A Blue-Enriched Light Intervention Counteracts the Alertness Decrement Among Mine Workers on Extended 12-Hour Night Shift Periods

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Objective: The aim of the study is to assess whether a blue-enriched light intervention improves nocturnal alertness and daytime sleep of night workers. **Methods:** Thirteen miners performing 12-hour night shifts for 12 consecutive nights were exposed to a baseline and a blue-enriched light condition. All subjects wore an actigraph and completed a Psychomotor Vigilance Task at the beginning and at the end of each shift. Data were analyzed with linear mixed models. **Results:** In the blue-enriched light condition, the daily increase in median reaction time (RT), mean RT, slowest 10% of RT, and fastest 10% of RT was lower than that observed in the baseline condition between day 1 and 12 ($P \leq 0.05$). **Conclusions:** The addition of blue-enriched light during a long period of extended night shifts counteracts most of the daily decline in nocturnal alertness observed in the standard lighting condition, irrespectively of sleep duration and sleep efficiency.

Keywords: actigraphy, shift work, blue-enriched white light, miners, alertness, sleep, vigilance

LEARNING OUTCOMES

- Evaluate the weekly decrement in nocturnal alertness of night workers using the psychomotor vigilance test
- Apply a blue-enriched light intervention to improve alertness and performance of night shift workers.

Numerous studies suggest that shift workers have a significantly higher risk of workplace accidents and injuries, comparatively to workers in regular daytime schedules.[1] Improving alertness at night is therefore a concern for any industry that employs workers 24 hours a day. The negative effects of night work are caused by the misalignment of the circadian clock with the reverse schedule.[2] However, light is the most powerful synchronizer[3] and the circadian clock has been shown to be most sensitive to blue wavelengths,[4,5] a nonvisual effect known to be mediated by melanopsin-dependent intrinsically photosensitive retinal ganglions cells (ipRGCs) with peak sensitivity at 480 nm.[6,7] In addition to its effects on the ipRGCs blue light also affects other nonvisual functions. In fact, compared with green and red light, blue light has been shown to increase heart rate, body temperature, and alertness while inducing greater melatonin suppression.[8] The effects of blue light on subjective and objective alertness have also been confirmed in studies conducted in the evening[9] and at night.[10]

Unsurprisingly, these findings have sparked some interest in using blue-enriched light to optimize the work environment (see review by Wong et al[11]). However, field studies performed in night workers are scarce. In 30 control room workers of the petrochemical industry, Motamedzadeh et al[12] (2017) conducted a 1-week baseline assessment under existing lighting followed by a 1-week exposure to two new lighting conditions, namely, 17,000K and 6500K blue-enriched white light at an intensity of 350 lux. These lights were found to be similar in terms of spectral power distribution, except for the wavelengths between 420 and 480 nm (blue range), which had higher power in the 17,000K lighting condition. Both lighting conditions resulted in reduced sleepiness, working memory errors, and omission errors while improving reaction times (RTs). In addition, both conditions were associated with a significant decrease in salivary melatonin secretion compared with baseline, but the 17,000K condition induced a significantly stronger effect than the 6500K condition.[12–13] However, results of a laboratory study in night shift workers showed that subjective alertness and objective alertness were not improved after a three-night exposure to a lower intensity 17,000K blue-enriched white light (89 lux) compared with standard 4000K white light of similar intensity (84 lux).[14] Blue-enriched light was though associated with higher subjective alertness near the timing of the peak of the melatonin rhythm, as assessed using its urinary metabolite (aMT6s). These results contrast with a study conducted with subjects exposed to 20 lux of monochromatic blue light (468 ± 8 nm) while driving 400 km at night. Compared with a placebo (2 cups of decaffeinated coffee), the use of blue light was found to produce the same results as two cups of coffee containing 200 mg of caffeine, namely, reduced line crossings and decreased deviation of the lateral position.[15]

Despite differences in study design, populations sampled, age ranges, and ascertainment methods, including the type of light used (monochromatic vs polychromatic), the previously mentioned results point toward a significant effect of blue-enriched light exposure at night upon alertness levels. Still, in the context of night work, the use of lower light intensities would be preferable to more intense light, namely, for workers who wish to reduce the level of ambient light for best visual contrast when monitoring operations on screen displays. Although blue-enriched light exposure reportedly shows some benefits in night workers, there is a paucity of data regarding its effect on subsequent daytime sleep. The aim of the present study was to explore whether the addition of an auxiliary, blue-enriched light can alleviate

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FIGURE 1. Pictures of the blue-enriched light custom-made device on the left, and when in use on the right.

the decrement in nocturnal alertness and improve daytime sleep of mine workers during long periods of extended shifts.

MATERIAL AND METHODS

Subjects

Subjects were rotating fly-in:fly-out shift workers performing computer work and screen monitoring at the Raglan mine (Glencore) concentrator/smelter in the Far North (61°69′N) of the province of Quebec (Canada). They were studied for 12 consecutive 12-hour (7:00 PM–7:00 AM) night shifts. Recruitment was performed by the company supervisor who requested volunteers for the study. To be included in the study, subjects had to be able to complete both conditions and must not have performed a transmeridian flight in the last 3 months. Of the 16 male individuals who participated in the study, 13 workers (mean ± SD = 48.5 ± 7.7 years) completed the study protocol and 3 abandoned for various reasons (illness, paternity leave, job change). Most of the shift was spent in a cabin, except when needed to intervene if an alarm sounded. At the end of the shift (≈7 am), subjects went back to the main complex where they slept, ate, and could engage in social activities. It should be noted that the use of drugs and alcohol consumption is strictly prohibited on site. This study was approved by the CIUSSS de la Capitale-Nationale Neurosciences and mental health sectorial research ethics committee (project number: 395-2015). Each subject provided informed written consent. No compensation was provided to subjects for their time.

Measures

Using a counterbalanced design, all subjects completed both the baseline condition and the blue-enriched light condition.

At the start of the study, subjects were asked to complete a questionnaire collecting information on age, smoking and caffeinated beverage consumption, as well as use of melatonin supplements or medications known to affect the sleep-wake cycle (tranquilizers, antidepressants, antihistaminic, sedative/hypnotics, and heart medications). Subjects were also asked to wear an actigraph (Actiwatch Spectrum Plus; Philips Respironics, Bend, OR) on their nondominant wrist, 24 hours a day, and to complete a sleep diary. A 5-minute portable, touch-screen psychomotor vigilance test (PVT)[16–17] was used to measure sustained vigilance performance or alertness at the beginning and at the end of each 12-hour shift during both conditions. More particularly, subjects are required to touch the portable PVT screen when they see a visual stimulus (random interstimulus interval between 2 and 10 seconds). Testing took place in an isolated room to avoid distraction. The mean RT, median RT, slowest 10% of RT, fastest 10% of RT, as well as the number of lapses (log(lapses+1)) were considered as dependent variables in the analysis.

Experimental Light Condition

The blue-enriched light was provided by a custom-made light device composed of a control box (10 × 5 cm) on which were fixed two small pods (5 × 1.5 cm) composed of 4 LED RGB (Fig. 1). Light devices were mounted above the computer screen and directed toward subjects' eyes at approximately 90 cm. Subjects were instructed to turn on the light at the beginning of their shift. It must be noted that the device included a timer that automatically turned off the light at 5:00 AM to reduce the possibility that the stimulating effect of blue-enriched light impinge upon diurnal sleep. A member of the research team conducted random checks during each night shift to verify that the blue-enriched light system was on.

In addition, subjects were asked to adjust the intensity of the light according to their own preferences. Illuminance (photopic and melanopic lux) and irradiance (in microwatts per square centimeter) were measured using a photometer (ILT5000 Research Radiometer; International Light Technologies, Peabody, MA) for the minimum and maximum intensities emitted by the light device at approximately 90 cm (Table 1).

The intensity used was based on the comments of the workers so that the blue-enriched light would not interfere with vision to effectively monitor screens in the control rooms. Spectral wavelengths were 639 to 646 nm (half peak) for the red LED, 533 to 539 nm (half peak) for the green LED, and 459 to 462 nm (half peak) for the blue LED. This mix of color resulted in a blue-enriched light of 21,452K (Chroma Meter CL 200A, Konica Minolta, Inc, New Jersey, USA). Room operators also received light from standard fluorescents (4100K; Alto F32 T8, Philips) of approximately 110 photopic lux and computer screen of approximately 14 photopic lux, measured at eye level. Table 2 provides the α-opic Equivalent Daylight (D65) illuminance based on the CIE S 026 Toolbox (V1.049a-2020/11) and the respective light spectra (in µW.cm^2.nm) as measured with an HR4000 Spectrometer (Ocean Insight, Largo, FL). Figure 2 presents the light spectra of the blue-enriched light device.

Sleep Analysis

Actigraphy-based assessment of sleep parameters was performed using Actiware 6.0.9 (Philips Respironics, Bend, OR). Data were sampled in 15-second epochs. Rest and active intervals were established manually, according to the self-reported "rise time" and "bedtime"

TABLE 1. Light Measures of the Custom, Blue-Enriched Light Device Provided by an ILT5000 Research Radiometer

	Photopic, Lux		Irradiance, µW/cm^2		Melanopic, Lux	
Distance, cm	Min	Max	Min	Max	Min	Max
90	14	41	7	21	24.5	73.7

TABLE 2. α-Opic Equivalent Daylight (D65) Illuminance in Lux

	S-Cone Opic	M-Cone Opic	L-Cone Opic	Rhodopic	Melanopic
Standard light	66 lx	122 lx	138 lx	89 lx	76 lx
Blue-enriched light, min–max	34–97 lx	16–48 lx	16–48 lx	22–63 lx	24–70 lx
SL + BL, min–max	102–167 lx	140–172 lx	158–190 lx	112–153 lx	102–147 lx

Note: Standard light includes light emitted by computer screen which was about 14 lux photopic and 13 lux melanopic EDI, respectively.

from subjects' sleep diary. Each actogram was carefully inspected to exclude artifacts, namely, off-wrist occurrences reported in the diary and episodes of sudden dim light that did not match information provided in the diary. Sleep parameters included sleep duration and sleep efficiency.

Statistical Analysis

All statistical analyses were performed using SAS software (Version 9.4; SAS Institute, Inc, Cary, NC).[18] To consider the repeated measures and the nested structure of the data, a linear regression model with mixed effects was used for each dependent variable, that is nocturnal alertness (ie, median RT, slowest 10% of RT, mean RT, fastest 10% of RT, number of lapses) as well as sleep (ie, sleep duration and sleep efficiency).[19] More specifically, a two-level growth curve model was used (ie, the 12-night shifts nested in the 13 subjects) with random effects for time trajectory (intercept and slope) while the condition (ie, baseline or light condition) and the period (ie, start or end of night shift; only applicable to the PVT measure) were estimated as fixed repeated factors. Log transformation was applied to sleep efficiency scores to improve symmetry. Full maximum likelihood was used to estimate parameters, because it is considered to produce stable, more efficient, and less biased estimates for the parameters of interest.[20] Model fit was evaluated using various criteria, such as the Akaike information criterion, the Bayesian information criterion, and the log-likelihood (deviance) statistics.[19] In addition, the examination of conditional residuals indicated no major violation of the postulates of normality and homoscedasticity.

RESULTS

Eleven of the 13 mine workers reported daily consumption of caffeinated beverages, while two workers reported being current smokers. Seven workers reported taking hypnotics/sedatives, three workers reported taking heart medicines, and one worker reported taking an antidepressant. None of the worker reported the use of melatonin during the study period.

Nocturnal Alertness

Figure 3 presents the mean median RT for the baseline and the blue-enriched light conditions at the beginning and end of each shift for workdays 1 to 12.

More precisely, results of the linear mixed model indicated that the mean median RT in the baseline condition is approximately 16 ms longer at the end of the shift compared with the beginning of the shift on workday 1 ($P < 0.05$). In addition, in the baseline condition, the mean median RT at the beginning of the shift is increased by 3.5 ms for each successive shift, from workday 1 to workday 12 ($P < 0.01$) (Table 3). Moreover, in the blue-enriched light condition, the daily increase in mean median RT was 2.4 ms less than that observed in the baseline condition between day 1 and day 12 ($P < 0.05$) (see End of shift in Table 3). The increase in mean median RT was significantly slowed down or even canceled out (see end of shift), in the blue-enriched light condition, for each successive shift.

Figure 4 illustrates the mean slowest 10% of RT for the baseline and the blue-enriched light conditions at the beginning and end of each shift for workdays 1 to 12. More particularly, Table 4 shows that in the blue-enriched light condition, the daily increase in mean slowest 10% of RT was 4.9 ms less than that observed in the baseline condition between day 1 and day 12 ($P < 0.05$). Alike the previously mentioned results for median RT, the blue-enriched light condition significantly reduces, or even cancels out, the average daily increase of 10% slowest RT.

Futhermore in the baseline condition, the mean RT at the beginning of the shift is increased by 3.5 ms for each successive shift, from workday 1 to workday 12 ($P < 0.05$). In addition, in the blue-enriched light condition, the daily increase in mean RT was 3.2 ms less than

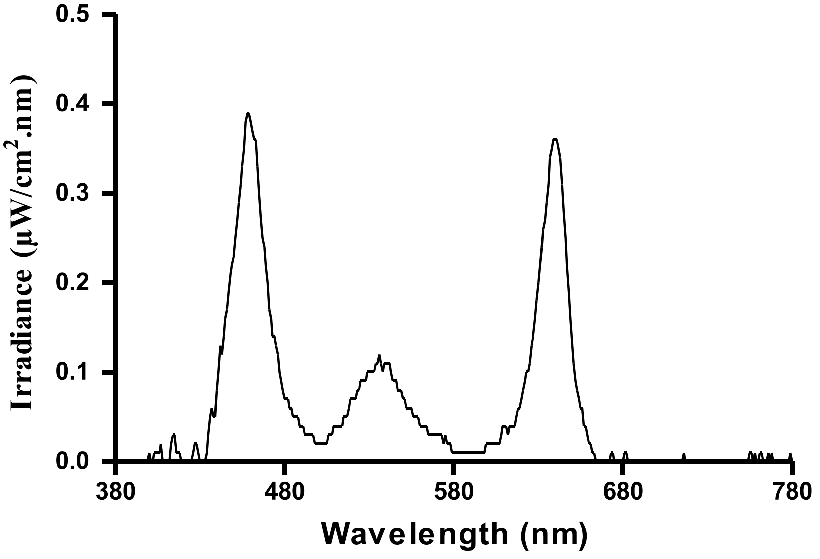

FIGURE 2. Absolute spectral irradiance of the custom, blue-enriched light device (distance 90 cm).

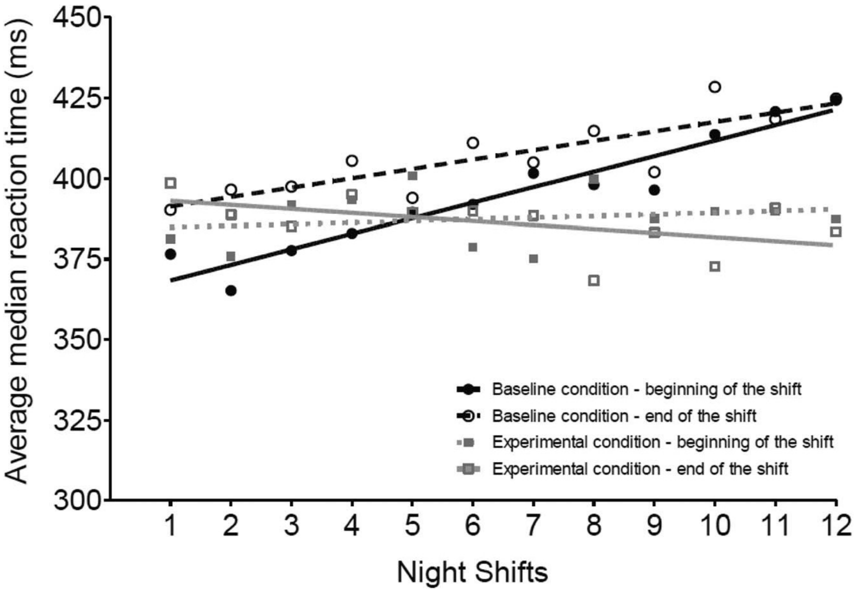

FIGURE 3. Mean median RT (in milliseconds) at the beginning and at the end of each night shift during baseline and experimental (blue-enriched light) conditions.

that observed in the baseline condition between day 1 and day 12 ($P < 0.05$) (results not shown). In the same line of evidence, in the baseline condition the 10% fastest RT at the beginning of the shift is increased by 2.6 ms for each successive shift, from workday 1 to workday 12 ($P < 0.01$). Besides, in the blue-enriched light condition, the daily increase in the 10% fastest RT was 2.0 ms less than that observed in the baseline condition between day 1 and day 12 ($P < 0.05$) (results not shown). Finally, in the baseline condition, the number of lapses is increased significantly with each successive shift, from the first to the 12th working day ($P < 0.05$) while it remains constant in the blue-enriched light condition (results not shown).

Sleep Duration and Efficiency

Neither the mean sleep duration (7:01 hour vs 7:07 hour, not significant) nor the mean sleep efficiency (efficiency 96.8% vs 96.9%, not significant) differs between the baseline and the blue-enriched light conditions. In the same vein, no difference was observed in sleep duration and sleep efficiency between workday 1 and workday 12.

DISCUSSION

Results show that the exposure of indoor mine workers to blue-enriched light for 12 consecutive night shifts counteracts most of the daily decline in alertness observed in normal nocturnal lighting conditions. Importantly, this finding may not be ascribed to a change in sleep duration or sleep efficiency, which did not vary between conditions and across shifts. In the only other field study whose objective was to improve nocturnal alertness using a blue-enriched light intervention during night shifts, Motamedzadeh and coworkers[12] (2017) demonstrated that control room workers' sleepiness declined using the Karolinska Sleepiness Scale, a subjective measure of sleepiness. It is noteworthy that the present results based on an objective measure of sleepiness, that is, the PVT, are concordant with this previous study.

While the effects of working night shifts are well known in terms of reduction of both nighttime alertness and daytime sleep quality and quantity,[21] the impact of a long period of extended night shifts on performance has rarely been studied, especially with an objective assessment of alertness. In a previous study conducted at the same site in underground miners doing 14 consecutive nights of work, we noted that subjective alertness (measured by a visual analog scale at the end of the 12-hour shift) improved drastically on the first four nights with a plateau from night 10 and onward.[22] In the present study, the objective assessment of performance revealed the opposite, namely, a daily decline in nocturnal alertness, both at the beginning and at the end of the shift. This result is, however, consistent with another study showing that the number of consecutive night shifts had a significant effect on parameters such as RT and commission errors.[23] This is also supported by a study of Balk and coworkers[24] (2009) who found a performance deterioration across each nightshift that was not present in dayshift. Similarly, to our study, they used 5-minute PVTs rather than the standard 10-minute version, which is considered a reasonable alternative in time-constrained experimental conditions.[25] Because performance assessment tools such as RT tests have a sufficient level of reliability to assess fatigue,[24] the decrease in RT over 12 consecutive night shifts in the baseline condition suggests that the long duration of the rotational night shift causes fatigue, which seems to be counteracted with the addition of a blue-enriched light.

It nonetheless remains unclear why the daily decline in alertness observed in the baseline condition was canceled out in the blue-enriched light condition throughout the 12-night evaluation. In fact, similarly to a recent study by Barger et al[26] conducted in NASA

TABLE 3. Results of the Linear Mixed-Effects Regression Model for Median RT

Solution for Fixed Effects

Effect	Estimate	Standard Error	*df*	*t*	Pr > |*t*|
Intercept	374.15	16.99	12	22.02	**<0.0001**
End of shift[a]	15.66	6.65	532	2.36	**0.0188**
Blue-enriched light[b]	6.48	6.66	532	0.97	0.3309
Workday[c]	3.53	1.15	12	3.07	**0.0096**
Workday*end of shift	−1.88	1.07	532	−1.76	0.0782
Workday*blue-enriched light	−2.41	1.09	532	−2.21	**0.0277**

[a]Compared with beginning of shift.
[b]Compared with baseline condition.
[c]Workdays 1 to 12.

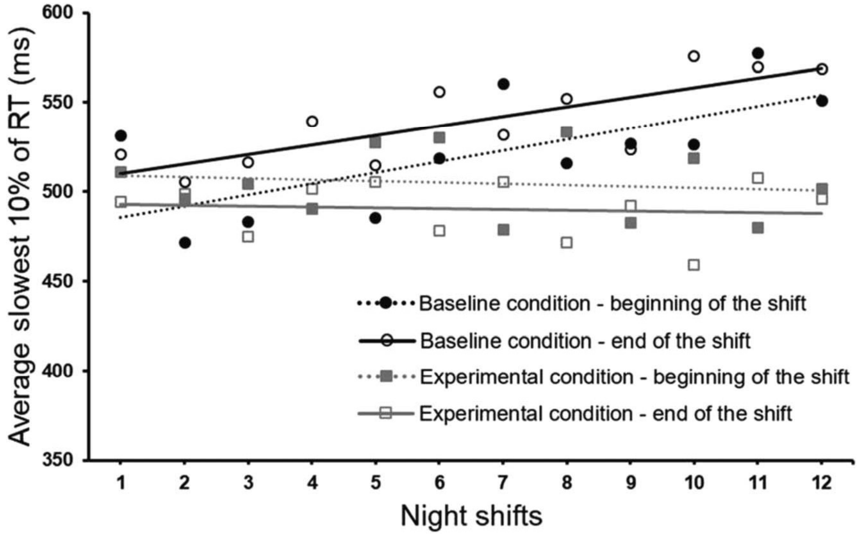

FIGURE 4. Mean slowest 10% of RT (in milliseconds) at the beginning and at the end of each night shift during baseline and experimental (blue-enriched light) conditions.

flight controllers working night shifts, the addition of a blue-enriched white fluorescent light resulted in improved alertness and RT, which could not be ascribed to differences in sleep, because there was no change in sleep duration between the results of the control and experimental conditions. However, one could postulate that the use of blue-enriched light at night improves sleep quality, which cannot be accurately assessed by actigraphy. In fact, one study that compared light exposure and sleep using polysomnography proposed that the timing and intensity of light exposure modulate aspects of sleep determined not only by the circadian clock but also by the homeostatic pressure.[27] Future studies should include polysomnography and explore whether the addition of blue-enriched light at night duly has a positive effect upon subsequent sleep, namely, by increasing slow wave sleep.

Comparing studies in terms of lighting is quite difficult because only recent studies are providing melanopic lux assessments. More particularly, Sletten et al[28] showed that exposure to 108 melanopic EDI lux (17,000K) light improved RTs of rotating night shift workers in a chemical plant in the middle and at the end of the night (relative to the beginning of the night) compared with a standard exposure at 24 melanopic EDI lux (4000K). On the other hand, Barger et al[26] demonstrated the efficacy of 168 melanopic EDI lux (8000K) compared with 30 melanopic EDI lux (4100K). While in the present study between 102 and 147 melanopic EDI lux seemed sufficient to significantly decelerate the increase in RTs (compared with baseline at 76 melanopic EDI lux), it did not significantly increase alertness per se. Hence, further research must identify the light threshold necessary to produce meaningful improvements in nocturnal alertness during long periods of extended night shifts.

The studies on light intervention applications for reducing the negative impacts of night work remain scarce. It must be borne in mind that field studies are fraught with challenges such as varying work conditions, limited access to workers during their shift for reasons of productivity and safety, and the necessity to constantly address the needs of both union and employers. As advanced by Jensen and colleagues,[29] field studies still provide important knowledge on how people are affected by night work in real-life settings. Conversely, it could be argued that while the findings may be directly applicable, they may be too specific to the environment they have come from. Nonetheless, the present study shows several limitations. We were not able to assess the exact intensity to which workers were exposed because they had the option of adjusting the intensity to their own preferences, although there were lower and upper limits. In addition, it was not possible to perform the PVT during the shift, which would have been necessary to assess the direct impact of light on alertness. Moreover, no circadian rhythm measure such as melatonin was collected, which would have been necessary to assess the state of synchronization of the circadian clock. To measure circadian change, the pre–dim light melatonin onset would have ideally been assessed in workers one night before their first night shift to obtain a baseline of melatonin production (saliva samples collected in total darkness), and then redo saliva sampling one night after their last night shift to assess the post–dim light melatonin onset.[30–31] Both financial and logistic reasons have precluded this option. It must also be mentioned that the use of caffeine and of certain medications may have influenced the results. Finally, although all workers performed both conditions, the sample size remains relatively small.

TABLE 4. Results of the Linear Mixed-Effects Regression Model for Slowest 10% of RT

Solution for Fixed Effects

Effect	Estimate	Standard Error	*df*	*t*	Pr > |*t*|
Intercept	498.48	24.03	12	20.75	**<0.0001**
End of shift[a]	5.00	12.81	530	0.39	0.6961
Blue-enriched light[b]	−0.05	12.83	530	−0.00	0.9971
Workday[c]	4.31	2.13	12	2.03	0.0654
Workday*end of shift	−0.41	2.05	530	−0.20	0.8402
Workday*blue-enriched light	−4.89	2.10	530	−2.33	**0.0199**

[a] Compared with beginning of shift.

[b] Compared with baseline condition.

[c] Workdays 1 to 12.

CONCLUSIONS

Long shifts for extended periods are quite standard for work in remote, isolated locations. Our study revealed a progressive decrement in alertness across each shift likely due to the accumulation of fatigue that can increase the likelihood of errors, incidents, and accidents. On the other hand, the exposure of mine workers to an auxiliary, blue-enriched light seemingly halts the daily decline in nocturnal alertness. Anyhow, more research is needed to better understand the underlying process that account for this finding, namely, by assessing the relationship of sleep architecture and quality to prior, blue-enriched light exposure in night workers.

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