



The Experience and Management of Fatigue: A Study of Mine Haulage Operators

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Abstract

Fatigue in mining operations is a serious issue and a significant contributor to incidents and accidents. While mine operators are using or introducing new technology to monitor operator fatigue, there is little work that focuses on the subjective experience of fatigue and the use of fatigue monitoring technology. To investigate this issue, eight focus groups with a total of 44 operators of heavy haulage equipment working for two mining companies in the Mountain West of the USA participated in 1-h focus groups. The topic of the focus groups was the experience of operator fatigue and issues surrounding fatigue at the workplace. The results of the content analyses suggest that operators are well aware of the signs of fatigue, and that they understand the severity of these signs as well. In addition, they are aware of the effect of fatigue on driving performance and are using a wide range of methods to manage fatigue. Finally, based on participants' assessment, current fatigue monitoring systems lack face validity and reliability and are perceived as not being effective. The results of this study emphasize the importance of a socio-technical systems perspective in the context of miner health and safety management. Only such a comprehensive perspective can result in improvements that are sustainable.

Keywords Mine worker fatigue · Fatigue · Fatigue modeling · Emerging technologies · Miner health and safety

1 Introduction

Fatigue in the surface transportation industry has been relatively well investigated [1] with the focus of the majority of this work on fatigue-inducing factors associated with lack of sleep and circadian rhythm. Estimates are that as much as 33% of all vehicle accidents on European roads are caused by

sleepiness [2]. In the USA, studies of highway crashes find that drowsy drivers account for approximately 75,000 crashes annually, resulting in approximately 725 fatalities and 35,000 injuries [3]. Overall, fatigue is clearly a significant contributor to vehicle crashes.

Unlike in transportation, relatively little work investigated the effects of fatigue in mining. For example, in their literature review, Bauerle et al. (2018) list only 12 empirical papers that investigated the impact of miner fatigue on performance. Among the performance measures that were investigated were accidents, injuries, reaction times, and cognition. Bauerle et al. report that the studies assessed fatigue using a variety of measures, for example, self-reported sleepiness ratings, work/sleep diaries, actigraphy measurements, and in some cases physiological measurements like heart rate monitoring [4]. Overall, while some empirical work already exists, Bauerle et al. point out the great need for additional research to study the impact of fatigue in mining.

Another issue that supports the need for additional empirical work on miner fatigue relates to the fact that it is difficult to extrapolate from research on fatigue in non-mining industries to the mining industry due to mining-specific environmental factors. For example, the mining environment can be described as "...dim lighting, limited visual acuity, hot

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temperatures, loud noise, highly repetitive, sustained, and monotonous tasks, shiftwork, long work hours, early morning awakenings, and generally poor sleeping habits” [4]. This quote highlights the unusual combination of factors that make the mining industry unique. However, it is still the case that certain jobs in the mining industry may have factors common with jobs in other industries. For example, operating haulage equipment in mining may have a number of similarities to operating a truck outside of a mine, while other aspects set those activities apart. For example, in mining, the heavy material haulage equipment is moving at much lower speeds, using the same route day in and day out, with the operators being exposed to high levels of environmental monotony, whereas truck drivers experience variation in the surrounding environment while driving at relatively high speeds. Thus, the relatively high monotony of equipment operation in mining haulage operations may contribute significantly to operator fatigue.

Below, we present a general background of research on workforce fatigue and develop a conceptual fatigue model considering distal and proximal factors contributing to fatigue. The results of focus groups on the experience of fatigue in mining haulage operators are then presented. These results of this research are part of a multiyear research project focused on mine worker fatigue in the mining industry.

2 Background

As suggested above, the literature on fatigue in mining is sparse. For a recent and thorough literature review of mine worker fatigue, we refer to Bauerle et al. (2018) [4]. The goal of this “**Background**” section is to present general models of fatigue that were used to develop the conceptual model of fatigue that is guiding this research.

Several fatigue models have been developed focusing on the relationship between fatigue and injuries in the workplace. Among those models are biomathematical models that estimate fatigue levels based on sleep and work shift schedule [5]. Often, these models use assumptions that are derived from the classic two-process model of sleep regulation which estimates the timing and the intensity of sleep by assuming two separate biological systems responsible for the regulation of sleep (i.e., the circadian rhythm and the sleep-wake homeostasis) [6]. Other models include additional processes involved in regulating sleep (i.e., three-process model [7] and four-process model [8]).

A more recent conceptualization of fatigue in a three-factor model describes work fatigue as [9]:

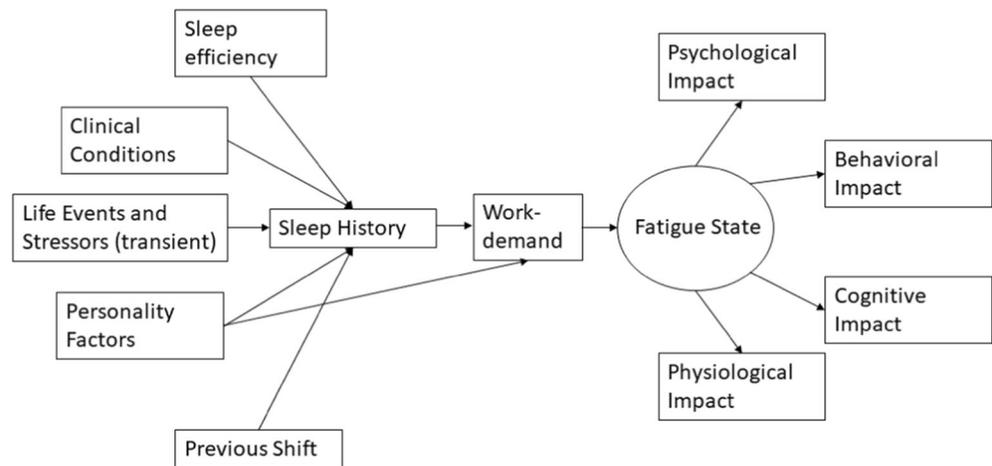
1. Fatigue involving equal parts of both “extreme tiredness” and “reduced functional capacity”
2. Fatigue is experienced physically, mentally, and/or emotionally, i.e., it affects these three types of energetic resources
3. Fatigue is “temporally tied to the workday” emphasizing the relationship between time of day at work and fatigue.

Another perspective that goes beyond biologically based models of fatigue is an approach that describes sleep-related fatigue as a result of previous sleep restrictions. Three types of sleep restriction can be identified: First, **transient fatigue** is acute in its nature and is brought by extreme sleep restrictions, or extended wake hours within 1–2 days; second, **cumulative fatigue** is a result of repeated mild sleep restriction or extended hours awake over series of days, which is associated with long shift durations; and third, **circadian fatigue** results in reduced performance during night time hours, particularly during an individual’s window of circadian low (WOCL) between 2 am and 6 am. Each factor separately or in combination with others can contribute to the overall level of fatigue experienced by an individual [10].

Most existing models are using either physiological or in some cases psychological contributors to predict potential fatigue levels. However, what is not included are the types of activities that a person engages in that also affect fatigue state. Currently, little work exists that considers the impact of work demand–, or task demand–related fatigue. Work demand-related fatigue can have a potentially negative impact on task performance, and two types of work demand-related fatigue can be distinguished: passive and active fatigue. Desmond and Hancock defined active fatigue as the worker’s state change resulting from “continuous and prolonged, task-related psychomotor adjustment.” For example, high levels of demanding physical and cognitive activity and active involvement in varying tasks can result in active fatigue [11]. Overall, active fatigue is associated with high cognitive workload. By contrast, passive fatigue develops when there is a requirement for activities that have “either rare or even no overt perceptual-motor requirements” [12]. For example, operating a vehicle over long periods of time on the same road by driving back and forth between a loading and dumping point can result in passive fatigue. Passive fatigue also can result from low-workload conditions, requiring infrequent physical activities, but continued vigilance for alarms. Both active and passive fatigue may generate a subjective fatigue response, such as tiredness and aversion to effort [13, 14].

When describing the impact of fatigue on haulage operators, its impact can show in a number of ways. Shen et al. describe the impact at the psychological, the physiological, the cognitive, and the behavioral level [15]. Mathews (2002) developed a conceptual model of fatigue that distinguished between distal and proximal factors affecting fatigue [16]. In Fig. 1, we present an extended version of the original model that differentiates

Fig. 1 Fatigue conceptual model



the proximal factors (right) and adds sleep efficiency to the distal factors (left).

Distal factors include the sleep history, which is affected by factors like existing clinical conditions (e.g., sleep apnea), life events and stressors (e.g., financial or marital issues) with impact on sleep amount and quality, and personality factors (e.g., propensity to fatigue proneness) with the latter also affecting more directly the proximal factor of work demand-related fatigue. Some work suggests for example that certain individuals are more likely to experience fatigue in the context of vehicle operation than others [16]. While the original model distinguished the proximal factors cardiac activity, eye closures and movements, inattention, and subjective fatigue, we expanded these factors using broader categories that include these proximal factors. Therefore, we are differentiating between the psychological, the physiological, the cognitive, and the behavioral level of impact of the fatigue state [4, 15]. At the psychological level, the effect of the fatigue state may show as weariness due to a lack of motivation and changes in mood; at the physiological level, it finds its expression in loss of strength and stamina; at the cognitive level, it shows as changes in reaction times and forgetfulness; finally, at the behavioral level, it manifests in the presence of microsleeps, head nodding, slower speech, and decrease of productivity.

When examining the proximal factors, some are well understood, while others are still in need of further study. For example, laboratory-based research using a sustained attention task examined the impact of sleep deprivation (<5 h/night over 7 nights equal to 21 h of sleep deprivation) on cognitive functioning in general and attention in particular. The results suggest that reduced sleep time produces an increase in reaction times and omission errors (lapses) during the day-time circadian low (1–3 pm) [17]. Work from other authors confirms the finding that omissions increase as a result of sleep deprivation [18]. In addition, a recent literature review analyzing 61 studies found clear negative effects

of sleep restriction on cognitive processing such as executive functioning, sustained attention, and long-term memory [19].

2.1 Monitoring Fatigue

To address the issues surrounding fatigue at the workplace, a number of technology companies developed solutions to effectively monitor fatigue. Table 1 provides a sample set of technologies used within and out of mining to monitor fatigue. The table provides the type of technology and a description of the approach that is being used.

Overall, the technology-based approaches are using a range of physiological and behavioral measures to assess fatigue. Among those are the electrocardiogram (ECG), the electrooculogram (EOG), and the electroencephalogram (EEG). Today, existing systems to monitor fatigue levels in mining include camera-based measurements of eye blinking and PERCLOS [30], and EEG measurements. Other systems measure either physiological or behavioral reaction time of operators to estimate fatigue. Finally, using steering inputs into the vehicle, these data are being used to measure engagement and as a result fatigue. Unfortunately, what most of these systems have in common is that while they may offer some utility to assess fatigue, they are only able to measure fatigue at the point at which it has occurred. Thus, these systems are limited in their use as fatigue prevention or mitigation strategies. Due to this and other limitations, there are calls for systems that address the issues surrounding operator fatigue by applying a comprehensive, socio-technical systems perspective rather than one that focuses on the issue of fatigue as a purely technical and measurement issue.

The goal of the present work was to explore fatigue of haulage operators in the mining industry by conducting focus groups to discuss operator's experience of fatigue, the way they manage fatigue, and how they experience in-use fatigue monitoring technologies currently.

Table 1 Various fatigue monitoring and prediction system

Type of Technology	Description
Cognitive test	An employee's past 14-day work schedule and sleep history are used to evaluate a job risk profile. Other selected factors are included to build a comprehensive fatigue and alertness profile. Finally, the system will run a 60-s impairment test to confirm its findings and predict fatigue and alert employees and supervisors of upcoming fatigue [20].
Sleep pattern analysis using the smartwatch	Fatigue is predicted based on a biomathematical fatigue model and actigraphy-based sleep data [21].
Anti-drowsy alarm	This system raises driver awareness of momentary lapses caused by sleepiness. A device worn behind the driver's ear detects nodding movements and after crossing a threshold of the movement, it emits an alarm sound [22, 23].
Eyelid movement detection with infrared reflectance	Drowsiness or wakefulness is measured by a system that assesses infrared reflectance of the eye. Based on the reflectance data, eyelid movement is detected and used to assess eyelid closure. Other measures involve electro-oculography or video [24].
EEG cap/helmet	This system uses a cap that has EEG electrodes integrated to measure EEG. These measurements are used to recognize fatigue events [25].
Camera-based system	The system uses facial and eye recognition software to identify operator fatigue and to alert the driver if an instance of closed eyes for longer than a specific time was detected [26].
Fatigue warning kit	This system randomly emits a visual warning to which the operator has to respond by acknowledging the warning. Omission to do so activates a fatigue alarm [27].
Predictive and non-invasive monitoring	This approach uses a combination of two systems, one that is "knowledge-based" and provides an electronic template predicting hourly the likelihood of the driver falling asleep (circadian rhythm based), and the second using steering sensors to detect monotonous driving and steering movement characteristics to identify fatigued driving [22, 28].
Pupillometer	This system uses a light that flashes through the viewer's eyes and assesses the pupil response to this stimulus (constriction and dilation). The pupil response time is used to assess driver impairment such as lack of sleep [22, 29].

3 Methods

Focus groups were conducted at two mining sites in the rocky mountain region of the USA. A total of eight focus groups (four at each site) were conducted with participant numbers ranging from 5 to 7 per group. Overall, 42 participants participated in the focus groups of which five participants were female. All participants were haul truck drivers at the time of the focus groups and volunteered to participate in the University of Utah Institutional Review Board-approved study. Participants did not receive any compensation for participation. All focus groups were held immediately prior to the participant's workday.

Design Each focus group discussed up to 12 questions that covered the following four topics:

1. What are the factors that affect the frequency and severity of fatigue episodes experienced by operators?

2. What are current best practices operators use to reduce the number of fatigue episodes?
3. What are effective strategies to address fatigue?
4. What is the operators' understanding of mine specific in-use fatigue monitoring technology?

Setting The setting for conducting the focus group was either office spaces or larger meeting rooms at the participating mines. The discussions were held with the doors closed to allow for privacy. The spaces were easily accessible to participants and quiet to facilitate audio recording for later transcription and analysis.

Description of Measures The measures taken were qualitative in nature and allowed the identification of fatigue and fatigue monitoring technology-related issues and other topics and areas of concern. To complement the primary data source of the focus groups, field notes

were taken simultaneously to complement the audio recordings for later analyses.

Analysis Content analytical techniques identified issues related to operator fatigue and fatigue monitoring technology. Two team members were involved in the analysis process, which benefitted from insights from previously conducted focus groups informing subsequent data collection and analysis. After conducting the first focus group, team members independently reviewed field notes and created documents containing analytic insights and interpretations. A group meeting was used to inform the analysis. The analytical process was inductive in nature. Emerging themes of user needs and requirements were coded and applied to the focus group transcripts. The code development process was a team-based process that converged until a consensus is reached among team members on the categories and inclusion criteria.

4 Results

Below, we organize the focus group results based on the questions discussed and the conceptual framework shown above (Fig. 1). We will also describe the proximal and distal factors of fatigue and the specific subcategories in places provide quotes of participants to illustrate the results.

4.1 Proximal Factors

4.1.1 Cognitive and Psychological Impact: Symptoms of Fatigue

Participants mentioned symptoms ranging from general to those associated with perception, attention, memory, decision-making, and mood. Among the more general symptoms of fatigue were as follows: yawning (frequently mentioned), nodding or dozing off, eyes not staying open, fluttering of eyes (frequent), eyes getting tired, rubbing eyes, having microsleep episodes, falling asleep while driving, feeling that the arms getting heavy, or feeling very relaxed. Other participants mentioned that as a sign of fatigue, they felt weak and not having any energy.

Perception Participants described a number of symptoms related to changes in perceptual processes: For example, “I’ve been in a tunnel where there’s a blanket over me; because you’ll see a dark cloud where, you know you’re looking up, you get into space, that might sound weird, but it looks like you got a big cloud over you or an umbrella over you, and you’re looking around, and you’re going “wow, this looks strange.” Situations like these were described as being based on misperceptions or perceptual illusions. Another example was “I am literally dreaming and thought someone was

standing in front of me and then I have to realize “wait, I’m 20 feet in the air that would make a 20-foot person and there’s not someone right in front of me.” Changes in the location of shadows caused by the headlights illuminating the berms can lead to other perceptual illusions, for example, participants described that they “start to see things late night where you might see a shadow run across the road, or you’re looking at the berm and you see an animal figure in the berm.” This phenomenon was described as the “black dog” phenomenon, which according to participants, can take different shapes “looks like a, whatever, a tiger, a body.”

Another description of the perceptual changes was that participants felt “Like I’m in a dream, like if I’m really tired, it’s almost like I don’t, like everything is imagery sometimes. The world definitely doesn’t look the same,” or that the world looks “everything is just really strange.” Similarly, some participants described experiencing tunnel vision, with a narrowed area of visual attention that blocks out any peripheral vision.

Attention Other cognitive changes experienced by operators as a result of fatigue relate to changes in the allocation and maintenance of focused attention, which is a critical part of operating a vehicle. Participants described this as “I start losing my concentration and that’s just like your focus its gone. You’re no longer thinking about... I get to the point I’m thinking about other things or anything in particular and I’m just there.” Similarly, other participants described that they were losing concentration: “I am losing concentration, start kind of like, drifting off. I drive for a minute and I’ll be like “Oh”.” Participants described this situation as being on auto-pilot: “You’re just kind of on auto-pilot. It’s like, oh, I went for a minute and now I’m on this next road.” Lack of attention was described as a phenomenon associated with fatigue: “I wasn’t even paying attention, and those are definitely signs that I’m like, starting to getting more fatigue and need to pull off and take a break.”

The notion of driving as if on auto-pilot was shared among participants: “And you do that same thing over and over again, like autopilot, you’re running at remote control. Like autopilot driving, auto piloting. Because you’re driving up the tent, and like, oh, I’m supposed to go to the crusher.”

Memory Another cognitive process affected by fatigue was memory. Participants described that they had no recollection of how they got to a particular point while driving: “I understand you, halfway up and I don’t remember part of that.” Or “You don’t realize where you’ve been. Like you’re driving, how did I get up here already?” Some of these processes are a result of a lack of concentration or feeling dazed, dizzy, or disoriented. Phenomena like this are also referred to as highway hypnosis in commercial trucking [31].

Decision-making Participants also described the impact of fatigue on their decision-making. They described it as follows: “I’ve experienced where you hit a wall, where you’re totally just not making good choices. I want to say it’s almost like being intoxicated; you hit a wall where you gotta stop.”

Overall, fatigue was described as having an impact on higher cognitive processes as participants experience a “weak, slow mind.”

Mood A number of participants described mood changes as a symptom of fatigue. They described themselves as becoming “grumpy” or “irritable” as fatigue increased over the shift period.

Behavioral impact: How is your driving affected when you are getting fatigued?

The most frequently mentioned impact of fatigue was a slowing in reaction time to correct for lateral deviations, or to other vehicles breaking ahead of the own vehicle. In addition, participants were clear about the fact that any vehicle control behavior was not as precise when fatigued. Low control performance with regard to steering accuracy was mentioned due to a lack of focus during driving. To compensate for the increase in reaction time, some participants mentioned that they would compensate by driving slower. Other impacts of fatigue were related to lateral vehicle control “getting too close to the wall, drifting off to the berm,” speed maintenance “speed gets out of control,” or under certain circumstances that basic activities were not performed due to forgetting (e.g., “forgetting to shut your lights off during loading blinding all other drivers waiting in line” and “forgetting to put brakes on prior to loading”). Also, accuracy of standard maneuvers was described as low when fatigued, for example, drivers mentioned that they were “backing into the shovel in a crooked fashion.”

To summarize, operators identified the following behavioral impacts of fatigue: slowing of reaction times, lack of precise vehicle control, driving at lower speeds, issues with speed maintenance, forgetting to engage in routine behaviors, and lack of precision of standard maneuvers.

What are the most severe signs of fatigue?

Participants identified microsleep episodes, closing the eyelids, or nodding off as the most severe signs of fatigue, requiring them to stop the operation of the vehicle. Some participants referred to loss of concentration as a serious sign: “Well the loss of concentration; I feel like my brain is so tired, as in a fog.” Similarly, some participants also referred to perceptual issues as a serious sign of fatigue. One participant described imagining to act, but without doing: “...in your mind I’m pushing the brake right now. But you’re really not.” while another participant mentioned complacency “not being in

the present moment; your mind is elsewhere” as a severe sign of fatigue.

4.2 Distal and Proximal Factors Contributing to Fatigue

Participants listed a range of distal factors: diet, shift schedule, commuting time, amount and quality of sleep, domestic factors, level of physical fitness, and sickness. Each of these will be discussed in more detail below.

Among the diet-related contributors to fatigue are heavy foods, junk food, and foods high in carbohydrates. There was general awareness that carbohydrate-rich foods, while resulting in an immediate increase in alertness, lead to a delayed increase in fatigue. Participants also placed emphasis on good diet practices to avoid fatigue. Among those were eating protein bars or vegetable snacks or drinking protein drinks. Participants listed foods that should be avoided like granola chocolate bars and foods high in carbohydrates. Finally, participants pointed out that sometimes it was necessary to pick up food on the way to work, resulting in the purchase of junk food with negative impact on fatigue.

Another fatigue factor identified by participants related to the shift schedule. Among the shift-related contributors mentioned was mandatory overtime shifts, limiting the ability to recover from sleep debt accumulated during previous work periods.

A common concern was the frequent rotation between night and day shifts, which resulted in a “that flip-flop of days to nights.” A large number of participants mentioned that they would prefer to have a more consistent schedule with fewer changes between night and day shift. To facilitate sleep during the day when working night shifts, some participants mentioned sleep set-ups at home. To support sleep, these rooms often had black-out window shades and participants kept temperatures low and used earplugs to eliminate noise.

Another issue that contributes to fatigue was commuting time to work, with travel times ranging from 15 to 90 min one way for participants. Including the shift time, some participants estimated that the combination of commute and work time resulted in 16-h days, not including time for family or social activities, eating, and exercise.

Participants also mentioned some other factors that were related to an increase in fatigue. Among these factors were stress (i.e., domestic stress, having young children, financial stress), sickness, and physical condition (i.e., being overweight and not exercising regularly). Other participants mentioned that the rocking motion of the truck induces fatigue.

To summarize, distal factors that contribute to fatigue are diet, shift schedule, travel time to/from work, amount and quality of sleep (presence of a set-up for sleeping during the day), domestic factors, general level of physical fitness, and the presence of sickness.

4.3 When Do You Experience the Onset of Fatigue, and How Do You Experience It?

The most common answer was that participants experienced the onset of fatigue during the day shift as shortly after the sunrise and then in the early afternoon between 2 and 4 pm. For the night shift, participants also mentioned that the time between 1 and 4 am was the most difficult. Helping participants to reduce fatigue at the time close to shift change was that they were required to prepare the haulage truck for the next operator, with the required physical activities that increased alertness. However, there were substantive inter-individual differences between participants. This was especially the case when referring to themselves as early morning or late morning people. One individual mentioned, “during day-shift I get tired when the sun comes up because I’m not a morning person. I’m an afternoon person.” Similarly, others mentioned that during day shifts, “it can be an hour” until they experience fatigue, whereas during “night shifts and you’re still going to about midnight for me.”

The way participants experience the onset of fatigue followed a predictable pattern consisting of initial yawning, then eye rubbing, fidgeting in the seat to get comfortable, then the head starting to nod off.

Fatigue state: What do you do to deal with fatigue once you experience it?

Participants listed a wide range of strategies on how to deal with the onset of fatigue. These strategies range from cognitive, physical, or social strategies, to consuming food or beverages.

Among the cognitive strategies, participants mentioned that they were engaging cognitively by listening to podcasts, the radio, comedy shows, or to music. Other strategies mentioned were to “push through” the fatigue episode, to “just fight”. Practicing mindfulness was mentioned as well: “Basically just breathing and feeling every part of your body what its touching.” Finally, some participants mentioned that they would talk to themselves either aloud, or in their mind, to deal with fatigue onset.

Physical activities that participants engage in were to move to the tie line (i.e., a parking area), to leave the vehicle to stretch, and to “get some blood flowing.” Other activities involve to “do some push-ups, do some pull ups,” or “go exercise and stretch.” One participant mentioned air drumming as a way to combat fatigue. Related to physical strategies is changing the temperature in the vehicle cabin by rolling down the window or opening the cab door to let cool air in for brief periods of time.

Several participants mentioned that they would consume food or beverages (water) to fight fatigue or by starting to chew gum. Among the types of drinks that operators consume were energy drinks. Alternatively, they used caffeine pills, or medications like Ritalin, Adderall, or Nuvigil.

Finally, social interaction with other operators was also mentioned as a way to deal with fatigue. Here, behaviors include “drive by honking at each other, wave at each other, flash the light at each other, flip off each other or something. Just to get a reaction out of each other.”

To summarize, participants described the way how they address fatigue in a variety of ways ranging from cognitive, social, and physical strategies to taking a break, or taking medications or energy drinks.

4.4 Organizational Support in Fatigue Management

Participants’ answers provided information about a number of ways how the organizations support operators in dealing with fatigue. One of the most common answers to this question was related to the introduction and use of two fatigue monitoring technologies: an electroencephalography (EEG) system and a camera-based percentage eye openness tracking (PERCLOS) system. Each will be discussed below.

Other ways of supporting operators organizationally were that operators were permitted to take a number of breaks or ask for additional break time if they felt extremely fatigued.

Participants also mentioned that the presence of some of the contents in vending machines was not considered being helpful due to the high carbohydrate contents of the foods available. Providing better food options was identified as another way how the companies could support operators.

Overall, participants expressed that the main strategy how management helped them deal with fatigue was the use of fatigue monitoring technology. Additional support was provided by permitting operators to take breaks when fatigued; however, not all participants felt free to take such breaks when needed.

How does your employer monitor fatigue and what do you think of this approach?

Below, we will discuss the two fatigue monitoring systems used in the mines. We examined the systems considering common socio-technical factors: user acceptance, perceived utility, unintended consequences of use, and usability.

4.4.1 EEG System

Participants provided detailed feedback on EEG system. A number of issues surrounding the use and acceptance of the system were identified.

User Acceptance Overall, user acceptance of the EEG system was low. Participants were referring to the system as a “joke cap,” because “it doesn’t do anything.” As one participant summarizes this issue: “I’ll be driving and I’m totally wide awake, alert. And all of the sudden it’s reading 4’s and I’m like, ok. I am totally fine.”

Some operators articulated skepticism that the EEG system is not useful due to the field conditions in which the system is being used: “I don’t think it works like it supposed to”. When asked about the positives of the EEG system, the answer was: “I don’t see any. I see no positive whatsoever.” However, one participant noted: “I do have a positive for it. I rather have that than have a camera sitting there staring at me.” Another participant expressed one of the main limitations about current technology is the delayed feedback and lack of predictive capabilities.

Perceived Utility The perceived utility of the EEG system was low due to the above limitations. Participants described situations when the system was providing false alarms or incorrect measurements. One operator described his experience as “And I forgot to take the thing off. And I was out for 20 minutes. And when I woke up...it never went off”.

However, some participants noted that they would be in favor of a system that would work and provide correct alarms in potentially dangerous situations: “If there really was something, that would alert you that moment you take a microsleep, that would be ok.”

Unintended Consequences One of the concerns mentioned by participants was that the EEG system had the potential to be a significant source of distraction “It’s a distraction“, “When it does go off, it startles you.” In addition to situations when the system alarms operators, participants also mentioned having to switch the empty batteries several times per shift, which added to distraction. Another source of distraction for participants was the fact that the EEG system was at times offline which required them to restart the system.

Usability In terms of usability issues of the EEG system, participants mentioned that the battery life was too short “The batteries don’t last that long” and that wearing the EEG system was uncomfortable “I never wear a cap so it’s extremely uncomfortable”.

4.4.2 PERCLOS System

User Acceptance Overall, user acceptance of the PERCLOS monitoring system was relatively low with the system being described as a “nanny system” or “spy cam.” Complaints surrounded the high number of false alarms and low face validity of the system. In addition, participants expressed privacy concerns with regard to the system since there was no transparency of how the system is working and who is reviewing the video recordings under what conditions.

Perceived Utility The perceived utility of the PERCLOS monitoring system was described as relatively low. Participants provided many examples when the system was providing

false alarms or incorrect measurements. Alarms were also described as potentially startling participants and feedback was described as delayed and as a result, not useful.

Unintended Consequences One of the concerns mentioned by a number of participants was that the monitoring system has the potential to be a significant source of distraction due to its alarming functions (vibration of the seat and auditory alarms). Another issue was that the system provided false alerts when the operator was looking at the side-view mirrors or inside the vehicle cab. As a result, they avoided those side-view mirror glances to not trigger a false alarm. Finally, to many participants, it was not clear under what conditions recorded fatigue events would result in disciplinary measures and when not. Many anecdotes were reported, but there was a lack of transparency on the rules that were employed to issue disciplinary measures to employees.

Usability Due to the non-invasive nature of the system and minimal needs for interaction with it, participants did not make many comments concerning usability.

5 Discussion

Overall, the results of the focus groups demonstrate that operators have substantial knowledge regarding fatigue and its management at the workplace. Another positive result of the focus groups was that there was moderate to high awareness of how fatigue affects operator performance, a knowledge that is not necessarily common in other industries. This suggests that existing educational programs help in disseminating the necessary knowledge to operators. Similarly, participants demonstrated broad knowledge and awareness of the signs of fatigue and their seriousness, how fatigue affects their ability to operate the equipment, what factors contribute to fatigue, and how fatigue develops over the course of their shift. Among the more novel findings of the focus groups was that the impact of fatigue goes beyond some of the previously established cognitive processes, affecting all stages of cognition, from perception to decision-making, to response execution. In addition, our conceptual framework as outlined in Fig. 1 successfully distinguished the impact of fatigue impact by providing the categories of impact (psychological, behavioral, cognitive, and physiological) based on the work of Shen et al. [15]. While there is a need for additional research in describing and assessing the impact of fatigue on each of these different categories, it is also important to focus on the potentially cascading effects impairments on the early stages of information processing may have for later stages affecting both decision-making and behavioral aspects of operating the vehicle.

Another issue that was discussed relates to participants' knowledge of how nutrition and physical fitness affect fatigue. Participants expressed awareness of the relationship between those factors and also acknowledged that sustaining exercise and good nutritional practices can be challenging. One of the opportunities could be to provide support to operators by educating them in exercise practices to combat fatigue. Another route would be to provide selections of more nutritious and healthy food in the available vending machines on site.

Discussion of the current, technological approaches towards fatigue monitoring illustrated that operators experience limitations of these approaches involving EEG- and PERCLOS-based systems. In their discussion, participants emphasized the importance of the potential distraction associated with the fatigue monitoring systems and most importantly, the lack of face validity of alerts issued by the systems. Overall, there was strong agreement among participants that both technologies do not provide effective fatigue monitoring, which is especially meaningful given the low reliability and face validity of the technology.

Among the main themes in the discussions was that participants expressed an interest in playing a more active role in fatigue management. While there are substantial concerns related to privacy, operators expressed support for less invasive approaches towards fatigue monitoring compared with the currently used approaches.

Overall, the results of this work suggest that the issues related to fatigue management are complex in nature, and while it is tempting to implement technology-based solutions, it is also important to acknowledge that these solutions need to be accepted by the operators. If this is not the case, there is a risk that the technology will not be used as designed with a negative impact on its functionality. Clearly, the results of this research serve as an important reminder that fatigue monitoring is one facet of health and safety management, and a sole focus on technological solutions alone may create only an illusion of safety. Our results also remind of the work performed at the Tavistock Institute in the UK in the 1950s. This work done almost 70 years ago emphasized the importance of a socio-technical system's perspective when improving health and safety in the workforce [32]. Only a comprehensive approach can lead to sustainable improvements in health and safety.

5.1 Limitations

The results reported above are limited due to the nature of the way how data were collected. Focus groups provide detailed information about the issues that participants face. However, the data collected might be biased due to the fact that engaged and eloquent participants tend to be overrepresented in focus groups, limiting the generalizability of the results. This is the first outcome of a multi-year study examining mine worker

fatigue. Future work will build on this work with more surveys, modeling behavior and fatigue using operational technology systems, and advanced computing.

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Data Availability Not applicable.

Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

Ethics Approval The study was approved by the University of Utah Institutional Review Board (IRB).

Consent to Participate Recruitment of individual study participants occurred at the mine sites, following an invitation from operations and management contacts. Researchers obtained verbal consent to participate from each individual, while stressing that participation was voluntary; operators had the right to participate in the focus groups at any time, and that operators would not receive any compensation for their participation in the focus groups.

Consent of Publication Not applicable.

Code Availability Not applicable.

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