LED Area Lighting to Reduce Glare for Roof Bolter Operators

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Abstract

Researchers from the National Institute for Occupational Safety and Health (NIOSH) developed a light-emitting diode (LED) area luminaire called the Saturn and conducted a laboratory study using a Fletcher High Dual-boom Mast Feed (HDDR) roof bolting machine. The Saturn luminaire was designed to (1) enhance floor illumination to enable better detection of trip hazards in the interior spaces of a roof bolter and (2) reduce glare that has typically been an issue of concern on roof bolters. This paper reports on the results of achieving the second objective. The existing roof bolter lighting was the baseline and was compared with three versions of the Saturn luminaire relative to light intensity (100%, 75%, and 50%). Discomfort and disability glare data were obtained from 30 participants that comprised three age groups. Discomfort glare perceptions were obtained using the De Boer rating scale, and disability glare was quantified by using Mars Letter Contrast Sensitivity tests. Discomfort glare was reduced at least 3 levels with all Saturn versions. Also, a predictive model was used to estimate discomfort glare, and the results were similar. Disability glare was the least for the Saturn's 50% intensity, and all Saturn versions had significantly less disability glare than with the baseline lighting. Veiling luminance was calculated and used as another indicator of disability glare. Veiling luminance was 28 to 42 times greater with the baseline lighting as compared with that of the Saturn lighting. Lastly, visibility levels were calculated. The Saturn versions were 4 to 6.5 times better in terms of visibility level.

Keywords

Mining; Mine lighting; Machine-mounted lighting systems; Roof bolter; Glare; Visibility

1 Introduction

Roof bolting typically follows the mining process and is critical for securing an underground mine roof to help prevent a cave-in. The roof bolting machine is one of the most dangerous pieces of equipment to operate in underground coal mines [1]. Accident data indicate that operating the roof bolter is a leading cause of machine-related injuries, accounting for 21.7%

of these injuries [2]. The hazards encountered while operating a roof bolter machine include moving and rotating machine parts, confined spaces, a work zone with tripping hazards, and in general poor visibility due to low ambient, low contrast levels, and excessive glare. Therefore, roof bolter lighting is critical for miners to safely conduct the roof bolting process. Lighting glare is a frequent complaint among roof bolter operators. It is not uncommon to see roof bolter lighting inappropriately blocked or shrouded with pieces of wood, cardboard, paint, and even grease to decrease glare. Excessive glare is primarily due to the high luminance contrast between the background and high-intensity luminance of the luminaires mounted on the roof bolter. A high luminance contrast can result in discomfort glare, a loss or reduction in visibility, or both [3]. Thus, glare is a very important factor in determining the design of underground mining machine illumination systems.

Discomfort glare is defined as "a sensation of annoyance, or in extreme cases pain, caused by high or non-uniform distribution of brightness in the field of view. Discomfort glare is a measure of discomfort or annoyance only [4]." Disability glare is defined as "the glare resulting in reduced visual performance and visual ability caused by the action of stray light, which enters the eye and produces a scattering effect within. It causes a veiling luminance over the retina, which, in turn, has the effect of reducing the perceived contrast of the objects being viewed [4]."

Non-mining studies in the outdoors have focused on glare, mostly with respect to different aspects of automobile head-lamps while driving. Van Derlofske and Bullough reported that the light source spectrum contributed considerably to discomfort glare where in general yellowish light sources were perceived as having less discomfort glare, but the light source spectrum did not play a significant role for disability glare [5–7]. Researchers have investigated glare recovery according to age. Scheiber [8] reported that recovery time increased by a factor of 3 for older compared with younger study participants. Lulla and Bennett [9] studied the range of glare source luminance for 40 test participants concerning discomfort glare using a 10.28×10^5 cd/m^2 (300,000 fL) source and a 10.28×10^4 cd/m^2 (30,000 fL) source. A major finding was that a glare source luminance ratio of 10:1 resulted in a borderline "between comfort and discomfort" ratio of 7:1.

Researchers commonly use the De Boer subjective rating scale to evaluate discomfort glare. It is considered the current state-of-the-art method for subjectively assessing discomfort glare [10], and yet it is not without its critics. Bullough et al. [11] noted "the De Boer scale, like all subjective rating research, is prone to difficulties." Gellatly and Weintraub [12] studied the De Boer rating scale for effectiveness in rating discomfort glare and determined it is not optimal and suggested further research for possible improvements. Fotios [13] discusses evaluating the level of discomfort glare with the De Boer rating scale. He questions using this method because of the potential for "false alarms," since the rating scale forces a response without including "no glare" among the possible responses. Moreover, he suggests the possibility of increased response variance owing to uncertainty with the meaning of the magnitude descriptors [13].

A method for predicting discomfort glare is useful considering that determining glare empirically requires substantial resources for participant testing. Bullough et al. [11]

discusses a simple model using light source photometric characteristics for predicting discomfort glare from outdoor lighting installations. Using the model, the authors successfully demonstrated the effect of the photometric quantities—light source illuminance, surround illuminance, and ambient illuminance for predicting discomfort glare. A more recent study by Villa et al. [14] using psycho visual experiments conducted on a test track assessed discomfort glare for pedestrians from LED lighting in urban environments. Their study included the investigation of state-of-the-art models that predict discomfort glare levels with respect to the De Boer subjective rating scale. Models developed by Lin et al. [15] and Bullough et al. [10, 11] resulted in satisfactory performance.

Researchers from the National Institute for Occupational Safety and Health (NIOSH) have investigated glare from incandescent and LED cap lamps, as perceived by 30 participants [16]. The cap lamps had different beam patterns which would impact glare, so a diffusion filter was used to provide homogenous illumination levels and distributions. Hence, the spectral content (color) of the light was the main factor. The results indicated no statistically significant difference in discomfort glare among the incandescent and LED cap lamps. Building on this earlier work, NIOSH researchers focused on (1) investigating whether LED-based cap lamps with various beam distributions have a positive impact on discomfort glare and (2) comparing discomfort glare predictive models to discomfort glare data obtained by testing participants. The results indicated that the Bullough et al. method [10, 11] worked well to predict discomfort glare levels [17]. Another facet of the mining research included an empirical study of discomfort glare associated with machine-mounted area lighting, as perceived by 36 participants. The light sources were incandescent, fluorescent, and LED [18]. The results indicated that the fluorescent machine lights generally were associated with higher levels of discomfort glare, and lighting conditions that used LED machine luminaires were associated with the least amount of discomfort glare.

To address a need for improved roof bolter lighting to reduce the risks from tripping and glare hazards, NIOSH researchers have developed an LED area luminaire called the Saturn. The design documentation is freely available for downloading [19]. The Saturn was designed to meet two objectives: (1) improve floor illumination to enable better detection of trip hazards in the interior spaces of a roof bolter machine; (2) reduce glare that has historically been problematic on roof bolters. The first objective was achieved. There was up to a 48% reduction in average trip detection time compared with the roof bolter's standard lighting. More importantly, the Saturn trip object miss rates were < 0.5% for all age groups in contrast to the standard lighting that ranged from 32.5% for the youngest group to 50.4% for the oldest group [20]. Therefore, the primary objective of the present study was to determine if the Saturn luminaire can reduce discomfort and disability glare as determined by tests conducted with 30 participants. Additionally, a predictive model was used for discomfort glare and veiling luminance was used to indicate disability glare. The second objective was to determine if various Saturn intensities (100%, 75%, and 50%) result in differences in discomfort and disability glare.

2 Methods

2.1 Study Description

The current study focuses on evaluating roof bolter lighting relative to discomfort and disability glare. The existing roof bolter lighting served as the baseline and was compared with several intensities of the Saturn luminaire. A within-subjects design was used where all participants received all treatments. The study was conducted in two phases: Phase 1 was conducted at the middle location of the roof bolter and phase 2 was conducted at the front of the roof bolter (Fig. 1). The phases 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.

The study used a combination of subjective and objective empirical research involving subjective glare perceptions based on the standardized De Boer scale for discomfort glare and disability glare as indicated and quantified by Mars Letter Contrast Sensitivity tests.

2.2 Participants

The participants were federal employees. Thirty participants underwent pre-screening vision tests that included the following criteria:

1. Must not have had prior radial keratotomy or other eye surgeries (self-reported).

2. Must not have monocular vision (self-reported).

3. Must satisfy the following vision criteria:

    a. Visual acuity: Normal or corrected vision with an acuity of 20/40 or better.

    b. Contrast sensitivity: 1.6 to 1.92 values of log contrast sensitivity are acceptable for participants 60 years of age; 1.52 to 1.76 values of log contrast sensitivity are acceptable for participants > 60 years of age.

    c. Peripheral vision of at least 80° for each eye.

4. Must be able to stand unassisted for 30 min (self-reported).

5. Must consent to performing study.

Three age categories were established: youngest from 18 to 25 years, middle from 40 to 50 years, and 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 [21]. There were 10 people in each age group. The average participant ages were: youngest 23.3 years, middle 45.1 years, and oldest 57.7 years. The 40 to 50 years and over-50 groups were 44.8 ± 3.2 and 57.7 ± 2.9, respectively. The average age of all participants was 42 years.

2.3 Experimental Layout

The research was conducted at the NIOSH research facility in Bruceton, PA, within the Human Performance Laboratory. A Fletcher model HDDR roof bolter served as the test machine.

Figure 1 illustrates the layout for the two phases of the study. The work spaces of interest were in the middle walkway section of the machine and the front of the machine. Mine workers walk or crawl through the walkway as they carry materials back and forth from the front of the machine A lighting survey indicated that the location near the end of the walkway (Fig. 1, location 1) had the lowest levels of floor illumination. The front (Fig. 1, location 2) is close to where the mine worker spends most of the time conducting the drilling and bolting tasks. The general locations of the Saturn and compact fluorescent lamp (CFL) luminaires are also shown in Fig. 1.

The walk-through roof bolter also has a roof support mechanism that is raised to temporarily support the roof during bolting. Since the luminaires were mounted to the roof support, illumination would vary with the height of the roof support the during work activities in the phase 2 area. Thus, to eliminate variations in light levels in this work area, the roof support height was fixed at 2.3 m (7.5 ft) from the underside of the roof support to the floor.

2.3.1   Test Placards—Figure 1 depicts the test placard locations that were used to help assess disability and discomfort glare. Disability glare was quantified by using the Mars Letter Contrast Sensitivity Test to measure a participant's visual performance for contrast sensitivity while a given glare source was present. Contrast sensitivity concerns the ability to distinguish an object from its background. This is especially important for mining where low ambient light levels exist and low contrasts are prevalent. For instance, a tripping object on the floor of a mine covered with coal dust would have a very low contrast compared with the mine floor.

The Mars Letter Contrast Sensitivity Test uses a chart of letters of varying contrast (Fig. 2), designed for viewing at a distance of 40 to 59 cm. The chart has 48 letters that are 1.75 cm high, and the letters are arranged in eight rows of decreasing contrast. The results of this standard test can be used as an indicator of disability glare because disability glare can reduce contrast sensitivity [22].

The De Boer 9-point rating scale (Fig. 3) was used as a qualitative method for estimating discomfort glare from lighting systems [23]. Each participant was asked to make a number selection from the De Boer scale that best described their level of discomfort from each lighting condition tested.

2.3.2   Luminaires—The existing roof bolter lighting system included luminaires equipped with 25-watt compact fluorescent (CFL) lamps protected by amber polycarbonate globes. The light output for existing lighting was at 100% intensity.

The Saturn luminaire has an array of 12 cool-white LEDs and includes a secondary optic to provide a light distribution pattern designed for luminaires mounted at or near the side of medium-width roadways. Twelve watts are needed to power a single Saturn luminaire. Test trials included 3 variations in the intensity of the Saturn luminaire (100%, 75%, and 50%). This was done in order to investigate the effect of light intensity on glare. Variations in light intensity were accomplished with neutral density filters fastened to the bezel of the Saturn luminaire. Table 1 lists the lighting parameters. Figure 4 contrasts the amber-colored light

from the CFLs (left) and the Saturn (right) at 100% intensity as mounted on the bottom of the roof support at the front of a roof bolter.

2.4 Statistical Methods

Separate analyses were conducted for phase 1 (middle of roof bolter) and phase 2 (front of roof bolter). Prior to carrying out the main analysis, the distributions of both dependent variables, disability glare and discomfort glare, were examined to evaluate the normality assumption. The distribution of disability glare appeared to be approximately normal, but the distribution of discomfort glare was noticeably skewed to the left, with most participants reporting low levels of discomfort.

The effects of age and light and the age by light interaction were analyzed using mixed linear models. The method is a generalization of standard linear models that allows for correlated data, which is present in within-subjects designs, and non-constant variability. Analysis was performed using the MIXED procedure in SAS 9.4. The effects of age, light, and the interaction were treated as fixed, and the effect of subjects was treated as random. To better approximate normality, a linear transformation was carried out on discomfort glare data to reverse the negative skew to a positive skew, and then a log transformation was applied to the reversed data. However, the transformation made very little difference in the results of tests for the significance of fixed effects. Therefore, for ease of interpretation, results based on non-transformed data are reported.

2.5 Procedures

Each participant in the study completed a 20-min period for dark adaptation to the reduced light levels provided by the lighting system of the roof bolting machine The De Boer chart and the Mars Letter Contrast Sensitivity chart were explained to participants during dark adaptation. Participants were informed that they could quit the study at any time and that they could take a break whenever they felt the need to do so.

The study began with a warmup session to familiarize the participants with the test setup and procedures. Participants randomly received an identification number. Odd number participants started the tests at location 1 and even numbers started at location 2; thus, the test location sequences were counterbalanced. Participants were given a break after tests were completed at their starting location to reduce the potential of fatigue, boredom, and carry-over effects. The luminaire presentation order was randomly selected for each participant.

While standing at the test location, the vertical illumination at the participant's eyes was measured. Table 2 lists the average vertical eye illuminance for each luminaire and test location. Next, they were asked to think about the discomfort ratings for the given lighting condition. They subsequently gave a discomfort glare rating from 1 to 9. Then, they were instructed to look at the Mars Letter Contrast Sensitivity chart to begin the disability glare tests and read aloud the chart letters from left to right for each row of letters beginning at the top row and moving down the chart. When in doubt about any letter, they made their best guess. The test continued until they failed to correctly identify two consecutive letters. After

completing both discomfort and disability tests, the participants were all asked to rest for a few minutes, then walk to the next location to repeat the test procedures.

3 Results

3.1 Empirical Results

Phase 1 and 2 data were analyzed using a mixed-model analysis of variance (ANOVA) to determine the effects of discomfort and disability glare (dependent variables) with respect to age for conditions when using the existing machine lighting system and the Saturn luminaire at 100%, 75%, and 50% intensities.

3.1.1 Phase 1—No main effects were significant, and there were no interactions (Table 3) for discomfort and disability glare. The median De Boer rating level was 8 for the CFL, Saturn 100%, and Saturn 75%; the Saturn 50% median rating was 7. The average contrast sensitivity scores ranged from 1.2 to 1.4, thus indicating a moderate degree of contrast sensitivity loss, so disability glare does not appear to be an issue at the phase 1 location.

3.1.2 Phase 2—For discomfort glare, the luminaire was significant, and there were no significant interactions; age and luminaire were significant for disability glare with no significant interactions (Table 4). Figure 5 depicts the median De Boer rating of discomfort glare for each luminaire. Analysis of the luminaires indicated that there are no statistical differences among the Saturn 100%, Saturn 75%, and Saturn 50%, while each of the Saturn luminaires were statistically different from the CFL with respect to discomfort glare. There were statistically significant differences among all luminaires with respect to disability glare. Post hoc analysis on luminaire showed that all pairwise differences were significant. In other words, not only were all the Saturn luminaires significantly different from the CFL, but also all differences among Saturn luminaires were significant. Post hoc analysis on age showed that both the younger and middle groups were significantly different from the older group, but the difference between the younger group and the middle group was not significant. Figure 6 depicts the average log contrast sensitivity for each luminaire and age group. This figure is provided because the effects of age and luminaire were significant.

Phase 2 data indicate that all intensities of Saturn luminaire can reduce discomfort and disability glare as compared with those of the CFL; therefore, additional analysis was conducted for discomfort and disability glare.

Calculating Discomfort Glare: An objective method was utilized for predicting the De Boer subjective rating [11] [17]. The predicted De Boer ratings of discomfort glare provide another indicator of discomfort glare. The method of prediction uses Eqs. 1 and 2 as follows:

$$DG = a(log(E_l + Es)) + b(log(E_l/Es)) - c(log(Ea)) \tag{1}$$

where

DG = discomfort glare

E_l = luminaire source illuminance (in lux)

Es = surround illuminance (in lux)

Ea = ambient illuminance (in lux)

Coefficients a, b, and c are set at 1.0, 0.6, and 0.5, respectively.

$$DB = 6.6 - 6.4 \log DG \qquad (2)$$

where

DB is predicted De Boer rating

The surround illuminance Es was determined by designing and 3-D printing small baffles of different sizes, ranging in diameter from 2.62 to 4.60 cm that slid along a small cantilevered rod (length, 17.9 cm; diameter, 0.32 cm). The assembled baffle accessory is shown in Fig. 7 and was attached to the Konica-Minolta T-10A sensor head in Fig. 8. The baffle enabled a shadow to be cast on the sensor surface so that surround illuminance could be measured. Similarly, ambient illuminance Ea was measured without the baffle.

Figure 9 depicts the predicted De Boer ratings and the participants' De Boer ratings for the phase 2 testing location.

Calculating Veiling Luminance to Indicate Disability Glare: Veiling luminance can be used to indicate the extent of disability glare from the luminaire sources because it indicates the contrast reduction. Equation 3 was used to calculate veiling luminance to provide another indicator of disability glare. [24]

$$L_v = 9.2 \, E_o / \theta (\theta + 1.5) \qquad (3)$$

where

L_v = equivalent veiling luminance in cd/m^2 (nits)

E_o = illuminance from the glare source at the eye in lux

Θ = angle between the primary object and the glare source in degrees

Figure 10 displays a comparison of the different luminaire sources relative to veiling luminance that can be used to estimate the extent of disability glare.

3.1.3 Visibility Level—Visibility level was also assessed for phase 2 because visibility and glare are important factors to consider so that the miners' visual abilities are sufficient for safely working. Discomfort and disability glare could be low for a given luminaire, but the luminaire would be unsuitable because visibility is reduced. The visibility level of a 11.4-cm (4.5-in.) white target disk at phase 1 and phase 2 locations was calculated using Eq. 4 [25]. Luminance values were determined using the image file obtained with the Photo Research PR920A video photometer system. Threshold contrast values were obtained from interpolations of values from tables developed by Blackwell et al. [26]. Figure 11 shows a

comparison of computed values of visibility level for the various luminaire conditions at the phase 2 location.

$$VL = L_c/C_{Threshold} \qquad (4)$$

where

VL = visibility level

L_c = luminance contrast $(L_T - L_B)/L_B$

L_T = luminance of the target object

L_B = background luminance

$C_{Threshold}$ = threshold contrast

4 Discussion

The discomfort and disability glare empirical results for phase 1 indicated no statistically significant differences among the Saturn luminaires and the CFL lighting conditions. These results are as expected because discomfort and disability glare were not problematic and were very similar for all lighting conditions. Specifically, the median De Boer ratings for the Saturn 100%, Saturn 75%, and CFL were equal at a rating of eight, indicating that the glare was better than satisfactory except for the Saturn 50% rating of seven indicating that the glare was satisfactory. Disability glare was indicated by average contrast sensitivity scores ranging from 1.2 to 1.4, thus indicating a moderate degree of contrast sensitivity loss for all the lighting conditions. With respect to the primary and secondary study objectives, the Saturn luminaires do not enable reductions in discomfort and disability glare. This does not infer that the Saturn luminaires have no merit for location 1. A prior study concerning trip object detection at location 1 indicated that the Saturn enabled drastic differences in the ability of people to see the trip hazards, as quantified by trip object miss rates that were 41.7% with the CFL compared with only 0.3% with the Saturn [20].

The discomfort and disability glare results for phase 2 did indicate statistically different results. Discomfort glare improved up to four levels from level 5 (just acceptable) glare with the CFL luminaire to level 9 (just noticeable) with the Saturn luminaire. The predicted De Boer ratings of discomfort glare (Fig. 9) appear to support the participant data that indicated the CFL discomfort glare was the worst, and that the discomfort glare ratings among the Saturn luminaires were relatively similar. The eye illuminance data correspond to the discomfort glare ratings given that as eye luminance (Table 2) increases, discomfort glare increases [27]. Specifically, the CFL average eye illuminance was 25.1 lx and had a discomfort glare rating of 5, while the Saturn luminaires' average eye illuminance ranged from 0.6 to 1.2 lx and had discomfort glare ratings of 9 or 8. Thus, with respect to the primary objective, each of the Saturn luminaires improved discomfort glare. With respect to the secondary objective, there are no differences among the Saturn luminaires to improve discomfort glare. For disability glare, age and luminaire were significant. Figure 6 depicts

the Mars Contrast Sensitivity Test results with respect to age. The CFL tests resulted in the worst average log contrast sensitivity values for all age groups. In general, for the Saturn luminaires, the average log contrast sensitivity improved as the Saturn luminaire intensity decreased. The CFL and Saturn results are as expected because the average vertical eye illumination (Table 2) was highest for the CFL and decreased as the Saturn intensity decreased. Increasing eye illuminance decreases contrast [28]. The additional analysis of veiling luminance (Fig. 10) also supports that participant disability glare was worst for the CFL and decreased as the Saturn luminaire intensity decreased. The calculated veiling luminance (Fig. 10) data correspond to the Mars Contrast Sensitivity Test results (Fig. 6), which would be expected given that as veiling luminance increases contrast decreases. Again, the results show that the Saturn luminaire sources provided superior performance compared with the CFL source. Thus, with respect to the primary objective of this study, each of the Saturn luminaires improved discomfort glare. In terms of the secondary study objective, there is merit in reducing the Saturn luminaire intensity to 50% given this enabled the least amount of discomfort and disability glare.

Next, the visibility level analysis indicated that all the Saturn luminaires were superior to the CFL (Fig. 11) at the phase 2 location. Note that the Saturn 50% had the highest visibility level, which would be expected given that it enabled the best contrast sensitivity (Fig. 6), and it had the lowest veiling luminance (Fig. 10), which is an indicator for disability glare that can impede visibility. Overall, the discomfort and disability glare improvements from the Saturn luminaires did not result in a decrease in visibility, which is important because miners depend most heavily on visual clarity to work safely [29].

Lastly, the results indicate that mounting location of the luminaires, with respect to the position of the participant, can greatly affect the results. Specifically, there were no significant differences for discomfort and disability glare among the Saturn and CFL luminaires for the phase 1 condition, while there were significant differences for the phase 2 location. A comparison between phase 1 and 2 results indicates that the CFL discomfort glare rating was worse for the phase 2 location (just acceptable rating) compared with that for the phase 1 location (satisfactory). Table 2 data of average vertical illuminance at the eyes also exemplify the differences for the CFL where the phase 1 illuminance was 5.3 lx and 25.1 lx for the phase 2 location.

4.1 Limitations

The study was carried out in a controlled environment, in a laboratory that represented an underground coal mine. Test conditions did not include factors such as airborne dust and the settling of coal/rock dust on the luminaires that likely would affect glare. Secondly, the research was limited to two locations within the interior working space walk-through roof bolter and did not measure glare at the exterior working spaces of the machine. The Saturn luminaire was designed for the interior working space, so glare when illuminating the external work spaces is unknown.

5 Conclusions and Summary

Overall, the Saturn luminaires performed significantly better relative to discomfort and disability glare and visual performance than the CFL luminaires at the phase 2 location of the roof bolter; thus, the first study objective to determine if the Saturn luminaires could reduce discomfort and disability glare has been realized. The second objective to determine if there are differences among the Saturn luminaires has been realized. Among the Saturn luminaires, the Saturn 50% enabled the least amount of disability glare and the highest visibility level at the phase 2 location, so it appears that the Saturn 50% would be the most desirable luminaire in terms of reducing glare. Note that the phase 1 data analysis indicated no significant differences among the Saturn luminaires and the CFL lighting condition with respect to discomfort and disability glare because glare was not an issue at the phase 1 location.

Acknowledgments

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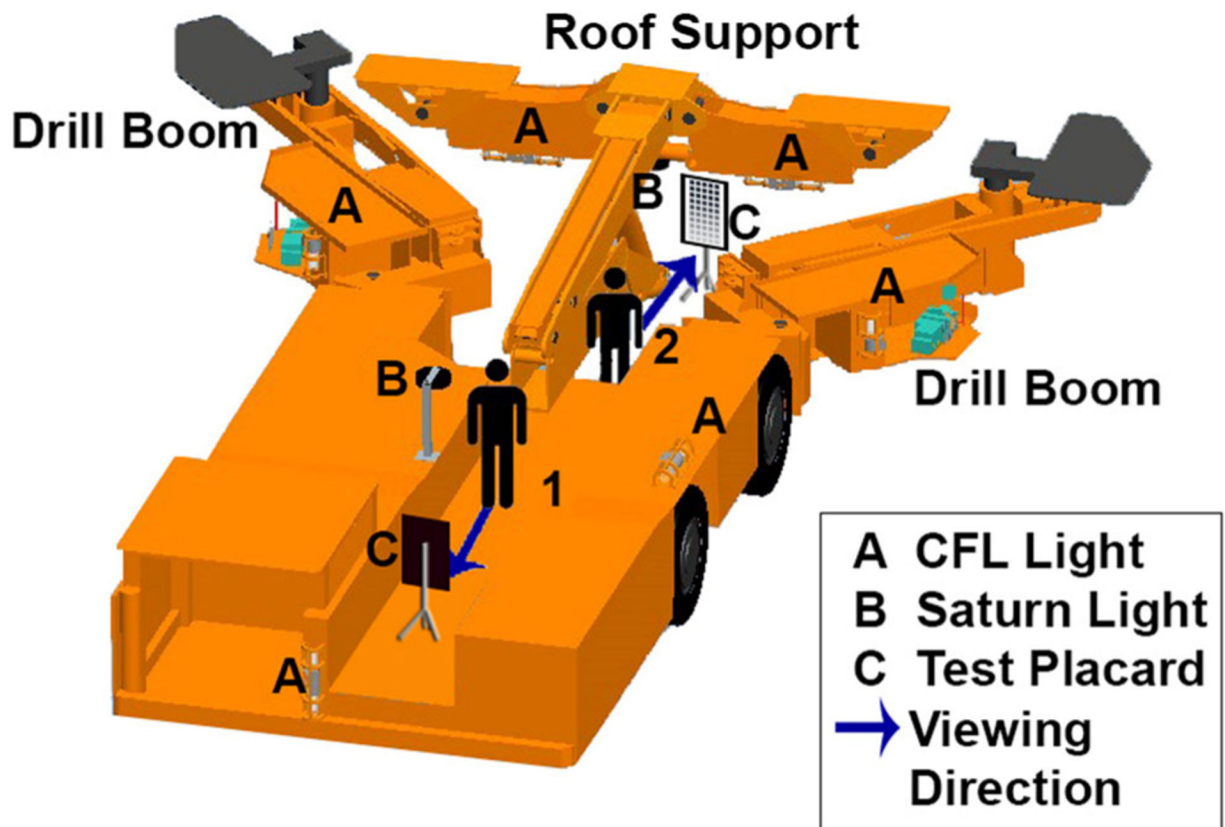
Fig. 1.
The center location (1) of the bolting machine is where phase 1 trials were conducted, whereas the front location (2) is where phase 2 trials were conducted. Also depicted are the luminaire locations, viewing directions of participants, and test placard locations

Fig. 2.
The Mars Letter Contrast Sensitivity chart used to indicate disability glare

Fig. 3.
The De Boer rating scale for discomfort glare
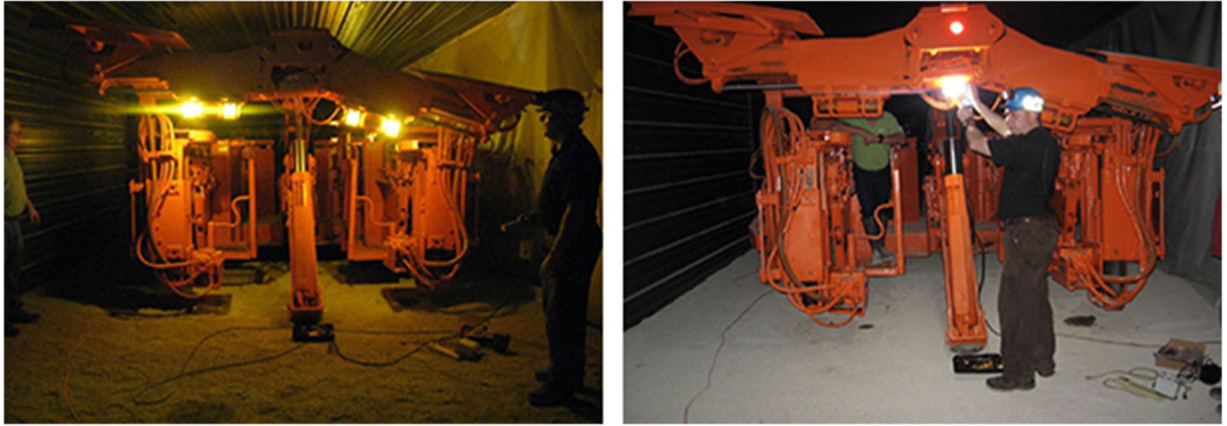
Fig. 4.
The roof bolter front area illuminated with the CFL luminaires (left) and with the Saturn luminaire (right)
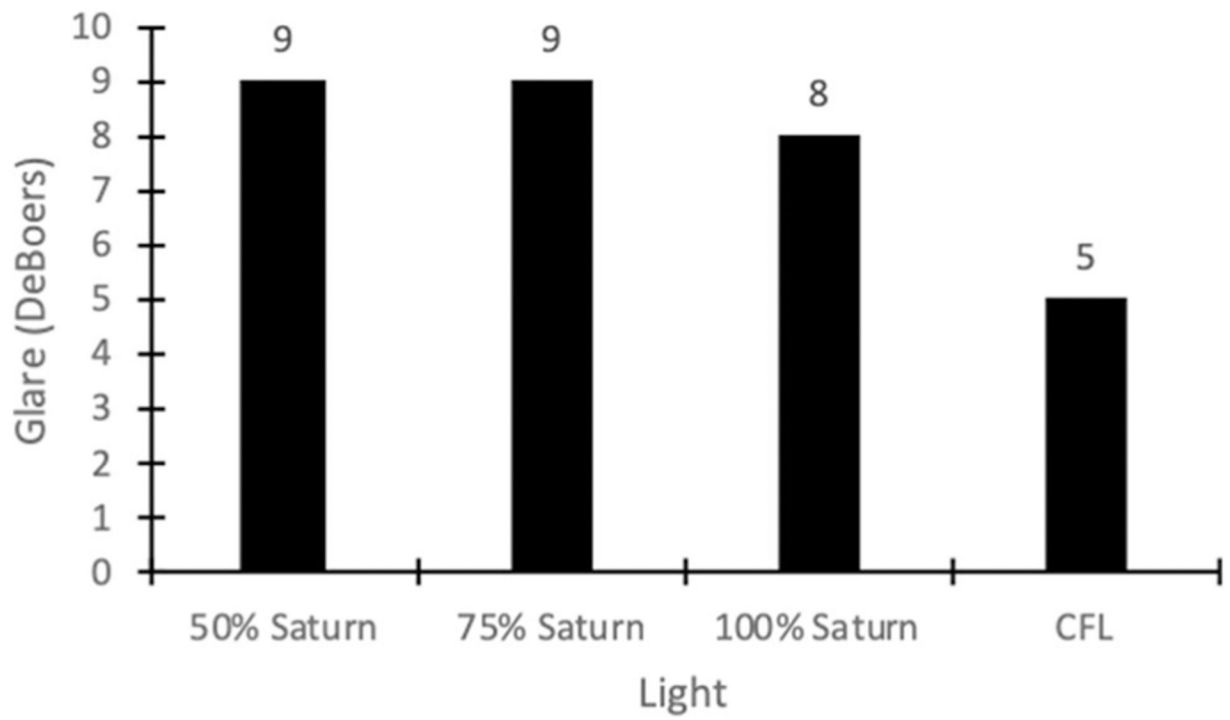
Fig. 5.
Median De Boer rating for phase 2. Note that smaller numbers indicate higher discomfort glare
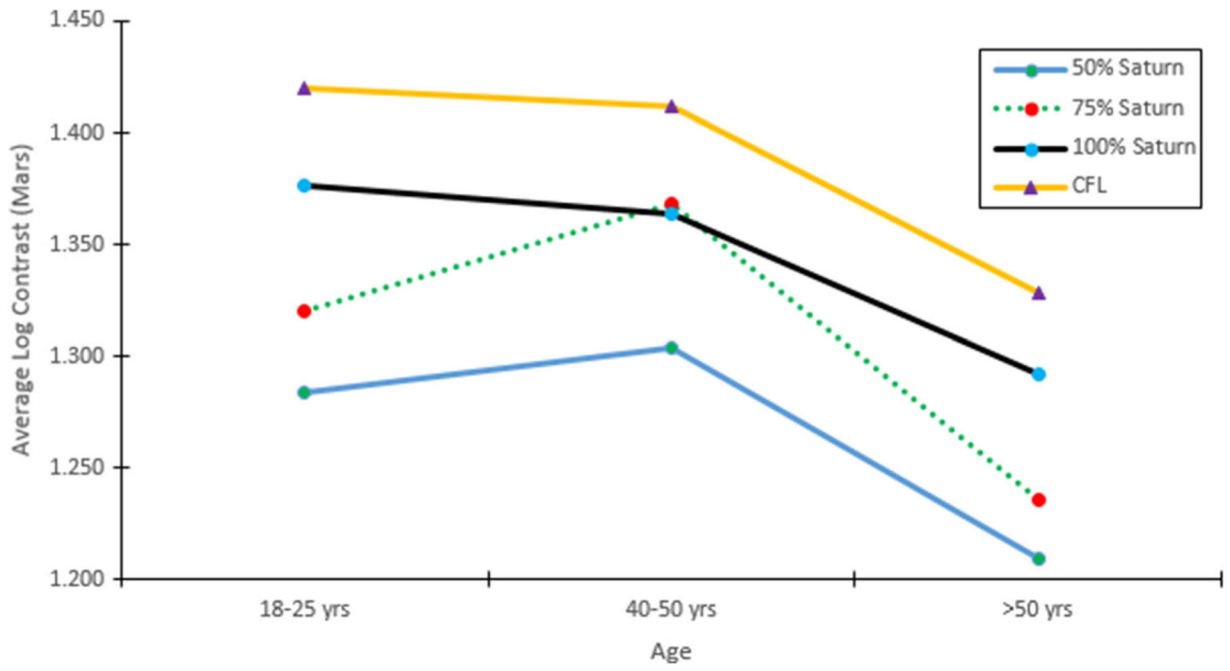
Fig. 6.
Average log contrast sensitivity with respect to age for phase 2. Note that higher average log
contrast sensitivity values indicate less contrast sensitivity
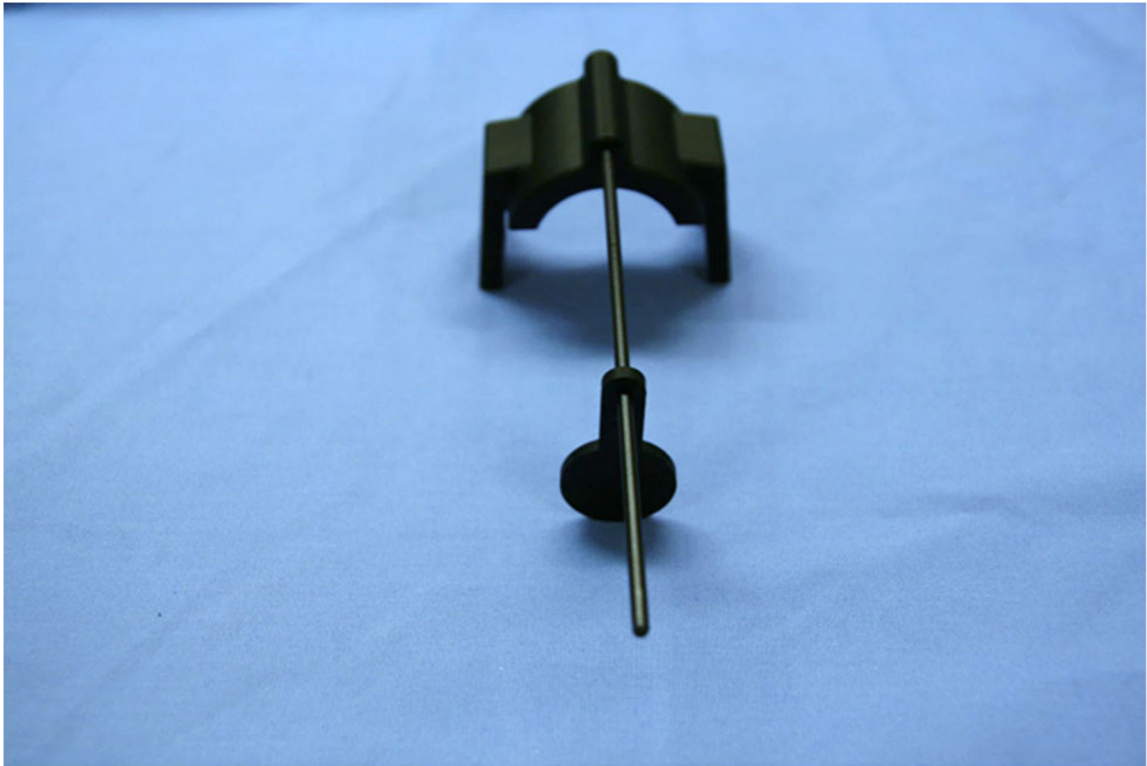
Fig. 7.
The 3-D printed T10A sensor head shroud and baffle assembly

Fig. 8.
Shroud and baffle rod assembly mounted to the T10A sensor head
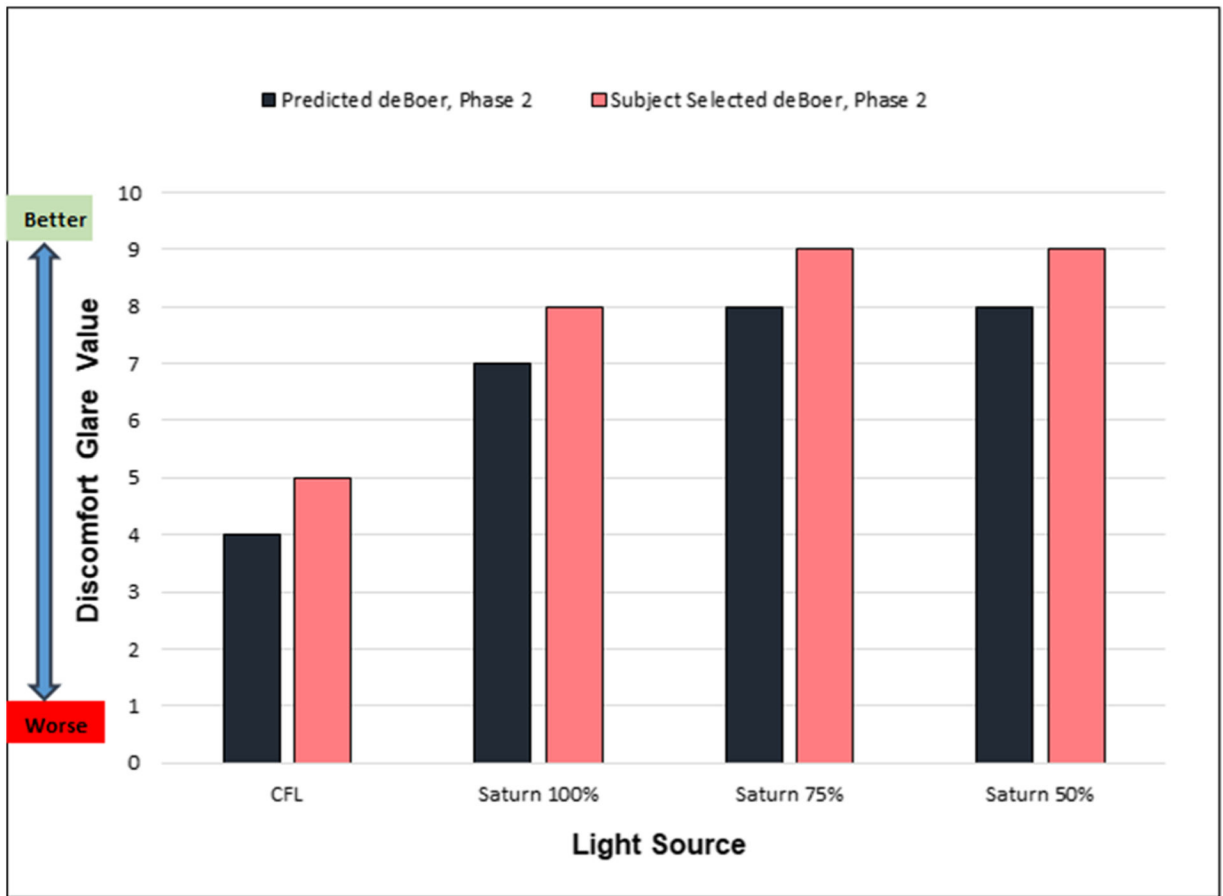
Fig. 9.
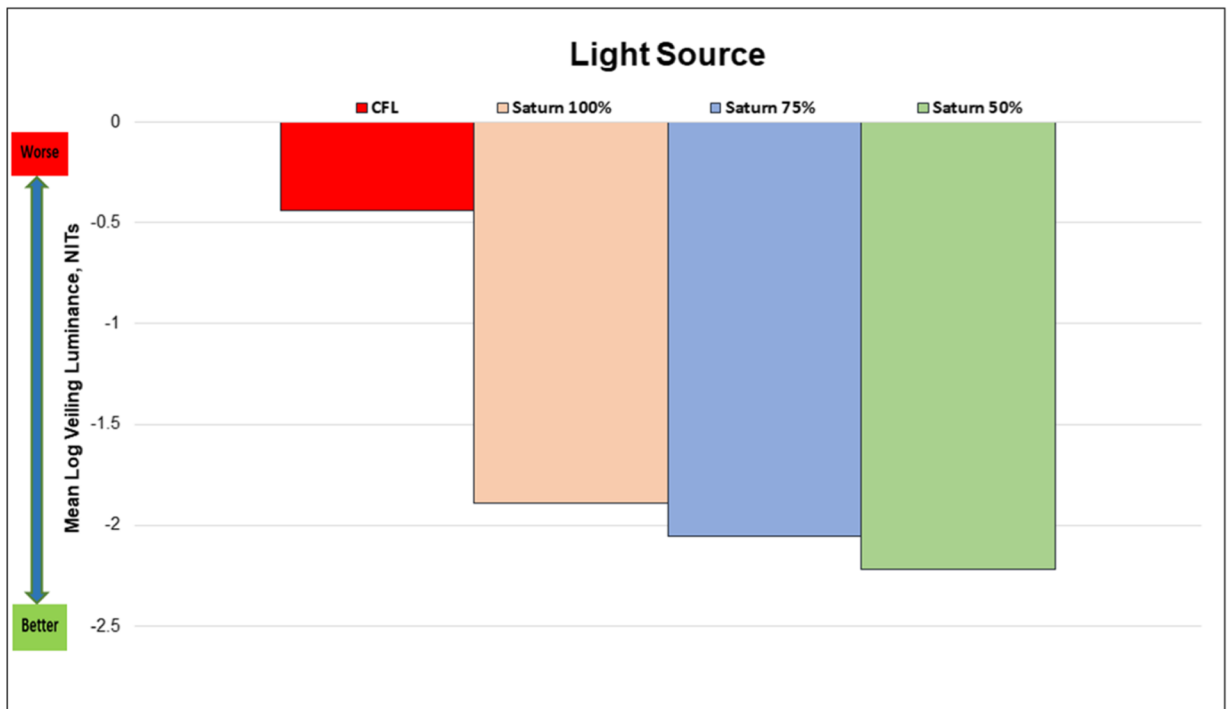Predicted De Boer ratings of discomfort glare and participant-selected median values from the phase 2 testing

Fig. 10.
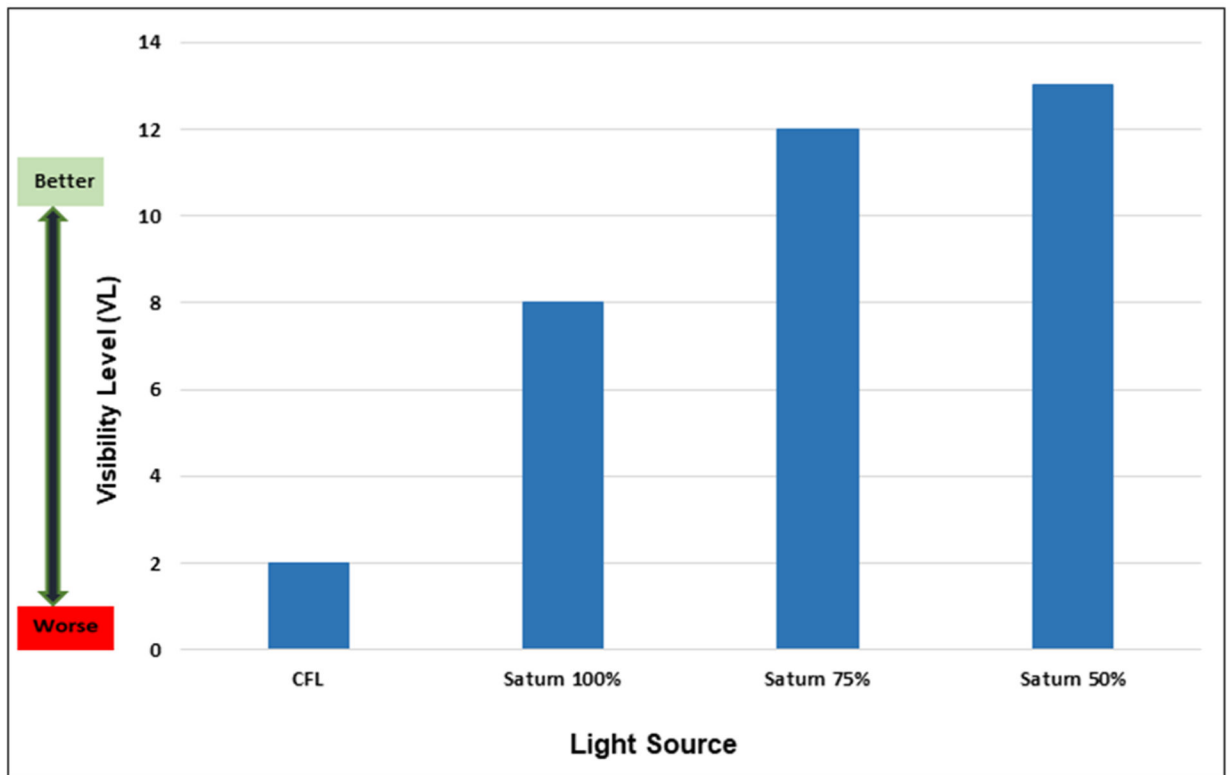Comparison of mean log veiling luminance for each luminaire source at the phase 2 location

Fig. 11.
Comparison of visibility level (VL) for different luminaire sources of phase 2 testing

Table 1

The Saturn and CFL parameters that include output (lumens), color-correlated temperature (CCT), and the scotopic/photopic ratio (S/P)

Luminaire	Output (lumens)	CCT (K)	S/P
Saturn 100%	663	4584	1.69
Saturn 75%	494	4428	1.67
Saturn 50%	332	4456	1.67
CFL	2100	1937	0.61

Table 2

Average vertical illumination at participants' eyes

Luminaire	Location 1 illuminance (lx)	Location 2 illuminance (lx)
50% Saturn	8.1	0.6
75% Saturn	9.3	0.8
100% Saturn	12.0	1.2
CFL	5.3	25.1

Table 3

Type III tests of fixed effects for phase 1

Glare Type	Factor	DFN[*]	DFD[*]	F	p
Discomfort	Age	2	81	0.33	0.7199
Discomfort	Luminaire	3	81	2.40	0.0743
Discomfort	Age × luminaire	6	81	1.15	0.3398
Disability	Age	2	81	2.70	0.0735
Disability	Luminaire	3	81	1.40	0.2494
Disability	Age × luminaire	6	81	1.91	0.0896

[*] Degrees of freedom numerator (DFN) and denominator (DFD)

Table 4

Type III tests of fixed effects for phase 2

Glare type	Factor	DFN[*]	DFD[*]	F	p
Discomfort	Age	2	80	1.45	0.2412
Discomfort	Luminaire	3	80	50.03	<0.0001
Discomfort	Age × luminaire	6	80	0.18	0.9821
Disability	Age	2	80	5.87	0.0042
Disability	Luminaire	3	80	35.45	<0.0001
Disability	Age × luminaire	6	80	1.08	0.3800

[*] Degrees of freedom numerator (DFN) and denominator (DFD)