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LED lighting for improving trip object detection for a walk-thru roof bolter

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Abstract

Proper lighting plays a critical role in enabling miners to detect hazards when operating a roof bolter, one of the most dangerous mining machines to operate; however, there has not been any lighting research to address the walk-thru type of roof bolter commonly used today. To address this, the Saturn light was designed to directly address walk-thru roof bolter safety by improving trip hazard illumination. The visual performances of 30 participants that comprised three age groups were quantified by measuring each participant's visual performance in detecting trip objects positioned on the two floor locations within the machine's interior working space. The lighting conditions were the existing compact fluorescent lights (CFLs) and the Saturn LED area light developed by NIOSH researchers. Three intensities of the Saturn lights were used, 100%, 75%, and 50%, all of which resulted in better visual performance, and up to a 48% reduction in average trip detection time compared to the CFL. For the Saturn trip object miss rates were <0.5% for all age groups in contrast to the CFL, which ranged between 32.5% for the youngest group and 50.4% for the oldest group.

1. Introduction

Historically, mining has been one of the most dangerous industry sectors. Fortunately, there is a trend of increasing mine worker safety, with the rate, per 100 full-time equivalent employees, of mining nonfatal lost-time injuries having been reduced 65% during the period from 2001 to 2015; however, mining fatalities and injuries are still at unacceptable levels. During 2016, U.S. underground mines had 10 fatalities, 1295 nonfatal days lost (NFDL) injuries, and 543 no days lost injuries (NDL).[1] During 2000–2007, mining machine-related incidents had the highest number of fatalities,[2,3] and 41% of all serious accidents.[4,5] Operating a roof bolter was determined to have the second highest number of nonfatal lost-time and no days lost injuries.[2] Mine Safety and Health Administration (MSHA) data (2007–2016) indicate that there were 96 roof bolter machine NFDLs at underground

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locations in coal mines where the injury was classified as a slip or fall, resulting in a total of 5580 lost work days.[1]

Roof bolting is a critical underground mining activity following the extraction of commodities such as coal, metal, ore, or stone, to help keep the roof from collapsing. The roof bolting process involves drilling a hole into the roof, then inserting a roof bolt and epoxy resin to secure the overlying roof strata. Unfortunately, there are many hazards associated with operating a roof bolting machine. Examples of these hazards are working under an unsupported roof that can fall, operating machinery with moving and rotating parts in a confined space, and navigating a work zone with tripping hazards such as debris and bolting supplies. Moreover, the visual environment has been poor given the machine's size, limited space for mounting lighting, low contrast levels, and excessive glare due to the workers' close proximity to the machine. Anecdotal evidence demonstrating the undesirable effects of glare includes miners painting over or covering luminaires, thus reducing illumination to unsafe levels.

The Federal Mine Safety and Health Act of 1977 required a luminance of 0.06 fL (0.21 cd/m^2) for the roof, floor and side areas within a distance of 1.5m from the roof bolter perimeter.[6] Hence, the regulations in effect today are based on 40-year-old machine designs that required workers to be in these exterior areas. Major safety hazards exist in these exterior areas because workers can be struck by moving parts of the machine or become trapped or crushed between the walls of the mine and the roof bolting machine. Roof bolter designs have changed dramatically over the years to eliminate these hazards. Newer roof bolting machines employ a walk-thru design that enables the operator to walk through the centre of the roof bolter and then operate the machine from within the interior space. While this new design improves safety in many areas, it creates new hazards for trips because the lighting now becomes critical within the machine's interior work areas. However, with newer designs that now place workers in the interior areas, it is unknown if the current luminance mandate of 0.21 cd/m^2 is sufficient. There is a need to improve safety so that miners are empowered to better see hazards and take actions to reduce or eliminate roof bolter safety risks. Thus, lighting plays a critical role for miners to see hazards.

There is some related research concerning trip object detection by Fotios and Cheal that was intended to determine appropriate road illuminance for pedestrians to detect road obstacles in relatively low lighting conditions.[7,8] The road surface and its reflectivity would be somewhat similar to that of coal mines. Cylindrical objects were raised at various heights from a surface to model the trip stimulus. Various lamp types were used to illuminate these objects. The effect of age was noteworthy at low light levels (0.2 lux), but increased illuminance (20 lux) eliminated statistical differences in detection rates between age groups.[7] The authors found that the ability to detect the obstacles increased as the illuminance increased up to a given threshold. Further increases of light yielded little improvement where a threshold illuminance of 5.7 lux was determined to be appropriate. However, the research was not intended to establish actual roadway illuminance thresholds.[8]

Performance of LED light sources has been studied in comparison to legacy and competing technologies. In industrial applications, LED sources have potential advantages in providing superior visual performance with lower luminous flux output and power use, superior performance in low-light (mesopic) conditions, the ability to minimise discomfort glare through the use of optics,[9–12] and the longer life resulting in less maintenance being required.[13]

There has been very little study of mining machine lighting in the detection of trip hazards in a simulated underground mine environment. In one study by the National Institute of Occupational Safety and Health (NIOSH), incandescent, fluorescent, and cool-white light-emitting diodes were used to create four lighting combinations.[10] Three age groups of participants were used. Their visual performance was quantified as the speed in detecting the trip objects. The results indicate that the main effects of lighting and age were significant, but not the two-way interaction of light and age. Younger participants, detection time was about 17.6% faster (a three-second reduction) than the older age groups on average. The lighting combinations that included LED lights had about a 6.1% (1 second) reduction in detection time.[14] Age is an important factor. The physiology of the human eye degrades as a person ages, resulting in decreased visual performance. These age-related changes include yellowing of the eye lens, loss of rod photoreceptors, and increased susceptibility to glare. Older age is related to a deterioration in optical transmission and ciliary muscles, resulting in lower retinal illuminance.[15] Thus, given an aging workforce, the need for effective underground lighting becomes even more pressing.

Unfortunately, there has not been any roof bolter lighting research to address the walk-thru design. Thus far, roof bolter research has addressed operational errors that have caused fatalities and injuries. A visual feedback system has been developed to reduce errors while operating roof bolting machines.[16] Earlier efforts to improve roof bolter safety focused on training[17] and safety interventions that included interlocks.[18]

To address this need for improved area lighting and lighting research that addresses modern roof bolter design, NIOSH researchers have developed an LED area luminaire called the Saturn. The Saturn was designed to directly address walk-thru roof bolter safety by improving hazard illumination to reduce the likelihood of trip accidents in the interior spaces of a roof bolter. The research presented here focuses on the visibility of trip hazards located within the interior working areas of the roof bolting machine for various lighting conditions that include the NIOSH-developed Saturn LED area luminaire. Several research questions are addressed by the present paper: (1) Does the Saturn luminaire improve trip hazard detection compared to the existing compact fluorescent (CFL) lighting used on a roof bolter? (2) Do various light outputs of the Saturn (100%, 75%, and 50%) show significant differences in trip hazard detection? (3) What is the significance of age for trip hazard detection? (4) Is the Federal requirement of a luminance of 0.06 fL (0.21 cd/m^2) sufficient for the interior working areas of a roof bolter?

2. Method

2.1 Study description

The present study is a comparative evaluation of visual performance for the detection and recognition of trip hazards using the traditional roof bolter lighting as compared to the

Saturn luminaire. The experimental design is based upon prior NIOSH research that evaluated trip object recognition given various mining machine lighting conditions.[11,12] A 2 × 6×3 (two light sources × six trip objects × three age groups) mixed-factorial within-participant design was used. Visual performance was quantified as the time to detect a trip hazard visual stimulus and the accuracy in recognising the location of the visual stimulus.

2.2 Experimental layout and apparatus

The study took place in the Human Performance Laboratory (HPL) at the NIOSH research facility in Bruceton, PA, with the laboratory simulating an underground coal mine environment. A Fletcher model HDDR roof bolting machine was placed within the HPL. The HDDR served as the test vehicle for the study. The roof bolter is painted orange and the reflectivity of the paint was measured at 25% percent.

Locations for the two phases of the study are shown in Figure 1. The interior work spaces were located in the middle walkway section of the machine and the front of the machine. Mine workers walk or crawl through the walkway section as they carry materials to the front of the machine.

A lighting survey indicated that the end of the walkway had the lowest levels of illumination. The front location is where the mine worker spends most of the time conducting the drilling and bolting tasks. Location 1 for Phase 1 is the walk-thru area. Location 2 for Phase 2 is in the area most used by the operator during bolting operations. The locations of the luminaires tested are also shown in Figure 1, with six CFLs being the existing luminaires located as they are on current bolters. A single Saturn luminaire was placed at each of the two locations to illuminate the working area. Participants remained stationary and standing at each location, at about 1.5m (5 ft.) away from the trip object apparatus (Figure 2).

The walk-thru roof bolter has a roof support mechanism that gets raised to reinforce the roof of a mine while the roof bolting operations take place. The height of the roof support affects the angle of the luminaire placed on the bolter and the illumination of the working area in Phase 2. The height was set at a 2.3 m, which is representative of the height of a mine roof, and was not varied during the study.

An electro-mechanical trip object apparatus (Figures 2 and 3) was used to randomly present the trip objects for the warmup session used to familiarise participants with the testing, and for the trip object detection and recognition testing of Phases 1 and 2. One apparatus was placed on the centre walk-through area floor and another on the floor near the roof support at the front of the roof bolter. Each apparatus was 216mm in height and contained six cylindrical trip objects that projected from the top surface of the apparatus. The trip objects were raised by an electro-mechanical solenoid at random intervals when the participant held down a computer mouse button. The trip objects were fully raised within 100 ms. Each trip object was 25.4mm long with an outer diameter of 3.3 cm and an inner diameter of 2.2 cm. The objects were painted a dark gray colour so that they would have a very low contrast and a reflectivity of about 6%, which is similar to an object (mine cable, pipe, or tool) coated with the coal dust and other material from the mine floor. A data acquisition computer was present behind the participant during all trials for manually entering data voiced by the participant. Headphones playing an audio file of sound from a roof bolter during operation were placed on a participant in order to isolate the participant from audio cues of the mechanical actuation of the trip objects and to create a more realistic environment.

2.3 Participants

The participants were federal employees. Three age categories were established: youngest 18–25 years; middle 40–50 years; oldest>50 years. The age group from 26 to 39 years was not included because there are generally minimal changes in vision for those ages.[19] Thirty people participated, with 10 in each age group. The average ages were 23.3 years (St. Dev=1.77), 45.1 years (St. Dev=3.40), and 57.7 years St. Dev=3.30), for the age groups of youngest, middle, and oldest, respectively. The average age of all volunteers was 42 years. Age was an important factor to consider for mining given the median coal miner age of 44.7 years.[20] There were no exclusions based on sex, race, or ethnicity. Only the participants that passed vision tests for distance visual acuity, contrast sensitivity, and peripheral vision were accepted for the study. The visual acuity and peripheral vision tests were conducted using the Titmus V4 vision screener and contrast sensitivity tests were conducted using the Mars Letter Contrast Sensitivity charts. Participants were required to have: normal or corrected vision with an acuity of 20/40 or better; contrast sensitivity values of 1.60 to 1.92 for participants ≤60 years old and 1.52 to 1.76 for participants >60 years old; peripheral vision of at least 80 degrees for each eye. Participants that had self-reported radial keratotomy, monocular vision, glaucoma, or macular degeneration were excluded. Miners were not recruited because of potential expectancy biases that could confound empirical data. Miners could immediately determine that some of the lighting conditions were very different; thus, a negative bias could exist because the lighting is not what they are accustomed to, or a positive bias could exist if the person perceives something new as better.

The protocol was approved by the NIOSH Institutional Review Board. Informed consent was obtained from all participants in the study. Participants could withdraw from the study at any time. All participants completed all parts of the study.

2.4 Luminaires

The existing roof bolter luminaire uses a compact fluorescent (CFL) light source that is shrouded by an amber polycarbonate globe to protect it. The existing machine lighting was at 100% light output.

The Saturn luminaire uses an array of 12 cool-white LEDs with a secondary optic to provide a type III light distribution intended for luminaires mounted at or near the side of medium-width roadways. The light output of the Saturn luminaire was dimmed to 75% and 50% of maximum to enable the study of how the light output affects trip hazard detection. This dimming was achieved by placing neutral density filters onto the Saturn luminaire bezel. Table 1 and Figure 4 define the lighting parameters.

Figure 4 depicts the SPDs where the CFL has a predominance of medium and long-wavelengths in contrast to the Saturn LED light that has more short-wavelengths. This is an important distinction because in low light mesopic conditions, the eye rod photoreceptors dominate relative to the cone photoreceptors. The rod photoreceptors are more sensitive to the short wavelengths while the cone photoreceptors are more sensitive to the medium and long wavelengths. The relative stimulation of the rods is quantified by the S/P ratio where a higher S/P ratio indicates greater stimulation of the rods with respect to the cones, so obstacle detection in mesopic conditions improves as the S/P ratio increases.[21]

Figure 5 shows CFL and Saturn luminaires. Figure 6 shows the light distribution patterns of these luminaires. Table 2 lists the average luminance for the trip objects associated with Phases 1 and 2. The luminance was measured at the top, middle, and bottom surface of each trip object in the up position and measured with a Konica Minolta LS-100 luminance meter. The measurements were taken once the light output stabilised, which took about 30 minutes, when viewed from where the participant would stand for Phases 1 and 2.

As Table 2 shows, there was a drastic difference between Phase I and Phase II in the average luminances for the CFL luminaires. This was due to the placement of the CFL luminaires with respect to the location of the trip objects. The CFL luminaires of Phase 1 were placed much farther away and only provided indirect illumination of the trip objects.

2.5 Statistical methods

Data were analyzed through a mixed linear model using Proc Mixed SAS version 9.4. Participant and trip object were treated as random effects, and the remaining independent variables of light, age, and object were treated as fixed effects. Trip object was treated as a random effect because object locations were varied to control for the learning effect that would occur if the objects were always presented in the same location. The researchers did not have a primary interest in the effect of a limited set of object locations on detection time.

Data screening revealed two data points which represented unreasonably fast detection times (53 ms in Phase 1 and 61 ms in Phase 2); these data points were excluded from the analysis. Examination of graphs and descriptive statistics showed that the detection time data were positively skewed; therefore, prior to running the mixed model, a log transformation was applied to better meet the assumption of normality. Subsequently, back translation was applied so that means and confidence intervals could be reported using the original metric. Separate analyses for each phase were conducted given that the overall lighting conditions differ significantly. *Post hoc* contrasts were also conducted using SAS. The Bonferroni correction was applied.

2.6 Test procedures

The study began with a warmup session that was intended to familiarise the participants with the test setup. To obtain individual reaction times, the participants completed a baseline test of trip object detection trials under well-lit laboratory illumination conditions. Participants then underwent a 20-min dark adaptation time to adapt to the reduced illumination afforded by the roof bolter lighting.

The study was conducted in two phases that were counterbalanced where 50% of the participants began Phase 1, took a short break, then began Phase 2; for the other 50% of the participants, this order was reversed.

2.7 Trip object detection and object misses

The presentation of the objects was randomised and controlled by a micro-controller. The participants pressed and held down a mouse switch when they were ready to begin the test. Next, at a random time from 0.5 to 2 s, one trip target was presented for 1 s. Participants released the mouse switch when they saw an object and the datum recorded was the time from presentation of the object to the release of the mouse switch. Next, participants verbalised the location of the trip object (locations 1–6). The responses were recorded along with the actual location of the trip object. This datum was used for measuring the accuracy of detection. For a given trial, the six trip objects appeared 24 times and a null condition appeared six times. The presentation order was shuffled using the Fisher–Yates shuffle. There were 30 trials each for the baseline test and each of the four lighting conditions, resulting in a total of 150 trials.

Four seconds was the maximum time that the switch could be depressed. A 4-s timeout was recorded as a missed object and a value of −1 was assigned for the detection time. A value of zero was assigned for a false positive detection such as when the participant released the mouse button before a trip object appeared.

2.8 Data collection

Data collection was accomplished by a combination of automated and manual methods. The automated method used a PC-based data acquisition system to acquire data and then store the data in a spreadsheet-compatible file. The automated data were for trip object detection and detection time. The manually collected data were for participant identification of the trip object and were stored on the data acquisition PC.

3. Results

3.1 Detection times

3.1.1 Phase 1—A mixed model analysis of variance (ANOVA) was conducted to examine the effects of lighting (Saturn 100%, Saturn 75%, Saturn 50%, and CFL), and age (youngest, middle, and oldest) on the dependent variable of detection time. For Phase 1, the main effect of lighting ($F(3,2509)=638.0$, $p < 0.001$) was statistically significant. Although the main effect of age was not significant ($F(2,2509)=2.59$, $p=0.076$), the light by age interaction was statistically significant ($F(6,2509)=8.60$, $p<0.001$). Results for the random effects part of the model showed greater variability among participants than among objects.

The two-way light by age interaction was examined (Figure 7). It can be seen in Figure 7 that detection time was slowest for the CFL luminaire in all age groups. The lines denoting the three age groups are roughly parallel for the three Saturn luminaire conditions, with the slowest detection time for the over 50 age group. However, the positions of the over 50 and 40–50 groups are reversed for the CFL luminaire, with the 40–50 age group having the slower detection time. Overall, Figure 7 depicts a pattern of increasing average detection time with increasing age and decreasing light output.

It was considered justifiable to interpret the main effect of lighting for Phase 1 (see Figure 8) based on the size of the light F-ratio in comparison to the F-ratio of the light by age interaction and because the average detection time was always slowest for the CFL luminaire.

3.1.2 Phase 2—

In Phase 2, the main effect of lighting ($F(3,2779)=67.96$, $p<0.001$), the main effect of age ($F(2,2779)=4.90$, $p<0.01$), and the light by age interaction ($F(6,2779)=8.95$, $p<0.001$) were all statistically significant. Results for the random effects part of the model showed greater variability among participants than among objects. The light by age interaction was examined first. As seen in Figure 9, detection time was slowest for the CFL luminaire in all age groups, and detection time was slowest in the >50 age group for all lighting conditions. A general pattern of increasing average detection time with increasing age and with decreasing light output may be observed in Figure 9. Because of the somewhat similar pattern seen across age groups, it was considered appropriate to interpret the main effect of lighting for Phase 2 (see Figure 10).

3.2 *Post hoc* tests

Pair-wise comparisons of all lighting condition were conducted for Phase 1 and Phase 2. The Bonferroni correction was used to control for inflated Type I error rate. Because there were six pairwise comparisons for each phase, the significance level for each comparison was set at 0.008 (0.05/6). In both phases all comparisons were statistically significant at the corrected level except for the comparison between the Saturn 75% and the Saturn 50% conditions. Differences among the Saturn luminaires were much smaller than differences between the CFL and the Saturn luminaires. The largest difference among the Saturn luminaires for both Phase 1 and Phase 2 was between the Saturn 50% and 100%, with the Saturn 100% having the faster average detection time.

Post hoc contrasts of luminaires were also conducted within each age group. Because there were 18 contrasts for each phase (six contrasts by three age groups), the significance level for each comparison was set at 0.0028 (0.05/18). In Phase 1, differences between the CFL luminaires and each of the three Saturn luminaires were significant (at the corrected level) in every age group. The results indicate that the detection times when using any of the Saturn luminaires were significantly faster compared to the CFL luminaire in all age groups. The difference between the Saturn 100% and the Saturn 50% was significant for both the young and middle age groups, and the difference between the Saturn 100% and the Saturn 75% was significant for the young group.

In Phase 2 differences between the CFL luminaire and each of the three Saturn luminaires were significant for each age group with one exception. In the young group, the difference between the CFL luminaires and the Saturn 50% condition was not significant at the corrected level. While none of the differences among the three Saturn luminaires were significant at the corrected level in the middle and old groups, in the young group the Saturn 50% was significantly different from both the Saturn 75% and the Saturn 100% conditions, with the slowest detection time being for the Saturn 50% condition.

3.3 Miss rate

Signal detection theory (SDT) can indicate decision quality under conditions of uncertainty.[8] SDT defines four categories: a 'hit' is correctly identifying that a trip obstacle was present; a 'miss' is a failure to identify a trip object when it is present; a 'false positive' is identifying a trip object when none was present (null condition); a 'correct rejection' is identifying the null condition. The sensitivity index (*d'*) statistic, shown in equation (1), is commonly used in SDT to quantify the detectability of a signal (trip object) that is present or not present.[22] Detectability increases as *d'* increases, while a *d'* near zero indicates chance detection (no detectability).

$$d' = Z(\text{hit rate}) - Z(\text{false positive rate}) \quad (1)$$

Where Z is the Z-transform.

Table 3 depicts the miss rates, false positive rates, and *d'* values for the age groups and lighting conditions. There were no significant differences (maximum difference of 0.4%) in miss rates among the Saturn lighting conditions, so only the 100% Saturn luminaire values are listed. All values of *d'* were considerably greater than zero, indicating that the results are not by chance.

4. Discussion

The research questions of this study were to determine if the lighting provided by the Saturn luminaire enabled better detection than the lighting provided by the CFL luminaire; to determine if there are clear advantages among the three light output variations of the Saturn luminaire; to evaluate the role played by age given the various lighting conditions; and to determine if the Federal requirement of a luminance of 0.06 fL (0.21 cd/m^2) is sufficient. To address these questions, we examine the mean detection times, miss rates, and the effects of age.

4.1 Mean detection times

For Phases 1 and 2, all light output levels of the Saturn luminaire resulted in more rapid detection time, regardless of age group as compared to the CFL luminaire that is the current standard for roof bolting machines. We infer from the results that the Saturn luminaires enabled better detection times because of the higher S/P ratio, higher CCT, and the greater object luminance produced by the Saturn luminaire. In general, there is an improvement in detection when luminance increases and when the S/Ps of the light source increases.[14,21,23] The lowest Saturn luminaire S/P ratio was 1.67 compared to 0.61 for the CFL. Median object luminance was only 0.019 cd/m^2 for the CFL luminaire compared to 0.216 cd/m^2 for the Saturn luminaire at 50% light output of Phase 1. The Phase 2 median object luminance afforded by the CFL and Saturn luminaires was similar; for instance, there was 0.627 cd/m^2 and 0.597 cd/m^2 for the CFL luminaire and the Saturn luminaire at 50% light output, respectively. The Saturn luminaire at 50% light output resulted in an 8% improvement in average detection time compared to the CFL luminaire even though the CFL luminaire provided slightly higher mean luminance. The 8% improvement with the Saturn luminaire at 50% light output is likely due to the much higher S/P ratio.

Post hoc tests of the Saturn luminaires indicated that the Saturn luminaire at 100% light output provided the best mean detection time which was likely due to it affording the highest median object luminance and a much higher S/P ratio than the CFL luminaire. However, the differences were very small between the Saturn luminaire at 100% and 50% light output – a 30 ms reduction for Phase 1 and a 26 ms reduction for Phase 2. It does not appear there is a significant practical advantage for using the Saturn luminaire at 75% or 100% light output based on mean detection time.

Overall the results are somewhat similar to a prior study of mining machine lighting that compared the use of LED lighting as an auxiliary source for the existing incandescent and fluorescent machine lighting. The addition of an LED light source resulted in mean detection times that were significantly faster by approximately one second than mean detection times achieved without the LEDs.[10] The mean object luminance was much greater with the auxiliary LED sources (0.18cd/m^2 versus 0.052 cd/m^2) thus accounting for the faster mean detection times. It is difficult to make direct comparisons to this prior study because the mean object luminance was very different and because the S/P values were not provided in the prior study. However, both studies indicate that increasing object luminance can improve object detection.

4.2 Miss rate

Miss rates are of prime importance for safety because workers cannot avoid a trip hazard if they do not see it. The results for miss rates (Table 3) provide compelling evidence for the benefits of all the Saturn lighting conditions of Phase 1, where the miss rates were <0.5% for all age groups using Saturn luminaires in contrast to the CFL luminaires, which ranged between 32.5% for the youngest group and 50.4% for the oldest group. There were no statistically significant differences (maximum difference of 0.4%) in miss rates among the Saturn lighting conditions, so miss rates do not appear to be a primary consideration for selecting the Saturn light output. The Phase 1 miss rate results are likely due to the increased object luminance provided by the Saturn luminaires, which had an average object luminance up to more than six times that provided by the CFL luminaires. The Phase 2 miss rate results were less dramatic and seem to support the view that the luminances provided by either the Saturn or CFL luminaires was sufficient given the maximum miss rates of 0.4% and 1.5%, respectively.

4.3 Age

Overall, age does not appear to be a major factor given it was not statistically significant for Phase 1 ($F(2,2509)=2.59$, $p=0.076$ and it had the smallest effect ($F(2,2779)=4.90$), $p<.0.01$) for Phase 2. However, the Phase 1 two-way interaction of age and light is of interest given this interaction was statistically significant. The results for only the Saturn luminaires follow a trend of increasing average detection time with increasing age and decreasing light output, which would be expected because generally detection time improves with increased luminance[14,21,23] and decreasing age.[10–12] The amount of change in average detection time for Phase 1 is very small (about a 6% difference) among the Saturn luminaires and three age groups. In general the same average detection time trend for the CFL luminaire is apparent with the exception that the mean detection time for the 40–50-year age group was higher than that of the >50 age group where mean detection time was 888 ms compared to the oldest age group mean detection time of 833 ms. The eye test results for these age groups were compared and no significant differences were apparent, thus an explanation eludes us at this point. The significant Phase 2 two-way interaction of age and light indicates that, over all lighting conditions, the oldest age group had the worst average detection time and the youngest age group had the overall best average detection. The amount of change in average detection time for Phase 2 is very small (about a 5% difference) among the Saturn luminaires at different light outputs and three age groups which is similar to the Phase 1 results. Therefore, there does not appear to be a compelling justification to use the increased light output of the Saturn 75% and 100% given the interaction with age.

4.4 Federal luminance requirements

A luminance of 0.21 cd/m^2 is required for the areas about the perimeter of the roof bolter machine. This luminance also appears to be applicable for the interior working areas of the machine. The CFL luminaire median luminance for Phase 1 was only 0.019 cd/m^2 compared to 0.216 cd/m^2 afforded by the Saturn luminaire at 50% light output, which enabled a 45% improvement in average detection time and a miss rate of 0.4% compared to the 50.4% miss rate of the CFL luminaire for the oldest age group. We note that the 0.216 cd/m^2 enabled by the Saturn 50% is slightly higher than the Federal requirement but we believe this 2.8% luminance increase is likely insignificant. Median luminance values that exceeded 0.21 cd/m^2 resulted in modest improvements in average detection time and miss rates for the Saturn luminaire at 100% and 75% light output; thus it appears that exceeding the Federal luminance requirement would yield few benefits.

4.5 Limitations

The testing was conducted in a controlled laboratory environment that closely emulated an underground coal mine, but it did not include factors such as airborne dust and other environmental factors that might affect visual performance. Also, the participants were stationary and the targets popped up; hence the movement provided a visual cue that would not exist for the detection of static trip objects. Therefore, it is unknown how well the results can be generalised to the detection of static trip objects. Further, the cognitive demands on the test participants were relatively low compared to those of a miner working with the roof bolting machine in a confined, noisy environment. Thus, the significance of the working cognitive demand is unknown, but it is expected that the mean detection times and object miss rates would be higher.

Second, the research focused on the interior working spaces given one of the research questions to be addressed concerned the adequacy of the Federal requirement of a luminance of 0.06 fL (0.21 cd/m^2) with respect to interior working areas of a roof bolter. The research was very limited concerning luminances lower than the Federal requirement given that only the CFL luminaire for Phase 1 had a median luminance below the Federal requirement. Additionally, lighting for the exterior working spaces was not addressed because the Saturn luminaire was specifically designed for the interior work areas. The Saturn luminaire cannot replace the CFL luminaires used on the sides of the roof bolter because it will not provide the required luminance on the mine walls.

Next, positioning of the luminaires is likely a factor that affected the mean detection time and miss rates. Different positions would provide different luminances, contrasts and shadow patterns all of which are important in detecting trip objects. Varying the position of the luminaires was outside of the scope of this paper.

Lastly, a detailed evaluation of glare for each lighting condition was outside the scope of this paper. Glare is an important factor that needs to be taken into consideration and will be addressed in a future paper.

5. Concluding remarks

The Phases 1 and 2 data indicate faster average detection time and decreased miss rate when using the Saturn luminaires. For instance, for Phases 1 and 2, the average detection time, respectively, decreases by 48% and 13% when compared with the Saturn luminaire at 100% light output and the CFL luminaire. The Saturn luminaire at 50% light output appears adequate given that the increased luminances produced by the Saturn luminaire at 75% and 100% light output only enabled slight improvements in average detection time for Phases 1 and 2. Second, there was only a maximum difference of 0.4% in miss rates among the Saturn luminaire lighting conditions, so there appears to be very little advantage to using the increased light outputs of 75% and 100%. Lastly, age appears to have little effect on differences among the Saturn lighting conditions for both phases; therefore, there is no compelling evidence to justify the use of the higher light outputs of the Saturn luminaire.

To date, there has not been any roof bolter lighting research to address the interior lighting of a walk-thru roof bolter, nor are there federal regulations that define lighting requirements for the interior working spaces. Hence, this study addresses this major knowledge gap and has several practical applications. This study substantially adds knowledge on the determination of luminance needed for trip hazard detection for a walk-thru roof bolter. This research can be used for new roof bolter lighting that can potentially save the lives and reduce the severity and frequency of injury to miners by enabling miners to better detect roof bolter trip hazards.

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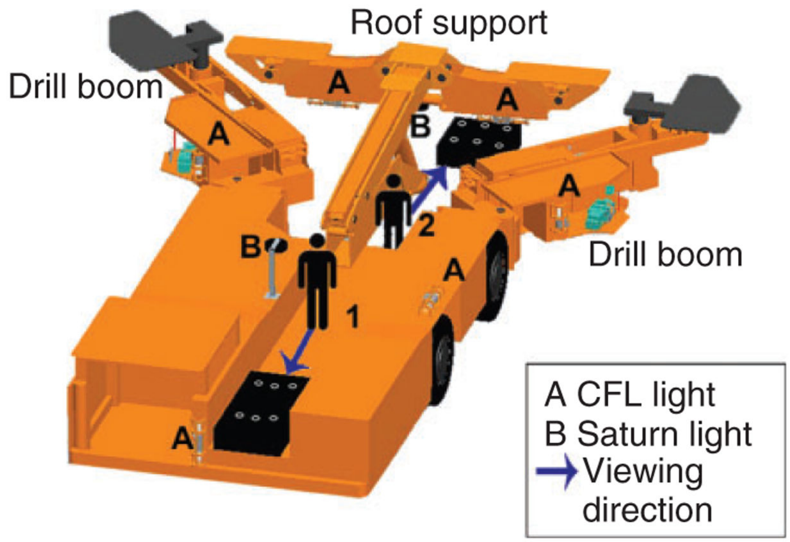

Figure 1.

Phase 1 of the study was conducted near the centre location 1 and Phase 2 was conducted at the front of the roof bolter at location 2. The luminaire locations, participant viewing directions, and trip object apparatuses are also depicted

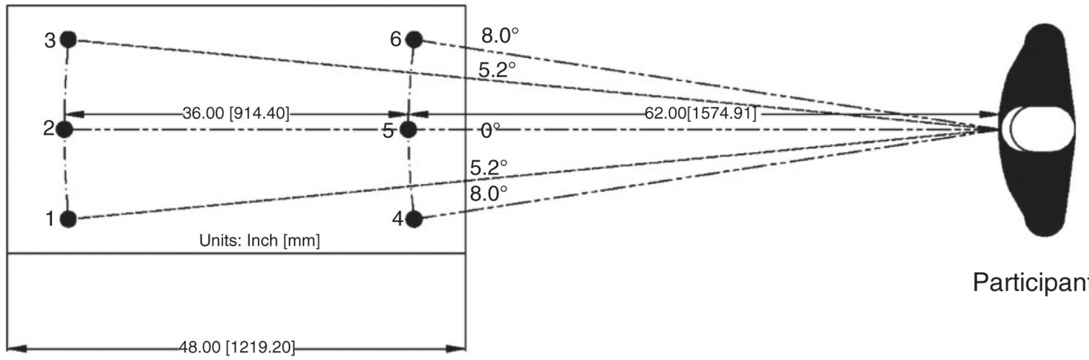

Figure 2.
Plan view of the experimental layout for trip hazard detection procedures (not to scale, units shown are in inches (mm)). The trip objects are labeled 1 through 6

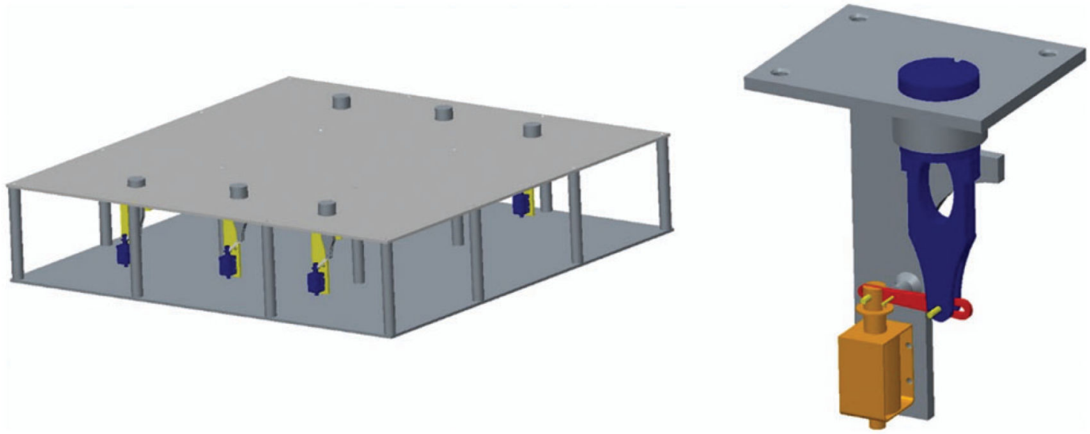

Figure 3.
The electro-mechanical trip object apparatus. The close-up depicts a single trip object mechanism. The colouring is for illustration purposes only

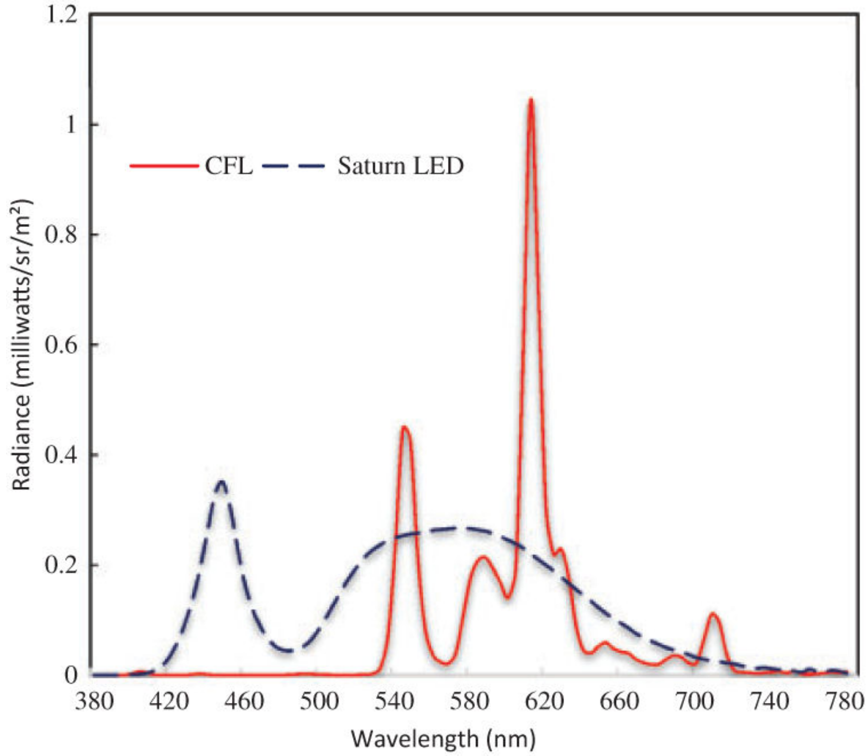

Figure 4.
The spectral power distributions (SPDs) for the CFL and Saturn luminaires at 100% light output

Figure 5.
The Saturn luminaire pictured next to two existing roof bolter CFL luminaires

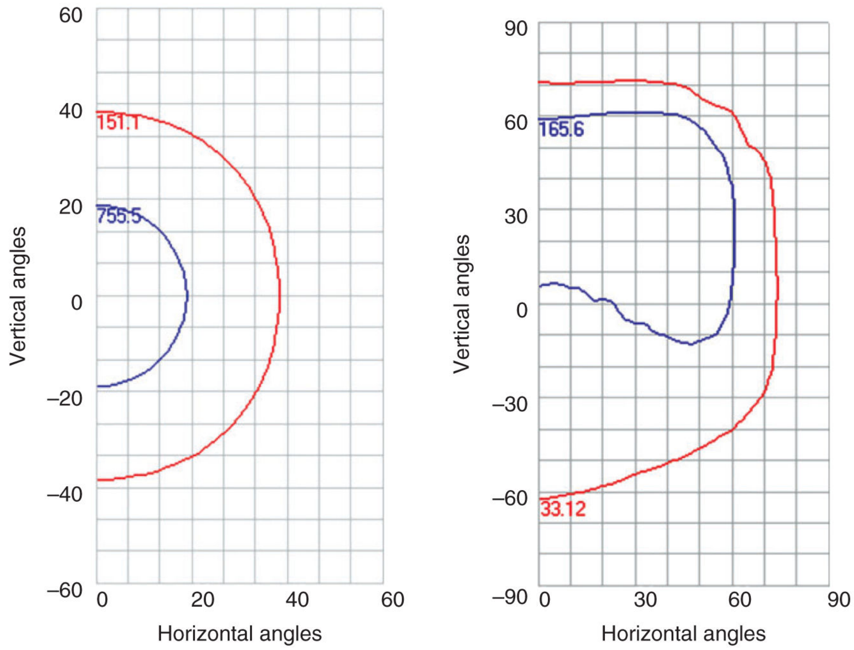

Figure 6.
Isocandela plots of the existing CFL (left) and the Saturn 100% (right) luminaires

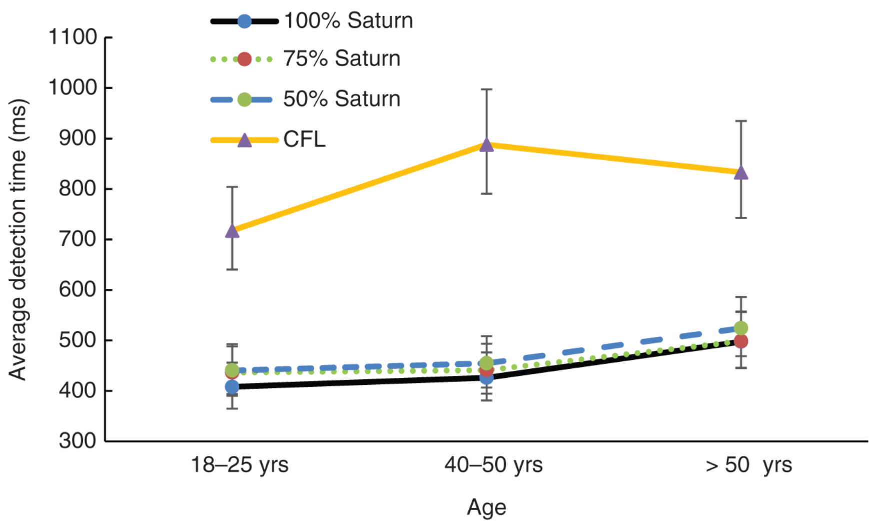

Figure 7.
The two-way interaction of lighting and age for Phase 1

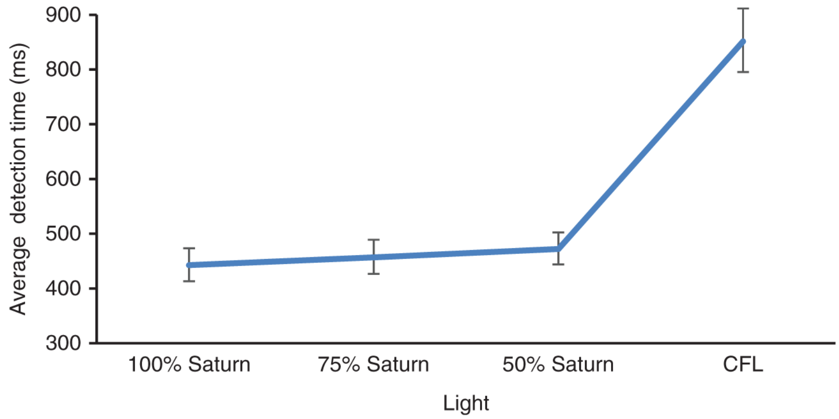

Figure 8.
The main effect of light for Phase 1

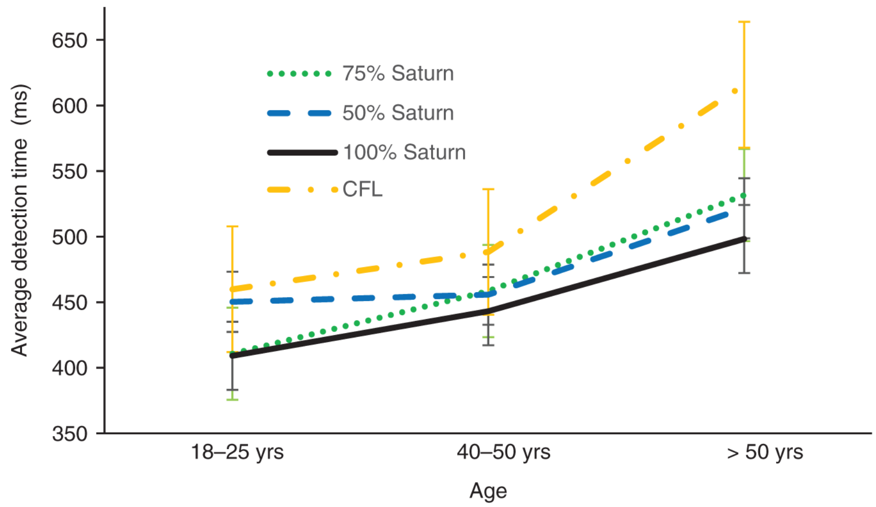

Figure 9.
Average detection time as a function of the two-way interaction of age and lighting for Phase 2

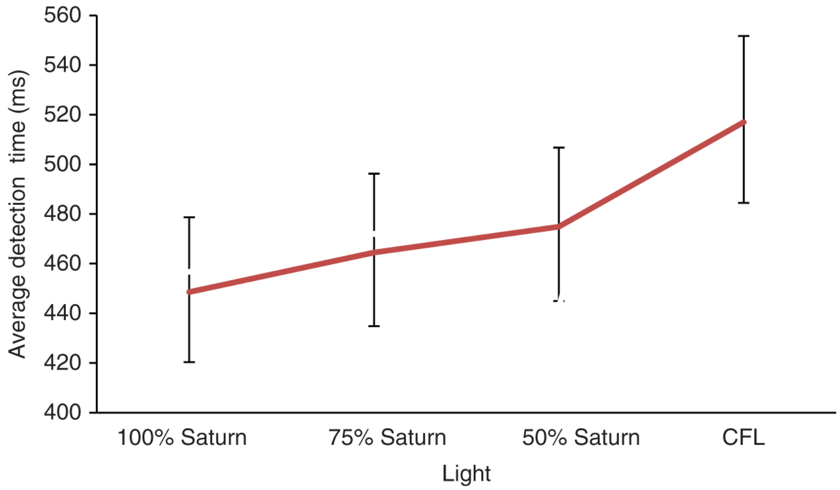

Figure 10.
The main effect of lighting for Phase 2

Table 1

Lighting parameters that include light output (lumens), CCT and the S/P ratio

Luminaire	Light output (lumens)	CCT (K)	S/P ratio
Saturn 100%	663	4584	1.69
Saturn 75%	464	4428	1.67
Saturn 50%	332	4456	1.67
CFL	2100	1937	0.61

CCT: correlated colour temperature; S/P: scotopic/photopic; CFL: compact fluorescent luminaire.

Table 2

Average luminance for each trip object and lighting condition for Phase 1 and Phase 2

	Object	Luminance (cd/m^2)				
		Baseline	CFL	Saturn 100%	Saturn 75%	Saturn 50%
Phase 1	1	2.954	0.022	0.171	0.100	0.070
	2	8.041	0.033	0.759	0.412	0.344
	3	3.085	0.022	0.648	0.375	0.251
	4	10.327	0.010	4.783	3.005	2.009
	5	16.167	0.011	4.656	2.970	1.936
	6	5.043	0.006	1.869	1.261	1.103
Phase 2	1	1.374	0.130	0.225	0.154	0.106
	2	0.754	0.199	0.305	0.240	0.152
	3	0.684	0.116	0.245	0.173	0.140
	4	1.459	0.066	0.112	0.092	0.050
	5	2.246	0.088	0.145	0.108	0.072
	6	2.454	0.106	0.125	0.107	0.042

Note: The baseline condition refers to the average luminances of the trip objects in a well-lit laboratory.

Table 3

Miss and false positive rates, and the sensitivity index *d'* for the lighting conditions, age groups and test phases

Luminaire	Age group	Miss rate %		False positive rate %		*d'*	
		Phase 1	Phase 2	Phase 1	Phase 2	Phase 1	Phase 2
Saturn	Youngest	0.0	0.0	1.75	1.67	2.13	2.18
CFL	Youngest	32.5	1.5	6.75	7.58	1.96	3.60
Saturn	Middle	0.4	0.4	5.00	3.33	4.28	4.47
CFL	Middle	42.1	0.8	11.70	1.67	1.39	4.84
Saturn	Oldest	0.4	0.0	0.00	1.85	na	2.09
CFL	Oldest	50.4	0.4	15.10	0.00	2.15	na

Note that *d'* cannot be calculated for conditions where no false positives exist. The 100% Saturn luminaire values are listed.