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The human factors of mineworker fatigue: An overview on prevalence, mitigation, and what's next

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Abstract

Background: Though mining remains a vital shiftwork industry for U.S. commerce, problems of continued prevalence of mineworker fatigue and its mitigation persist. Publications and reports on fatigue in mining appear to be rich and diverse, yet variable and remote, much like the industry itself.

Methods: The authors engaged in a brief nonexhaustive overview of the literature on sleep and fatigue among mineworking populations.

Results: This overview covers: potential sources of fatigue unique to mine work (e.g., monotonous and disengaging Work Tasks, underground environments and light exposure, remote work operations); evaluation of mitigation strategies for mineworker fatigue or working hours (e.g., shift-scheduling and training); and areas for future research and practice (e.g., fatigue risk management systems in mining, mineworker sleep and fatigue surveillance, lighting interventions, and automation).

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AUTHOR CONTRIBUTIONS

Timothy J. Bauerle: Lead author; draft preparation and editing; literature review; coordination of coauthor; internal reviews. **John J. Sammarco:** Draft preparation and editing; lighting literature review; provision of citations. **Zoë J. Dugdale:** Draft editing; critical evaluation of arguments; formatting. **Drew Dawson:** Critical evaluation of review in larger context of literature; provision of resources and citations; general subject matter expert for authors.

CONFLICTS OF INTEREST

The authors declare that there are no conflicts of interest.

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DISCLAIMER

The findings and conclusions in this paper are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention. Mention of any company or product does not constitute an endorsement by NIOSH.

Conclusions: Fatigue continues to be a critical challenge for the mining industry. While research on the problems and solutions of mineworker fatigue has been limited to date, the future of fatigue research in mining can expand these findings by exploring the origins, nature, and outcomes of fatigue using advancements in lighting, automation, and fatigue risk management.

Keywords

lighting; mineworker fatigue; mining; occupational health and safety; review; shift-scheduling; sleep; underground mining; work-life balance; workplace interventions

1 | INTRODUCTION

Once a prehistoric practice, mining remains a pivotal global industry positioned at the intersection of international geopolitics, natural resource management, infrastructure development, and environmental sustainability. Materials built with mining-derived minerals comprise most components found in infrastructure, computers, technology, medical devices, and military hardware,[1] to name only a few. As the saying goes: *if it can't be grown, it must be mined*.[2] There are an estimated 193,790 mineworkers in the United States,[3] while some estimate there could be as many as 672,000 total individuals employed by the mining industry nationally[4] spread across 13,046 active mine sites.[5]

While mining is a diverse industry where day-to-day operations vary greatly by sector (e.g., metal, coal, industrial minerals, sand, and gravel), excavation techniques (e.g., surface, underground, highwall, and dredging), machine equipment (e.g., haul trucks, continuous/longwall coal machines, drill rigs, and power shovels), and mine size (e.g., less than 12 working personnel and 1200+ mine production staff), one common experience among mineworkers is evident and that is worker fatigue. However, the characteristics of fatigue and sleepiness in the mining workforce, its burden on mining production and worker wellbeing, and evidence-based countermeasures to alleviate these burdens all remain largely undocumented or unknown. The present manuscript provides a brief nonexhaustive overview of potential sources of fatigue and sleepiness unique to mine work, the evidence regarding the prevalence and burden of fatigue and sleepiness in mining, evaluation of mitigation strategies for mineworker fatigue or working hours, and areas for future research and practice.

Before the overview is presented, we want to briefly acknowledge that differences exist between fatigue and sleepiness while at the same time noting that—throughout this manuscript—the term *fatigue* is at times used as a generic concept which can encapsulate various subdimensions such as sleepiness. In general, we use the term fatigue to most closely align with Phillips' definition[6]: "a suboptimal psychophysiological condition caused by exertion…such that original levels of mental processing or physical activity are maintained or reduced" (p. 53). Given the limited depth of research on this topic in mining, we attempt to note specific sources and relevant terms where applicable.

2 | MINING OCCUPATIONAL HAZARDS AND SOURCES OF FATIGUE

Despite having a reputation as a hazardous industry, it should be noted that the mining industry has made substantive safety improvements over the last century and particularly over the last few decades.[7–10] Nevertheless, various hazards from diverse sources (e.g., psychosocial, environmental, and physical) remain inherently present in many mining jobs and tasks. The problem is that many of the hazards prevalent in mining can also be common sources of different types of fatigue and sleepiness, such as cognitive, physical, psychological, and so forth. Some of the hazards most commonly noted among mining experts and researchers include: body positions and ergonomic issues, dim lighting, heat, heavy metal exposure, increased commute times, monotonous/disengaging tasks, noise, noxious/toxic fumes, remote/rural work locations, vibration (including hand and whole body), work-life balance, and workload.[11–17] Individual factors such as diet, physical fitness, and illness have also been identified as contributors toward fatigue for mineworkers.[18] Legault[19] argues that it is the simultaneous combination of these hazards and factors that can make mineworkers particularly susceptible to fatigue in comparison to other industries where these factors are often not all present at the same time. However, much like in construction and oil and gas, fatigue in mining remains a concern because mineworkers must constantly monitor and respond to the aforementioned hazards. It is the complex and dynamic interaction between the human, social, and organizational components (i.e., the sociotechnical system)[20] of a mining environment which necessitates human factors approaches to sleep and fatigue, such as error management, hazard assessment, and risk reduction. In other industries, such approaches have been utilized to address fatigue by formalizing the incorporation of task- and behavior-based protective behaviors to *fatigue-proof* work processes and reduce the safety risk associated with fatigue-related human error.[21]

The following is a brief, cursory overview of how some of the more distinctive factors inherent to mining contribute to the prevalence and unique combination of various subdimensions of mineworker fatigue.

2.1 | Monotonous and disengaging work tasks

The associations between long-haul trucking and cognitive fatigue have been well established.[22] Although, in comparison, there is far less research on mining haul trucks and fatigue, the similarities between long-haul and haul truck operation are noticeable. Operating a haul truck is usually an entry-level position in large-scale surface operations and has been described as monotonous work conducted for long periods in a sedentary position, often in a hot and un-comfortable cab.[23] In contrast to the tedium of haul truck operation, mines can be characterized as dynamic and highly variant work environments[24] where skills such as decision-making and hazard recognition are critical for worker safety.[25] Additionally, musculoskeletal disorders (MSDs) are relatively common in mining due to the "intermittent heavy physical work, reduced task variation, sedentary work in fixed postures and whole-body vibration" (p. 302).[16] Susceptibility to MSDs is pertinent, as pain due to MSD injury has been shown to negatively correspond with perceived sleep quality in mining populations.[26] A detailed 2018 analysis of five fatalities involving haul trucks at an

Indonesian coal mine revealed root causes to be either cell phone usage due to boredom and monotony or cognitive fatigue and sleepiness due to long commute times and shift schedules.[27]

2.2 | Underground environments and light exposure

The lack of natural light in underground mining environments is an important factor for fatigue, specifically with regard to circadian rhythms and the alerting effects of light exposure.[12] Underground miners have much less natural light exposure than other workers, even when they are on a steady daylight schedule. For instance, for a typical workday from 7:00 a.m. to 3:30 p.m., a miner in the Pittsburgh, PA, area would at best receive 47% of daylight on June 21 (the summer solstice) and only about 15% of daylight on December 21 (the winter solstice).[28] Thus, there is a high likelihood of fatigue, even among miners who work daylight shifts. A lack of the 24-h cycle of light and dark results in circadian disruption (CD) that can lead to sleepy and fatigued workers, who are 69% more likely to be involved in safety incidents.[29] Second, underground miners work in mines with artificial lighting where the ambient light levels are much lower compared to other workers in workplaces using artificial lighting. For instance, the ambient illuminance (lux, or lx) for a roof bolter operator would be about 22 lx, which is in comparison to night-shift nurses' ambient lighting environment of about 300 lx.[30] A significant portion of miners work in underground mines where they spend most of the working day in dim lighting conditions. Working in dim light has additional consequences by considerably decreasing cognitive functions, such as alertness and reaction time, which can lead to a greater likelihood of mistakes being made. This could be one factor why underground miners have higher fatality rates per 100,000 full-time equivalent employees in comparison to surface miners; for instance, 2015 data indicate an underground fatality rate of 20.8 versus the surface fatality rate of 7.0.[31]

2.3 | Effects of remote site mining operations on sleep and fatigue: Commute time, health, and work-life balance

Mines are typically far away from urban and residential areas, positioned instead closest to ore bodies and sedimentary locations that are sometimes situated in remote areas. This has several implications regarding sleepiness and cognitive fatigue for workers. Most notably, workers in the mining industry have, on average, the longest commutes of nearly any other industry.[32] In extreme cases, such as the fly-in fly-out (FIFO) and drive-in drive-out operations common in Australia or the so-called "man camp" arrangements, workers must choose between one-way commutes lasting several hours or living on-site for weeks on end. A 2008 survey of Australian coal miners ($n = 917$) revealed that two-thirds of the sample commuted between 1 and 3 h, about one-fifth between 3 and 5 h, and about one-eighth traveling more than 5 h.[33] More recently, it was discovered that this population drives on average 473 km (293.9 miles) to get home (with a third driving over 600 km or 372.8 miles), often-times driving after being awake for up to 20 h on the last day of shift.[34] Indeed, a 2005 analysis of commuting-related crashes to and from Australian coal mines found that 21.9% ($n = 28$) of vehicle incidents traveling home were because the driver fell asleep.[35]

3 | EXPOSURES TO LONG WORKING HOURS AND SHIFTWORK IN MINING AND THEIR ASSOCIATIONS WITH INJURIES AND FATALITIES

As with similar industries like construction and oil and gas extraction, a considerable degree of mine work is organized in continuous 24/7 shiftwork arrangements where fatigue remains a consistent concern for workers and mine management. While the precise burden of fatigue and sleepiness on the U.S. mining industry has not been specifically evaluated, there are some alarming data, nonetheless. For instance, the mining industry continues to lead other industries on average weekly hours worked, specifically with miners working an average of 46.6 h per week in 2019.[3] This is at least 4–5 h more on average per week than the construction (39.3), logging (42.0), and oil and gas industries (42.8), and more than 12 h greater than the average U.S. worker (34.0). According to Mine Safety and Health Administration (MSHA) data,[5] for all active U.S. mines with greater than 20 employees (n = 1,438), 98.5% of mining operations used shifts 8 h or longer (139,758 employees), 44.2% had shifts 10 h or longer (74,491 employees), and 19.7% had shifts at least 12 h long (46,808 employees). Long hours could partially explain why some estimates suggest an average of one “fatigue-related event” per 52 h of haul truck operation, and that an average of 1 s out of every 9 h of haul truck operation is spent with the driver on duty asleep at the wheel.[36]

Although it is difficult to determine the roles of sleep deprivation, different types of fatigue, or consecutive shifts/working hours in any given safety incident, these factors have been highlighted to varying degrees in several MSHA fatality investigations.[37–47] In one incident, sleep deprivation was identified as a contributing factor in the drowning death of a dredging operator foreman after it was discovered that the incident occurred during the 11th hour of his 15th consecutive 12-h shift (i.e., more than 180 work hours since having a day off).[39] A recent analysis of U.S. mining injury data revealed that nearly one-tenth of all MSHA reportable injuries between 1983 and 2015 occurred after 9 h on a shift (9.6%, n = 52,206), ranging from 5.5% of injuries in 1983 to 13.9% of injuries in 2015.[48] In this analysis, researchers discovered that significant predictors of long-working-hour injuries included irregular shift start time (e.g., outside of typical morning and evening shift start times), elevated ambient temperature, welding at time of injury, small mine size (less than 20 employees), being a contractor, working offsite at time of injury, and working on Sunday at time of injury. Study results found that long work hours increased the risk for workplace fatalities by 32% (odds ratio [OR] = 1.32; 95% CI: 1.18–1.48) and increased the risk for injuries among two or more workers by 73% (OR = 1.73; 95% CI: 1.58–1.89).

Not unlike other safety-sensitive industries, the accumulation of sleep debt over consecutive shifts—especially night shifts—can lead to elevated ratings of self-reported fatigue levels[49] and injury risk for miners. Additionally, Muller et al.[50] compared reaction times among miners working consecutive 12-h shifts (10 consecutive day shifts, 5 days off, 8 consecutive night shifts, 5 days off, etc.) to reaction times of participants with a blood alcohol content (BAC) of 0.05% and found that night-shift workers demonstrated impairment after only four consecutive shifts, whereas day-shift workers displayed impairment consistent with a BAC of 0.05% after eight consecutive shifts.

4 | RESEARCH ON FATIGUE MITIGATION STRATEGIES IN MINING

On the basis of what is known about the burden of fatigue and sleepiness in mining, as well as the environmental and psychosocial conditions that often result in mineworker fatigue, there remains very little peer-reviewed empirical work conducted in mine settings which aims to demonstrate beneficial and comprehensive improvements to worker sleep and fatigue. Most of the work in this area has focused on shift schedules, with studies generally falling into two camps: demonstrating deleterious effects of consecutive workdays on sleep and performance (especially night shifts)[51,52] and comparing fatigue or fitness for duty before and after a change in shift-scheduling or rotation.[53–58]

However, there are some notable exceptions of research focused on topics outside of shift-scheduling. Drory[59] demonstrated a reduction in perceived fatigue with rest breaks and secondary tasks (e.g., vigilance task, voice communication task) during a simulated haul truck driving task, and Paech et al.[60] found that night-time breaks were more conducive for sleep and recovery for Australian FIFO train workers than day-time breaks, which is consistent with other work in this area. While Kerin and Aguirre[58] discussed shift-scheduling at length, a training evaluation of a *Managing a Shiftwork Lifestyle* education session was also included, which resulted in decreased caffeine consumption and improvements in daytime hours of sleep when working night shifts and in gastrointestinal health. Finally, Eiter et al.[61] showcased a human factors-focused case study at a small mining operation which—through participatory design methodology—improved haul truck driving visibility and working hours.

5 | FATIGUE MITIGATION METHODS IN MINING: POTENTIAL FUTURE FOCI

While there are many potential future directions for innovative empirical research, applications, and discovery when it comes to mineworker fatigue,[62] we present five broad areas which are arguably the most needed or perhaps most fruitful in fatigue mitigation: fatigue risk management systems (FRMS), surveillance, intervention evaluations, lighting, and automation.

5.1 | FRMS

First and foremost, more research demonstrating the potential viability and translational value of FRMS in mining could be very beneficial for fatigue mitigation. A single intervention by itself—regardless of how systematically designed and executed—can have limited long-term applicability outside of a comprehensive FRMS, which allows for ongoing, iterative, and participative improvement. Future work could perhaps capitalize on existent FRMS structures, toolkits, and recommendations in other industries[63,64] and develop similar tools and guidance for mining. To this end, some more progressive Australian mining companies have adopted an error management approach that focuses on improving FRMS system resiliency over strictly risk-reduction strategies.[21]

5.2 | Surveillance

The true burden of fatigue on the mining industry is not fully understood. To address the magnitude and severity of this complex issue, further research and surveillance need to be conducted throughout the industry to assess and understand the risk and to study the intersection of people, tasks, equipment, and environment in relation to fatigue.

The U.S. mining industry is not required to record, collect, or maintain data on the role of sleep or fatigue in any given incident or fatality. Comparatively, the National Transportation Safety Board under the U.S. Department of Transportation uses a thorough and detailed methodology to determine whether fatigue was a probable cause or contributing factor in transportation incidents.[65] While such investigations are perhaps too complex and time-consuming to be enacted for every reportable incident in mining, there may be ways of incorporating additional information, questions, or items into existent surveillance methods so that the burden of fatigue in mining may be more accurately quantified and tracked longitudinally. For example, while capturing a 2-week sleep history for workers involved in a safety incident may be too difficult or burdensome, recording the number of consecutive shifts/hours worked before the incident took place would be fairly straightforward information to obtain. Regardless of the measurement method, concepts such as user acceptance and perceived utility are vital for this population, especially for technology-based measures.[18]

Such improvements in fatigue surveillance would allow researchers and practitioners to address critical questions that are unique to the sleep and fatigue experiences of mineworkers. One discernible use of surveillance would be to compare fatigue-related incidents among different operations and commodities in both underground and surface operations. Another potential area for investigation is determining what role exposure to chemicals and metals plays in the prevalence of fatigue among mineworkers. According to a 2004 overview of occupational health hazards in mining, mineworkers, in comparison to other similar sector workers (such as construction and logging), can be exposed to a wider array of inorganic compounds such as crystalline silica, diesel particulates, arsenic, nickel compounds, lead, cadmium, manganese, platinum, cobalt, coal dust, cyanide, xanthates, mercury, hydrofluoric acid, and sulfur dioxide gas, to name a few.[13,14] Not only can mining metal exposures pose general environmental and human health risks,[66] but metallic exposure (lead and cadmium, in particular) may potentially be associated with sleep–wake cycle disruption.[67]

5.3 | Intervention evaluations

Empirical studies focused on the mitigation of fatigue in the mining industry have often focused on isolated factors (e.g., sleep/shift schedules, environmental conditions), warranting a human–systems integration approach to fully investigate the multifaceted combination of factors associated with mine work and nonwork effects on mineworker fatigue. For example, secondary findings from mineworker fatigue studies suggest some anecdotal or ancillary benefits from miners engaging in self-pacing strategies to compensate for physically laborious work during extended shifts[54] and incorporating miner input into shift-scheduling design changes.[58,68] Implementing and evaluating worker-centered interventions aimed at mitigating mineworker fatigue and rooted in occupational health psychology and/or total worker health principles[69–71] would be of great benefit to researchers and practitioners alike, including the pre–post evaluation of frameworks such as the mineworker fatigue conceptual model.[18] Intervention strategies adopted by other industries that have been suggested for fatigue mitigation in mining include: establishing ergonomic requirements for job tasks, training on improving sleep quality and reducing stress factors, psychomotor performance monitoring, increasing opportunities for rest, systems analysis of fatigue-related incidents, recognizing and assessing symptoms of sleep disorders, sleep hygiene tips, and healthy lifestyle promotion.[12,15]

5.4 | Lighting interventions

One factor that could benefit from intervention research in mining is lighting. As mentioned earlier, light has both visual and nonvisual impacts on the human body, enabling us to visually perceive the world and nonvisually experience circadian effects and acute effects that include fatigue, alertness, concentration, and performance on cognitive tasks;[72] hence, light drives our fundamental physiological functioning. Light has been successfully implemented as an intervention to address shiftwork-related fatigue and CD in other industries, such as health care and aviation. Lighting interventions are the most effective means to address CD, given that circadian rhythms are driven by the day/night cycle of light. Although various studies indicate light can be an effective intervention,[73–75] it has not yet been used as a fatigue intervention in mining, perhaps due to the challenging and diverse underground environments. There are very few industries other than underground mining where workers spend almost the entirety of the working day in near-total darkness and must constantly adapt to a changing working environment.

Lastly, the application of a lighting intervention in underground mines is a necessary approach to a difficult problem. Implementation of a lighting intervention is the only way to address the lack of light during the workday and to potentially increase alertness and correct disruption to circadian rhythms, which are critical for preventing fatigue. Such an intervention would have widespread applicability to underground mines and could be adapted for use in other sectors where inadequate light is of major concern.

Providing light as an intervention is not without controversy. Using light-emitting diode (LED) lighting technologies has raised concerns of exposure to potential blue-light hazards resulting in retinal damage that is typically irreversible. A quantitative study conducted by the Lighting Research Center found that the blue-light hazard risk from LEDs is no greater than from other light sources.[76] Blue light at night can suppress melatonin and this has been linked to negative health consequences; however, red light exposure can induce alertness while reducing melatonin suppression.[77]

5.5 | Automation

As with other similar industries, automation continues to shape and change the nature of mine work. A recent report by the U.S. Mine Safety and Health Research Advisory Committee[78] estimates that leading automation practices (e.g., fully automated surface haul trucks and underground mining sections) might be broadly implemented in some commodities of large-scale mines within the next 10–15 years. Among other concerns regarding the general intersection of fatigue, automation, and human–machine interaction in mining, the added facets of isolation, remoteness, dynamicity, significantly sized equipment, and massive throughputs of big data within a historically archaic industry leave many questions still left unresolved, such as: *is automation the solution to all of our fatigue concerns?* Specifically: *to what extent* can *and* should *humans be involved in the human–computer interaction aspects of automated mining equipment, and what implications might this have for work design, training, and monitoring fatigue?* As with other industries, mining may run the risk of facing its own automation conundrum[79] in which automation lowers situation awareness in human operators, thus reducing the ability to safely and effectively utilize manual override (especially under conditions of compromised vigilance, i.e., fatigue and sleepiness). However, there may also exist an opportunity to utilize automation aspects of machine learning to improve fatigue-specific health and safety management responses in mining by analyzing leading indicators of sleepiness and performance decrements.[80] As automation expands its rapidly growing presence and permeation in the industry, the role of the human mineworker and concerns regarding their sleep health, job task requirements, alertness levels, and overall readiness for work will need to be a priority for researchers and practitioners, alike.

6 | CONCLUSION

Fatigue continues to be a critical challenge for the mining industry. While research on the problems and solutions of mineworker fatigue has been limited to date, the future of fatigue research in mining can expand on these findings by exploring the origins, nature, and outcomes of fatigue using advancements in lighting, automation, and fatigue risk management. Evaluations of sleep and fatigue interventions that target specific health and safety behavior could further advance our understanding of how best to mitigate hazardous consequences and focus on improving worker wellbeing.

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