from moving mining machinery [2]. An underground mine is a dynamic environment that includes dust, confined spaces, low reflective surfaces, low visual contrasts, and glare. Mine illumination typically consists of a low background light level but a relative high intensity light spot from a miner's cap lamp or machine-mounted lighting. This illumination presents high contrast that can lead to discomfort glare and decreased visibility.

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 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 readaptation (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 factors 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 glare source 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 observers, age, and visual health [3], [4].

Glare studies have been done in the past with underground coal miners [5], [6]. From a study of discomfort glare with underground coal miners, Guth [6] noted that results indicate that miners are less sensitive to discomfort glare than office workers. The evaluation procedure used had been developed for interior lighting conditions [7]. Concerning disability glare, Crouch [5] reported in a joint study by Bituminous Coal Research, Inc., and the Illuminating Engineering Research Institute 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, he 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 [8] listed ten methods to reduce glare. Most of these methods resulted in decreasing the illuminance 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 *et al.* [9] and Bullough *et al.* [10], [11] concluded that the light source spectrum, as measured by the SPD, played a significant role in causing discomfort glare but did not play a significant role for disability glare. Two studies [12], [13] investigated glare recovery according to age. Scheiber [13] noted that the recovery time for older compared to younger subjects increased by a factor of three. Bullough *et al.* [14] reported developing a simple model using light source photometric characteristics for predicting

Manuscript received June 11, 2010; accepted November 9, 2010. Date of publication March 10, 2011; date of current version May 18, 2011. Paper 2010-MIC-212, presented at the 2010 Industry Applications Society Annual Meeting, Houston, TX, October 3–7, and approved for publication in the IEEE Transactions on Industry Applications by the Mining Industry Committee of the IEEE Industry Applications Society. The mention of any company or product does not constitute endorsement by the NIOSH. The findings and conclusions in this paper are those of the authors and do not necessarily represent the views of NIOSH.

The authors are with the National Institute for Occupational Safety and Health, Pittsburgh, PA 15236 USA (e-mail: Jsammarco@cdc.gov; anm9@cdc.gov; tcl9@cdc.gov; sfg9@cdc.gov).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TIA.2011.2126016

discomfort glare from outdoor lighting installations. Using the model, the authors demonstrated the effect of these photometric quantities—light source illuminance, surround illuminance, and ambient illuminance—on subjective assessments of discomfort glare. Moreover, Lulla and Bennett [15] investigated the range effects associated with discomfort glare. Results of the study, among other findings, showed that the range of glare source luminance had a definite effect on the "between comfort and discomfort levels" of 40 human test subjects. Regarding the research use of the de Boer subjective rating scale in evaluating discomfort glare, it is not without its difficulties and shortcomings. Gellatly and Weintraub [16] studied the de Boer rating scale [17] for effectiveness in rating discomfort glare and possible improvements. They suggested that the scale is not optimal for rating discomfort glare and suggested improvements. Similarly, Bullough *et al.* [14] cited that "the de Boer scale, like all subjective rating research, is prone to difficulties." They also speak of shortcomings in using the model described by Schmidt-Clausen and Bindels [18] that was developed for predicting de Boer ratings of discomfort glare from motor vehicle lighting. Prediction of discomfort glare would be useful given that the empirical determination of glare requires significant resources involving human subject tests.

Researchers at the National Institute for Occupational Safety and Health (NIOSH) are investigating different lighting technologies with the objective of improving mine safety by improving visual performance and reducing glare. The scope is machine-mounted, auxiliary, and cap lamp luminaires for underground coal and metal/nonmetal mining. Three situations indicate the need for new research addressing cap lamp glare in the mining industry and motivate NIOSH research. First, a miner's cap lamp is typically the primary and most important source of light [19]. However, cap lamps are often a source of discomfort or disability glare which can impact both safety and task performance. Second, as stated earlier, age is a factor for glare. This is important to consider because of the aging U.S. coal mine workforce that has an average age of about 43 years. Lastly, light-emitting diodes (LEDs) are being used in new cap lamp designs. LEDs are an emerging technology for mine illumination, and there has been some prior research that addresses the safety of LEDs with respect to glare. NIOSH researchers conducted a comparative study of glare from incandescent and LED cap lamps, as perceived by 30 human subjects [20]. In this research, the color of light was the primary factor, and the lighting distribution (beam patterns) was relatively equal among all cap lamps, given that a diffusion filter was used to provide homogenous illumination levels and distributions. The results indicated no statistically significant difference in discomfort glare among the incandescent and LED cap lamps. However, an analysis of variance (ANOVA) for disability glare indicated that the LED cap lamps were superior for the older subjects. NIOSH researchers also conducted an empirical study of discomfort glare, as perceived by 36 human subjects, from machine-mounted area lighting. The lighting technologies were incandescent, fluorescent, and LED [21]. The results indicated that the fluorescent machine lights generally were associated with higher levels of discomfort glare, and lighting conditions that used LED machine lights were associated with the least amount of discomfort glare. Currently, NIOSH research of LED cap lamps is addressing how the cap lamp beam distribution affects visual performance with respect to detecting tripping hazards on the floor and detecting peripheral motion, which is important for avoiding pinning/striking accidents from moving machinery [22]. However, the effects on discomfort glare are unknown given various beam distributions.

1:	Unbearable
2:	_
3:	Disturbing
4:	_
5:	Just acceptable
6:	_
7:	Satisfactory
8:	_
9:	Just noticeable

Fig. 1. De Boer scale for rating discomfort glare.

Therefore, the primary objective of this paper was to determine if LED-based cap lamps with various beam distributions have an impact on discomfort glare. A secondary objective was to compare empirical discomfort glare data to results obtained from predictive models for discomfort glare.

II. Methods

A. Experimental Design

A randomized complete block (RCB) design (RCBD) was employed where subjects were treated as blocks and the treatment variable consisted of five glare sources: LED cap lamp 1, LED cap lamp 2, and a NIOSH prototype LED cap lamp 3 set at three power levels a (high), b (medium), and c (low). The RCBD randomization was applied only to treatments (glare sources) within blocks. The dependent variable was subjective discomfort glare rating. The glare sources were treated as a within-subjects variable with each subject rating the discomfort glare based on the de Boer scale. The de Boer scale is a nine-point subjective scale including qualifiers at the odd points (see Fig. 1). An RCB ANOVA was used to assess differences in de Boer ratings between glare sources. A companion analysis was performed using the Friedman nonparametric two-way ANOVA to assess the statistical significance between mean ranks of the glare sources. Glare ratings were factor A and subject factor B in the Friedman ANOVA on ranks. *Post hoc* multiple comparison tests for the Friedman ANOVA followed procedures provided by Siegal and Castellan [23].

B. Glare Sources

Three LED cap lamps were used. Each cap lamp was brand new and powered at levels for a fully charged battery. Each cap

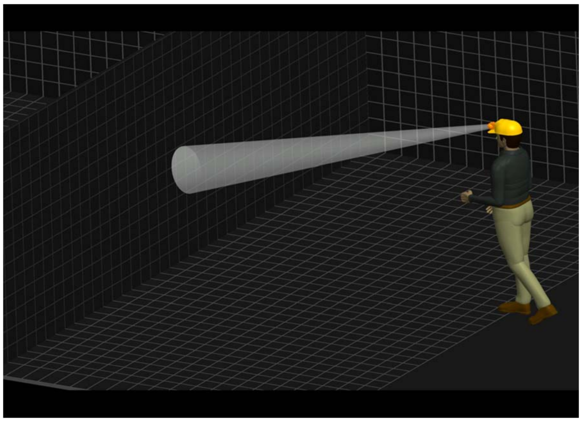

Fig. 2. Simulation of the circular beam spot of about 6° to 8° from cap lamps 1 and 2. The human model represents the 50th percentile male.

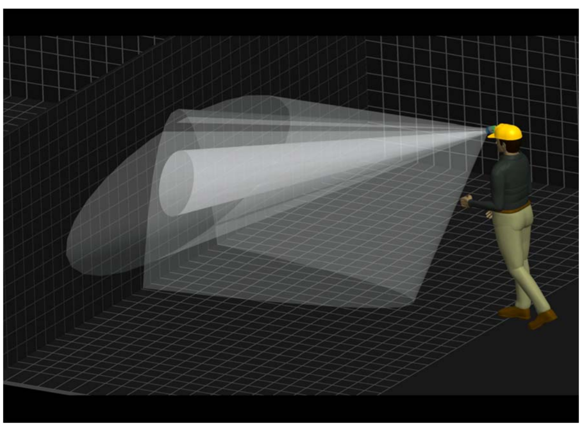

Fig. 3. Simulation of the multiple beam angles from the NIOSH prototype cap lamp 3. The human model represents the 50th percentile male.

lamp used LEDs that were categorized by the manufacturer as "cool white." Cap lamps 1 and 2 used a single phosphor-white LED as the primary light source, along with an optical reflector to direct the light to a circular spot ranging from about 6° to 8° as depicted by Fig. 2. Both were approved by the Mine Safety and Health Administration (MSHA). The third cap lamp was a laboratory prototype that was developed by NIOSH and tested at three different power levels. This prototype uses multiple phosphor-white LEDs as the primary light source along with secondary optics to direct the light to specific hazardous areas in the mine as depicted by Fig. 3. The intent is to provide more illumination in order for miners to better detect STF hazards located on the mine floor and detect moving machinery hazards associated with pinning/striking accidents. The NIOSH prototype LED cap lamp meets the photometric requirements specified by MSHA [24]. Each cap lamp had beam spots of varying size and intensity; therefore, the average illuminances at the subjects' eyes were as follows: 0.76 lx for cap lamp 1, 2.72 lx for cap lamp 2, 3.42 lx for cap lamp 3 (a), 2.74 lx for cap lamp 3 (b), and 2.07 lx for cap lamp 3 (c).

For each cap lamp, the electrical and photometric data are listed in Table I. Each cap lamp was energized from a regulated power supply to eliminate voltage fluctuations as a cap lamp battery discharged. The power supply voltages for the different glare source cap lamps were set according to the specifications for the particular make and model of the cap lamp. These voltages are representative of fully charged batteries.

TABLE I
Cap Lamp Electrical and Photometric Data

	Electrical Characteristics			Photometric characteristics	
Cap lamp	Supply voltage (Vdc)	Supply current (milli-amps	Supply power (watts)	Peak wavelength (nm)	Correlated color temp. (K)
1	4.00	760	3.04	452	8039
2	3.95	530	2.09	456	6603
3(a)	2.99	585	1.75	448	6304
3(b)	2.96	450	1.33	448	6356
3(c)	2.75	320	0.88	448	6402

Note that Figs. 2 and 3 depict the primary beam angle which is the angle on each side of the beam axis where the luminous intensity is 50% of the maximum luminous intensity. The remaining 50% is dispersed about the periphery of the beam angle.

C. Subjects

NIOSH personnel at the Bruceton, PA, location were recruited to be subjects. None of the subjects were specifically involved with this cap lamp research, and most of the subjects were not familiar with miner cap lamps, or they had used them infrequently. Only the subjects that passed vision tests for distance visual acuity, contrast sensitivity, and peripheral vision were accepted for the study. Subjects that had radial keratotomy, monocular vision, glaucoma, or macular degeneration were excluded. Subjects were not excluded for color vision deficiency.

Miners were not used as subjects because of potential expectancy biases that could confound empirical data. Miners could immediately determine that the bluish-white light from the LED cap lamps and the lighting distributions from the NIOSH prototype LED cap lamp were very different from the yellowish light of an incandescent cap lamp; thus, a negative bias could exist because the light color and distribution are not what they are accustomed to, or a positive bias could exist if the person perceives something new as better.

Fifteen subjects participated: 13 males and two females. While gender was not a variable in this study, the percentage distribution for gender was representative of the U.S. miner population. The average subject age was 54 years. This is somewhat older than the average U.S. coal miner's age of 43 years [25].

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

D. Predictive Methods for Calculating de Boer Ratings

Two quantitative methods were used to predict de Boer ratings of discomfort glare for comparison with the actual de

Boer subjective ratings. The first method included the Schmidt-Clausen and Bindels equation shown hereinafter as (1) [18]

$$W = 5.0 - 2.0LOG\left[E_i/(0.003) \times (1 + SQRT(L_A/0.04))\,(\theta)^{0.46}\right] \quad (1)$$

where

W mean de Boer rating;

E_i illuminance directed at the observer's eye (in lux);

L_A adaptation luminance (cd/m^2);

θ angle between the glare source and the observer's line of sight.

The second method of predicting utilizes the following (2) and (3) from [14]:

$$DG = a\,log(E_\ell + E_s) + b\,log(E_\ell/E_s) - c\,log(E_a) \quad (2)$$

where

DG discomfort glare;

E_ℓ light source illuminance (in lux);

E_s surround illuminance (in lux);

E_a ambient illuminance (in lux).

Coefficients a, b, and c were set at 1.0, 0.6, and 0.5, respectively. The values of b and c resulted from the best fit of the data from all of the experiments to the model equation and were determined through iterative trial and error [14].

The surround illuminance E_s was determined by constructing a small baffle of $\sim$1.6 cm in diameter that slid along a small cantilever-shaped piece of 15 AWG insulated copper wire. It was secured to the casing of the sensor measuring surface of an illuminance meter. The baffle allowed a shadow to be cast on the sensor so that surround illuminance could be measured (three for each eye for a total of six measurements). Similarly, ambient illuminance E_a was measured without the baffle at the subject's eyes with the subject incandescent cap lamp providing illumination.

Once the DG factor was determined, it was inserted into (3) whereby predicted de Boer ratings were computed

$$DB = 6.6 - 6.4\,log\ DG. \quad (3)$$

III. Experimental Layout and Apparatus

A. MIL

Testing was conducted at the Mine Illumination Laboratory (MIL) at the Bruceton, PA, location of NIOSH. The MIL is a simulated underground coal mine environment that has various test equipment, data acquisition and control systems, and 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 dark color and a uniform spectral reflectivity of about 5% for the visible spectrum, which is typical for coal.

B. Observation Station

Each subject was positioned at a fixed known coordinate with respect to the glare source and de Boer chart, and each subject's head position was fixed so that their point of view was the same regardless of their body size and so that each subject was tested at an eye height of 165.1 cm (see Fig. 4). This eye height, with reference to the floor, was based on the 50th percentile standing male [26]. Thus, this eliminated data confounding from variations in the subjects' position, point of view, and eye height. This positioning was enabled by the use of an observation station designed and constructed by NIOSH personnel (see Fig. 5). The seat height was designed to accommodate testing of subjects ranging from the 5th percentile female to the 95th percentile male.

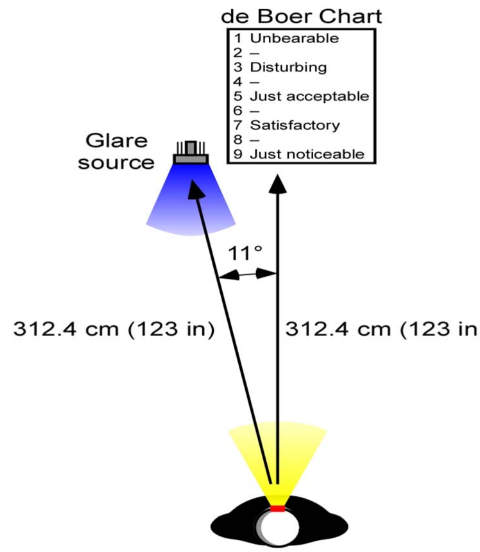

Fig. 4. Plan view of the experimental layout.

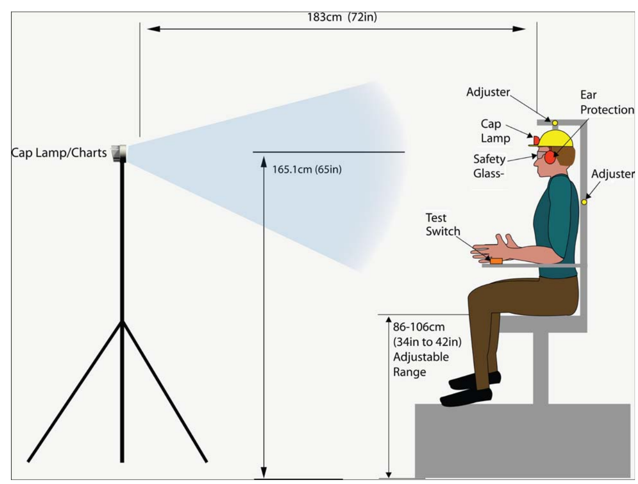

Fig. 5. Side view of the experimental layout. Subjects were seated on the observation station.

C. Experimental Layout

The experimental layout (see Figs. 4 and 5) was arranged to place the test subject in the observation station facing the test cap lamps to simulate glare from a coworker's cap lamp. The cap lamps were located 312.4 cm (123 in) away from the test subject at $-11°$ off axis from the de Boer chart (see Fig. 1) directly in front of the test subject. The cap lamp glare source was placed at the eye height of the test subject that was 165.1 cm (65 in) above the floor. For consistent alignment of each glare source during testing, a small laser was fastened to the top of the miner's hard hat to which each test cap lamp was mounted. The

TABLE II
AVERAGE DE BOER CHART LUMINANCE FOR EACH OF THE LED CAP LAMP CONDITIONS

Cap lamp	Supply power (watts)	Average chart luminance (cd/m^2)
None (ambient)	0	0.25
1	3.04	0.30
2	2.09	0.35
3(a)	1.75	0.43
3(b)	1.33	0.40
3(c)	0.88	0.36

laser was directed at a 3.2-cm-diameter chrome magnet (0.5 cm inner diameter) suspended 7 cm down from the MIL roof just to the left of the subject (in the direction of the de Boer chart).

D. de Boer Chart Luminance

Luminance in the vertical plane was measured at the de Boer chart (see Fig. 1) for each LED cap lamp in conjunction with the ambient lighting provided by the incandescent cap lamp worn by the subject. The de Boer chart was measured 38.10 cm (15 in) high by 33.02 cm (13 in) wide and was placed 312.4 cm (123 in) from the subject (see Fig. 4). Measurements were made on the de Boer chart at three locations (top, middle, and bottom). Table II lists the average ambient luminance at the chart without any glare sources and the average luminance at the chart for each cap lamp glare source.

E. Procedures

Each subject sat in a darkened environment for 15 min. to allow the retina to adapt to the dark environment. Next, the subject was seated on the observation station, and adjustments were made such that the eye height was 165.1 cm (65 in) from the floor. While seated, the subject wore a miner's hard hat with an incandescent cap lamp illuminated at a power level equal to that of a fully charged battery.

Prior to the start of the glare experiments, researchers gave an overview of the experiment to the subjects explaining the test procedures. In addition, the cap lamps, the glare sources, and the illuminance meters were switched on and given time to stabilize (warm up). The subjects were directed to focus their eyes on the de Boer chart at all times while seated on the observation station. The vertical illuminance at each of the subject's eyes was measured and recorded for the cap lamp under test. Finally, while sitting in the observation station, the subjects were asked to think about the discomfort ratings relative to the designated cap lamp. Subjects subsequently gave a numerical rating from 1 to 9 for the de Boer chart. The subject's response to discomfort glare was manually recorded once the subject verbalized the rating.

IV. RESULTS

Fig. 6 provides a summary of the mean de Boer ratings relative to the mean illuminance at the subjects' eyes (average of both eyes). Here, the actual subjective ratings are compared with the two quantitative methods for predicting de Boer ratings. The highest predictive ratings for all five LED cap lamp conditions were obtained using the simple model from Bullough *et al.* [14], whereas the values predicted using the Schmidt-Clausen and Bindels equation yielded, in nearly every case, the lowest de Boer ratings. The average illuminance (both eyes) for five LED cap lamp glare source conditions is also depicted. Interestingly, cap lamp 1 deviated from the other test cap lamps in that it had the worst predicted mean de Boer rating of about 3.5 (slightly better than disturbing) using the Schmidt-Clausen and Bindels equation, although the illuminance at the eyes was lowest.

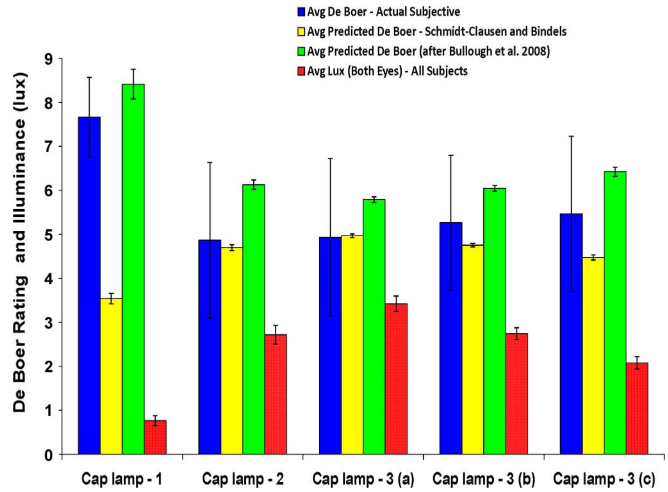

Fig. 6. De Boer discomfort glare assessments by 15 test subjects compared to two different predicted de Boer ratings.

TABLE III
RESULTS OF ANOVA POST HOC TESTS FOR RCB AND FRIEDMAN NONPARAMETRIC ANOVA ON RANKS. CONDITIONS CONTAINING THE SAME LETTER ARE NOT SIGNIFICANTLY DIFFERENT FROM ONE ANOTHER

	RBC ANOVA			Friedman ANOVA			
Cap lamp	Mean de Boer rating	Sidak *post hoc* test		Mean Rank	Friedman *post hoc* test		
Cap lamp 3a	4.93	A		2.07	A		
Cap lamp 2	4.87	A		2.27	A		
Cap lamp 3b	5.27	A		2.67	A	B	
Cap lamp 3c	5.47	A		3.23		B	
Cap lamp 1	7.67		B	4.77			C

Considering the results statistically, the RCB ANOVA found a significant difference in de Boer ratings with different glare sources ($F_{4,54}$=20.15, $p < 0.0001$). *Post hoc* tests show that de Boer ratings were not significantly different for any cap lamps other than cap lamp 1, which resulted in lower discomfort glare.

Results of the Friedman ANOVA indicated a significant influence of the glare source on the de Boer ratings ($F_r =$ 32.137, $p < 0.001$). Table III provides the mean ranks for de Boer ratings for each of the cap lamps used in this paper and the result of *post hoc* multiple comparison tests. The critical value for comparison of mean ranks was 0.936.

Results of the multiple comparison procedures (see Table III) indicated three groups of means that were not significantly different from one another. Cap lamp 1 had the highest mean rank (indicating the best de Boer discomfort glare rating) and was significantly different from all other cap lamps. Cap lamps 3a and 3b were not significantly different from one another, and cap lamp 2 was not significantly different from cap lamps 3b and 3c.

V. Discussion

A. Subjective de Boer Ratings

The results of the de Boer rating comparisons among the LED cap lamps indicate that cap lamp 1 had significantly less discomfort glare than the other cap lamps. While glare is an important consideration, one must also consider the visual performance afforded by the cap lamps. The tradeoff for having less discomfort glare from cap lamp 1 is that this cap lamp is associated with poorer visual performance with respect to the detection of tripping hazards on the floor and the detection of peripheral motion, which is important for avoiding pinning/striking accidents from moving machinery [25]. On the other hand, the NIOSH cap lamp 3b afforded the best visual performance, and this cap lamp provided an acceptable level of discomfort glare. Furthermore, it is interesting to note that cap lamp 3a gave the highest mean illuminance (3.42 lx) at the eye, mean luminance level ($0.43\ \text{cd/m}^2 + 0.08$) at the de Boer chart, and the largest source luminance of $14\,000\ \text{cd/m}^2$ yet did not show a mean de Boer rating worse than "just acceptable -5."

Cap lamp 1 had the least discomfort glare, mostly likely because it had the least illuminance at the subjects' eyes. Generally, discomfort glare increases as the illuminance increases. Cap lamp 1, attached to the hard hat of the glare source mounting fixture, pointed down to the floor more than the other cap lamps; hence, less light was directed to the subjects' eyes.

One limitation of this paper was that age was not included as a factor. Prior NIOSH research indicated that this is a significant factor [20], [21] for visual performance and glare. This research indicated that glare increases with age. Based on this prior research, it would be expected that younger subjects would perceive discomfort glare as less troubling compared to the glare rating presented in this paper.

B. Predictive Glare Ratings

Considering the de Boer ratings from the human test subjects and the two predictive methods, there is not much variation between the de Boer rating methods except for cap lamp 1. The Schmidt-Clausen and Bindels method gave the lowest (worst) glare rating of the entire cap lamps tested, which is odd since cap lamp 1 produced the lowest mean illuminance at the eyes, which should result in the best de Boer glare rating. Contrasting the Schmidt-Clausen and Bindels method with the Bullough [14] method shows the latter method as more in agreement with the subjective glare rating for cap lamp 1. This may suggest that multiple illuminances (i.e., from light source, surround, and ambient condition) are better photometric quantities to use in conjunction with a simple model to predict discomfort glare, and it may suggest that the Schmidt-Clausen and Bindels method has shortcomings for low levels of eye illuminance.

In addition, the range effect mentioned earlier is worth discussing briefly. The range effect is a tendency for a subject to use as much of the rating scale as possible relative to the experimental conditions. The range effect may provide an explanation when comparing the subjective glare rating for cap lamp 1 (de Boer rating of 7.5) with cap lamp 3a (de Boer rating of 4.9). In this case, the average eye illuminances were 0.76 lx (lowest of all cap lamps tested) and 3.42 lx (highest of all cap lamps tested) for cap lamps 1 and 3a, respectively. This large range of illuminance may have the effect of an artificially higher de Boer rating for cap lamp 1 given the wide range of illuminance afforded between cap lamps 1 and 3a.

C. Concluding Remarks

The discomfort glare results indicate that the multibeam pattern (see Fig. 3) of cap lamp 3b does not pose unacceptable discomfort glare. NIOSH research has inferred that cap lamp 3b enabled the best visual performance among LED cap lamps that included cap lamps 1 and 2 described by the research of this paper. Results show that the cap lamp 3b improved the ability to perceive objects in the visual field by improving detection times by as much as 79.5% in peripheral motion detection as well as a 194.1% detection time improvement for floor trip objects [22]. Thus, it appears that cap lamp 3b would enable the best visual performance without the tradeoff of unacceptable discomfort glare. This research provides important data for improving the design of future cap lamps and has the potential to positively affect the safety of employees in the underground mining industry.

Second, the Schmidt-Clausen and Bindels glare prediction model seems to have limited usefulness given that it erroneously predicted cap lamp 1 had the worst discomfort glare. Empirically, cap lamp 1 had the best discomfort glare. The predictive discomfort glare model by Bullough appears to be more useful given that it more closely matched the empirical data.

Lastly, the research presented in this paper was conducted in a simulated mine with human subjects that were not miners. Our next logical and planned step is to conduct a field comparative evaluation of the NIOSH LED cap lamp in a coal mine, using miners as the test subjects.

Acknowledgment

The studies described in this paper were conducted with assistance from J. Srednicki, J. Carr, T. Matty, and T. Minoski. The vision testing was conducted by M. A. Rossi, R.N., and all employees of the National Institute for Occupational Safety and Health (NIOSH) at the Bruceton, PA, location.

References

[1] M. S. Rea, Ed., *Lighting Handbook: Reference & Application*, 8th ed. New York: Illuminating Eng. Soc. North Amer., 1993, 666 p.

[2] K. Cornelius, L. Steiner, and F. Turin, "Using coal miners' experience to identify effective operating cues," in *Proc. 42nd Annu. Meeting Human Factors Ergonom. Soc.*, 1998, pp. 1098–1102.

[3] M. S. Rea, Ed., *Lighting Handbook: Reference & Application*, 9th ed. New York: Illuminating Eng. Soc. North Amer., 2000, pp. 3–14.

[4] J. Van Derlofske and J. D. Bullough, "Balancing visibility and glare," in *Proc. Nat. Highway Traffic Safety Workshop*, 2006, MS PowerPoint Presentation.

[5] C. L. Crouch, "Disability glare studies on underground mine personnel," in *Proc. 2nd Int. Mine Lighting Conf. Int. Comm. Illumination (CIE)*, 1982, pp. 186–191.

[6] S. K. Guth, "Discomfort glare sensitivity of underground mine personnel," in *Proc. 2nd Int. Mine Lighting Conf. Int. Comm. Illumination*, 1982, pp. 17–22.

[7] Illuminating Engineering Society (IES), "Outline of a standard procedure for computing visual comfort ratings for interior lighting," J. IES, Committee Recommendations Quality Quantity Illumination IES, New York, R00 Rep. 2 (1972), 1973.

[8] D. A. Trotter, *The Lighting of Underground Mines Gulf*, 216 pp., 1982.

[9] J. Van Derlofske, J. Bullough, P. Dee, J. Chen, and Y. Akashi, "Headlamp parameters and glare," Society of Automotive Engineers World Congress & Exhibition (SP-1875), Warrendale, PA, Rep. SAE 2004-01-1280, pp. 195–203, 2004.
[10] J. D. Bullough, Z. Fu, and J. Van Derlofske, "Discomfort and disability glare from halogen and HID headlamp systems," in *Proc. SAE World Congr.*, Detroit, MI, Mar. 4–7, 2002, SAE 2002-01-0010, 7p.
[11] J. D. Bullough, J. Van Derlofske, P. Dee, J. Chen, and Y. Akashi, "An Investigation of Headlamp Glare: Intensity, Spectrum, and Size," U.S. Dept. Transp., Nat. Highway Traffic Safety Admin., Rep. DOT HS 809 672, 57 p., 2003.
[12] M. Collins and B. Brown, "Glare recovery and its relation to other clinical findings in age related maculopathy," *Clin. Vis. Sci.*, vol. 4, no. 2, pp. 155–163, 1989.
[13] F. Scheiber, "Age and glare recovery time for low-contrast stimuli," in *Proc. Human Factors Ergonom. Soc.*, Santa Monica, CA, 1994, pp. 496–499.
[14] J. D. Bullough, J. A. Brons, R. Qi, and M. S. Rea, "Predicting discomfort glare from outdoor lighting installations," *Lighting Res. Technol.*, vol. 40, no. 3, pp. 225–242, Sep. 2008.
[15] A. B. Lulla and C. A. Bennett, "Discomfort glare: Range effects," *J. Illuminating Eng. Soc.*, vol. 10, no. 2, pp. 74–80, Jan. 1981.
[16] A. W. Gellatly and D. J. Weintraub, "User reconfigurations of the de Boer rating scale for discomfort glare," Univ. Michigan—Transp. Res. Inst., Rep. UMTRI-90-20, 21 p., 1990.
[17] J. B. De Boer, "Visual perception in road traffic and the field of vision of the motorist," in *Public Lighting*, J. B. De Boer, Ed. Eindhoven, The Netherlands: Philips Tech. Library, 1967, pp. 11–96.
[18] R. J. Porter, J. M. Hankey, S. C. Binder, and T. A. Dingus, *Enhanced Night Visibility Series, Volume VII: Phase II-Study 5: Evaluation of Discomfort Glare During Nighttime Driving in Clear Weather,* U.S. Department of Transportation, Office of Safety Research and Development Federal Highway Administration Contract No. DTFH61-98-C-00049, Publication No. FHWA-HRT-04-138, p. 74, Dec. 2005.
[19] D. A. Trotter and F. V. Kopeschny, "Cap lamp improvements in Canadian mines," *Appl. Occupat. Environ. Hygiene*, pp. 858–863, Dec. 1997.
[20] J. Sammarco, A. Mayton, T. J. Lutz, and S. Gallagher, "Evaluation of glare for incandescent and LED miner cap lamps in mesopic conditions," *Mining Eng., Soc. Mining, Metallurgy, Exploration*, vol. 61, no. 6, pp. 1–8, 2009.
[21] M. Reyes, S. Gallagher, and J. Sammarco, "Evaluation of visual performance when using incandescent, fluorescent, and LED machine lights in mesopic conditions," in *Conf. Rec. 44th IEEE IAS Annu. Meeting*, Houston, TX, Oct. 2009, pp. 1–7.
[22] M. Reyes, J. Srednicki, S. Gallagher, and J. Sammarco, "Comparative evaluation of light emitting diode cap lamps with an emphasis on visual performance in mesopic lighting conditions," in *Conf. Rec. 46th IEEE IAS Meeting*, Orlando, FL, Oct. 2011, in press.
[23] S. Siegel and N. J. Castellan, *Nonparametric Statistics for the Behavioral Sciences*, 2nd ed. Boston, MA: McGraw-Hill, 400 p., 1988.
[24] *Title 30, Chapter 1- Mine Safety and Health Administration, Department of Labor, Part 19 Electric Cap Lamps*, GPO, CFR 30—Code of Federal Regulations, Washington, DC, 2005.
[25] Bur. Labor Statist. (BLS), *Mining Employment*, 2008b. [Online]. Available: http://www.bls.gov/oco/cg/cgs004.htm#emply
[26] USDOT, FAA, "Human Factors Design Standard (HFDS)," Rep. DOT/FAA/CT-03/05 HF-STD-001, 2003.

John J. Sammarco (SM'91) received the B.S. degree in electrical engineering technology from The Pennsylvania State University, University Park, in 1978, the M.S. degree in industrial engineering from the University of Pittsburgh, Pittsburgh, PA, in 1986, the M.S. degree in computer engineering from the National Technical University of Fort Collins, CO, in 1986, and the Ph.D. degree in computer engineering from West Virginia University, Morgantown, in 2003.

He is currently a Senior Research Engineer with the National Institute for Occupational Safety and Health, Bruceton Facility, Pittsburgh. His Federal service has been devoted to mine safety research in a wide variety of areas, including mining machine navigation and guidance, control systems, and sensors. His recent research areas concern system safety, hazard/risk analysis of processor-controlled mining systems, smart wireless sensors, visual performance, and solid-state lighting systems for mine applications.

Alan G. Mayton received the B.S. degree in mining engineering from West Virginia University in 1978.

He serves as Research Engineer in the Musculoskeletal Disorders Prevention Team of the Office of Mine Safety and Health Research, Human Factors Branch, National Institute for Occupational Safety and Health, Pittsburgh, PA. His primary interests include the application of current LED lighting technology to underground mining, human body vibration control, vehicle dynamics, ergonomic design of seats and operator compartments, and improved knee-pad design for low-seam coal miners.

Mr. Mayton is a member of the American Society of Mechanical Engineers (ASME), the Vehicle Design Committee of the ASME Design Engineering Division, the International Minerals Association of North America—Ergonomics Task Force, and the International Society of Mine Safety Professionals. His memberships also include the Human Factors and Ergonomics Society (HFES) and the HFES Industrial Ergonomics Technical Group. He is a Certified Mine Safety Professional and a Registered Professional Engineer in Pennsylvania.

Timothy Lutz received the B.S. degree in mechanical engineering from The Pennsylvania State University, University Park, in 1983.

He is a Research Engineer with the Mining Injury Prevention Branch, National Institute for Occupational Safety and Health, Bruceton Facility, Pittsburgh, PA. He began his mining research career at the U.S. Bureau of Mines in 1990, in a variety of safety areas. Since 2005, his research has included underground mine lighting using LED technology which has emerged as an efficient and durable alternative to existing lighting.

Mr. Lutz is a Registered Professional Engineer in Pennsylvania.

Sean Gallagher received the Ph.D. degree in industrial and systems engineering from The Ohio State University, Columbus, in 2003. His dissertation examined the tolerance of the lumbar spine to repeated loading during lifting in forward bending postures.

Since 1984, he has been performing research to reduce musculoskeletal disorder risk in the mining industry, initially with the U.S. Bureau of Mines and currently with the National Institute for Occupational Safety and Health, Pittsburgh, PA. A major interest has been to quantify the physical demands associated with work in the underground coal mine environment and the biomechanical and physiological effects of working in restricted workspaces.