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Field-based longitudinal evaluation of multimodal worker fatigue assessments in offshore shiftwork

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ABSTRACT

Fatigue in offshore environments is a critical safety hazard, yet the utility of daily fatigue assessments has not been longitudinally examined in these environments. The aim of this exploratory longitudinal field study across two drillships in the Gulf of Mexico was to determine the changes in subjective, performance-based, and physiological fatigue measures over time across different shift types (day, night, and swing) and to identify correlations between these multimodal fatigue assessments. Repeated measures correlation analyses of daily fatigue data from seventy offshore workers revealed that while total sleep time remained unaffected by time on rig, workers' performances on the psychomotor vigilance test (PVT) deteriorated over time across all shift types. Several correlations between the various multimodal measures were consistent with the extant literature on worker fatigue symptoms and perceptual and physiological manifestations. These findings emphasize the utility of PVT and single item self-reports to capture worker fatigue in offshore shiftwork.

1. Introduction

Fatigue is a multidimensional construct and is defined as the physiological and/or psychophysiological response to prolonged physical activity , mental exertion , and/or sleep deprivation (Kang et al., 2021; Mehta et al., 2020; Shortz et al., 2018) . Health issues related to occupational fatigue are estimated to account for $136 billion in lost productivity annually (Ricci et al., 2007). Documented physical and cognitive impairments associated with fatigue have been shown to adversely affect task performance and work productivity, and is linked with workplace accidents, fatalities, and injuries (Lerman et al., 2012). For example, the Exxon Valdez Oil Spill and the Texas City Refinery Explosion have been linked to fatigue in the petrochemical and oil and gas sectors (CSB, 2007; National Transportation Safety Board, 1990). Exxon Valdez Oil Spill incident investigation concluded that impaired task performance was one of the major factors contributing to the spill since the third mate at the helm suffered from sleep deprivation and had to perform demanding work over time (National Transportation Safety Board, 1990). Consequently, there was an economic loss of $7 billion and extensive environmental damage. Texas City Refinery Explosion incident investigation concluded that operators' fatigue resulting from working 12-h shifts for 29 consecutive days was one of the major factors leading to the incident (CSB, 2007). The disaster led to the deaths of 15 workers and 180 worker injuries, as well as an economic loss of $1.5 billion (CSB, 2007). Similarly, the explosion at the Macondo Well resulted in 11 deaths, 17 injuries, and $60 billion in environmental and economic losses. Here too, sleep-related risk factors were identified as a contributing factor to human error (CSB, 2016). These incidents reveal that inadequate monitoring and management of fatigue increase the risk for something to go wrong. Appropriate and effective fatigue monitoring in offshore work settings is critical for timely fatigue management interventions to improve worker safety.

Fatigue in offshore oil and gas environments has been associated with high workload, sleep deprivation, and disruption of circadian rhythms (Lerman et al., 2012; Riethmeister et al., 2018b). In these environments, sleep deprivation includes total sleep deprivation (getting no sleep) and chronic sleep restriction (getting less sleep than usual on a regular basis) (Alhola and Polo-Kantola, 2007). The negative effects of sleep deprivation are well-documented, including cognitive impairments such as reduced ability to conduct long-duration vigilance tasks and reduced attention, all of which increase the risk of accidents (Dinges et al., 1997; Doran et al., 2001). Furthermore, sleep deprivation has been shown to produce performance declines similar to those caused by moderate alcohol intoxication (Dawson and Reid, 1997). Along with

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sleep deprivation, various studies have linked disruption of the circadian rhythm to impaired cognitive and physical performance (Lamond et al., 2004; Niu et al., 2011; Pilcher and Walters, 1997). In offshore drilling, workers' shifts may rotate from day to night or vice versa, also known as swing (or rotating) shifts. In general, swing shift was introduced to reduce the number of night shifts workers experience during the course of their hitch (Khan et al., 2021). However, due to the shift rotation process, swing shift workers experience circadian rhythm disruption and sleep deprivation, which may negatively impact their health and performance. The disruption to workers' circadian rhythms after the shift rotation may result in higher fatigue levels (Ross, 2009). Indeed, Parkes et al. (1997) found that swing shift workers exhibited reduced alertness and performance than night shift workers.

Several studies have examined fatigue in the petrochemical and oil and gas extraction (OGE) industries, but the majority of previous studies rely heavily on questionnaires to assess workers' perceptions of sleepiness, physical fatigue, and mental fatigue (Bazazan et al., 2014; Rasoulzadeh et al., 2015; Waage et al., 2010). Some studies have administered a combination of fatigue assessments in the field, but usually for a limited amount of time. For example, Soares and de Almondes (2017) monitored fatigue levels among day and night shift workers during the first three days of work using performance-based measures, whereas Mehta et al. (2017) administered both subjective and physiological measures over a period of six days. The most comprehensive effort to measure fatigue in offshore workers focused on day shift workers using subjective, sleep, performance-based, and biometric factors over a period of 14 days in offshore platforms (Riethmeister et al., 2018a, 2018b, 2019). While Riethmeister et al. (2018b) reported that performance and perceived responses may not be consistently aligned with each other, similar to prior evidence on symptom perception (Pennebaker and Epstein, 1983; Pennebaker et al., 1982), this relationship was qualitatively, rather than statistically, inferred. Additionally, these studies either conducted longitudinal examinations to observe workers in a specific shift schedule, selected phases during a worker's stay on the rig (i.e., hitch), or the number of work days to observe workers in multiple shift schedules using one or more fatigue measures but not all combined. However, studies that comprehensively employ multimodal fatigue assessments over the course of a hitch for different shift schedules (day, night, and swing) are lacking. Longitudinal multimodal assessments of fatigue, where each method captures different fatigue-related impairments or is associated with constraints for implementation in offshore environments, are necessary to identify the impacts and levels of fatigue on different shift schedules. For example, surveys are easy to administer compared to physiological responses but they suffer from recall and recency bias (Song, 2007). Performance-based measures (e.g., those obtained from device-based Psychomotor Vigilance Task) may be objective in nature but require considerable time to complete the tasks. In addition, convergent validity of various fatigue measurement methods, as well as their robustness to measure change over time, remain a general research gap in offshore work domains.

To address these gaps, the objectives of this study were to establish 1) correlations between a variety of fatigue measures and shift schedules on rig (day, night, and swing) over the course of hitch (length of working days that workers are assigned on offshore rigs), and 2) correlations between different fatigue measures over the course of a hitch. The study followed offshore workers for four weeks on two separate drillships in the Gulf of Mexico. Workers from different shift schedules (day, night, swing) were recruited, and subjective, performance, and physiological measures of fatigue measurements were gathered daily (i.e., before and after 12-h shifts).

2. Methods

2.1. Participants

Two offshore drillships in the Gulf of Mexico were approached to participate in the study. All offshore workers on these drillships who were beginning their hitch on the first day of data collection were invited to participate, regardless of their shift schedules (day, night, or swing). A total of 70 workers volunteered to participate for the four-week hitch duration, consistent across the two drillships. Table 1 summarizes the demographic and work information of the participants across the two drillships.

The study participants were monitored for four weeks; swing shift changes occurred after the second week (14th day) for those assigned to it. Fig. 1 shows the number of participants at each shift before and after swing shift occurred, pooled across both drillships. The research team did not have any control over the swing assignments.

2.2. Procedures

All participants signed informed consent forms and the study was approved by the Institutional Review Board. Seventy offshore workers were monitored every day using objective and subjective fatigue assessment methods over a 4-week period. Before and after their shifts, participants visited the study data collection site on the drillship, which was either a conference room or an auditorium. The day shifts began at either 06:00 or 12:00 and ended at 18:00 or 00:00, and the night shifts began at either 18:00 or 00:00 and ended at 06:00 or 12:00, respectively. To minimize distractions and maintain consistency throughout the data collection process, participants were instructed to keep the data collection site as quiet as possible. For the first two weeks, a researcher was present to guide and direct the data collection procedure. For the final two weeks, participants completed the various assessments independently.

As shown in Fig. 2, the participants' physiological data were collected twice a day, right before and right after their shifts (pre and post). Physiological data were collected while participants were seated and rested for up to 7 min using an Actiheart 5 device (CamNTech,

Table 1
Demographic variables across the two drillships (in Means (SD) where applicable).

	Drillship 1	Drillship 2
Sex		
Male	33	36
Female	1	0
Race/Ethnicity		
African American	3	5
Hispanic or Latin	1	0
White	29	30
Two or more races	1	1
Number of Participants		
Day Shift	20	16
Night Shift	5	10
Swing Shift	9	10
Age (years)		
Day Shift	40.00 (8.31)	43.63 (7.67)
Night Shift	41.60 (9.89)	44.40 (10.30)
Swing Shift	33.67 (5.74)	36.30 (6.09)
Body Mass Index (kg/m^2)		
Day Shift	30.60 (5.34)	30.13 (5.13)
Night Shift	28.59 (4.60)	31.94 (6.63)
Swing Shift	29.59 (5.89)	30.50 (4.59)
Experience (years)		
Day Shift	14.60 (7.98)	15.44 (8.20)
Night Shift	10.80 (5.40)	18.80 (11.26)
Swing Shift	9.89 (5.64)	11.10 (3.93)

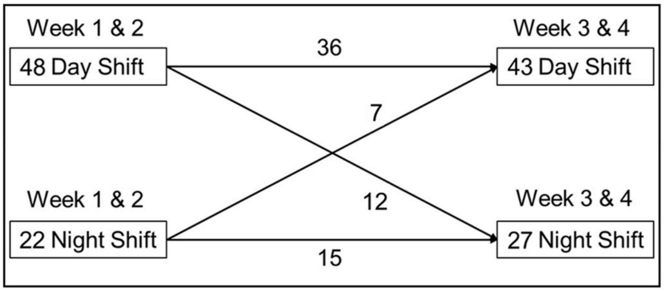

Fig. 1. Worker distribution by shift schedules pooled across the two drillships. In total, 36 day shift, 15 night shift, and 19 swing shift (12 day-to-night and 7 night-to-day) workers participated in the 23-day study.

Cambridge, UK) that was affixed to their chest based on manufacturer's guidelines (Camntech, 2022). The physiological data collection was limited to the first two weeks (i.e., in the presence of the researcher). After each shift, for the entire four weeks of data collection, participants completed the subjective assessments (Karolinska Sleepiness Scale (Åkerstedt and Gillberg, 1990), Borg Ratings of Perceived Exertion (Borg, 1998), Mental Fatigue, and Fatigue Risk Assessment and Management in high-risk Environments (Shortz et al., 2019)) and the 10-min Psychomotor Vigilance Task (Dinges et al., 1997) on electronic tablets. These measurements are described below. Each participant was provided with an Actigraph wrist watch and instructed to wear the device while in bed. Before and after sleeping, they were also instructed to complete a sleep log to record when they went to bed and woke up, time to fall asleep, number of times woken up, and perceived sleep quality. Study metadata can be retrieved from Payne et al. (2023).

2.3. Measurements

2.3.1. Subjective measures

The Karolinska Sleepiness Scale (KSS; (Åkerstedt and Gillberg, 1990)), Borg Ratings of Perceived Exertion (RPE; (Borg, 1998)), Mental Fatigue (MF), and Fatigue Risk Assessment and Management in high-risk Environments (FRAME; (Shortz et al., 2019)) surveys were used to assess participants' perceived sleepiness, physical exertion, mental fatigue, and overall fatigue respectively. KSS, RPE, and MF are single-item self-reports, as lengthy questionnaires have previously shown to pose implementation challenges in offshore environments (Mehta et al., 2017; Parkes, 2015; Riethmeister et al., 2018a). The FRAME survey was also used due to its relevance to oil and gas operations (Shortz et al., 2019). KSS is a subjective method for assessing perceived sleepiness, and has been validated using physiological and objective measures (Gillberg et al., 1994; Kaida et al., 2007). Studies have indicated that the KSS is effective in assessing workers' perceived sleepiness, with sleepiness increasing over the course of shifts and working days (Haidarimoghadam et al., 2017; Kazemi et al., 2018; Riethmeister et al., 2018b). Several studies have linked high RPE scores with physical fatigue (Aryal et al., 2017; Royal et al., 2006). By asking participants to rate the statement, "*Right now, I feel mentally exhausted*," the MF measure assessed perceived mental fatigue using a Likert scale. Response options ranged from 1 (Strongly Disagree) to 5 (Strongly Agree). FRAME was developed specifically to capture worker fatigue in the OGE industry as there were no prior subjective fatigue assessments designed for this occupation (Shortz et al., 2019). This questionnaire has a total of 15 questions with response options ranging from 0 (Not at all) to 10 (Extremely) focusing on four types of fatigue: general physical fatigue, localized physical fatigue, cognitive fatigue, and sleep-related fatigue. A high overall FRAME score, i.e., an average score across the four types of fatigue, can be interpreted as a higher level of fatigue. All four types of fatigue along with the overall FRAME score were analyzed to accurately capture and categorize workers' fatigue. FRAME was developed using a participatory process with OGE stakeholders, however it has not been administered in the field yet (Shortz et al., 2019).

2.3.2. Sleep

Participants' sleep data were collected using an Actigraph wGT3X-BT sensor (ActiGraph Corporation, Pensacola, FL, USA). Actigraphy, which uses a wristwatch-like device that measures wrist movements in order to assess sleep and wakefulness, has been validated against polysomnography and is an effective way to measure sleep quality (Full et al., 2018). Sleep quality was measured by collecting total sleep time (TST) and sleep efficiency (SE%), the time spent sleeping relative to the time lying in bed. Sleep quality is considered poor when a person takes 30 min or longer to fall asleep, if they wake up more than twice during the night, if it takes them more than 20 min to return to sleep, or if their sleep efficiency is less than 85% (National Sleep Foundation, 2020). After waking up, participants were instructed to fill out a sleep log, which was used as a backup to actigraphy watches, and remove the actigraphy watches because workers were not allowed to take any electronic devices on the platform that were not intrinsically safe. ActiLife software Version 6.13.4 (ActiGraph Corporation, Pensacola, FL, USA) was used to analyze sleep. A sampling rate of 60 Hz was used with an epoch length of 1 min. The Tudor-Locke algorithm (Tudor-Locke et al., 2014) was used to define sleep windows, and the Cole-Kripke algorithm (Cole et al., 1992) was used to calculate sleep measures. In rare cases when participants forgot their actigraphy watches (~7.9% or roughly equates to 2 days missed), the sleep logs were used to determine sleep time and calculate SE% utilizing sleep latency (time took to fall asleep) and wakefulness after sleep onset (total number of minutes awake after fallen asleep) (Schutte-Rodin et al., 2008).

2.3.3. Physiological measurements

Participants' physiological changes were measured to provide objective indicators of fatigue. Changes in physiological variables such as heart rate and heart rate variability have been associated with changes in fatigue and sleep deprivation levels (Mehta et al., 2017; Tran et al., 2009). Heart rate variability is a measure of variation in heartbeats for measuring the state of the autonomic nervous system (Acharya

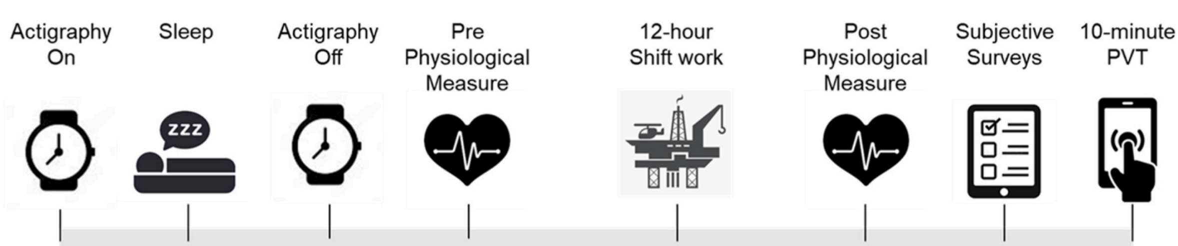

Fig. 2. Daily study protocol employed across the two drillships. Participants' sleep time and efficiency were monitored using actigraphy wrist watch. Pre- and post-shift physiological assessment was conducted using a chest-based physiological monitor. Subjective surveys of sleepiness, mental fatigue, ratings of perceived exertion, and the FRAME fatigue survey were administered post shift. A 10-min PVT was administered post shift to obtain performance-based markers of fatigue. All study measures were collected daily for 28 days, except for physiological measures (which were collected for 14 days).

et al., 2006; Shaffer and Ginsberg, 2017). Two main features of heart rate variability were extracted, namely the Root Mean Square of Successive Differences (RMSSD) and the Low Frequency/High Frequency (LF/HF) ratio. RMSSD is a measure of beat-to-beat variation in heartbeats, and fatigue causes the heart to beat more steadily than during a relaxed state (Beaumont et al., 2012). LF represents sympathetic nervous system and reflects fatigue and stress, and HF represents parasympathetic nervous system and reflects recovery (Tanaka et al., 2015; Tran et al., 2009). A decrease in RMSSD and increase in LF/HF ratio have been linked with increased levels of fatigue (Dutheil et al., 2012; Tran et al., 2009).

2.3.4. Performance-based measures

A 10-min Psychomotor Vigilance Task (PVT) (Dinges et al., 1997), a performance-based measure, was employed to capture fatigue levels objectively. Sleep deprivation and fatigue negatively impact cognitive performance, alertness, vigilance, and concentration (Alhola and Polo-Kantola, 2007; Goh et al., 2001). This measure captures participants' reaction times, number of lapses (i.e., trials associated with reaction times greater than 500 ms), and number of false starts (i.e., trials associated with reaction times less than 100 ms). Increases in reaction times and number of lapses indicate performance declines (Dinges et al., 1997; Doran et al., 2001), which is indicative of higher levels of fatigue.

2.4. Statistical analysis

Repeated measures correlation (RMCORR) analysis was conducted to establish 1) correlations between fatigue measures and shift schedules on rig (day, night, and swing) over the course of hitch, and 2) correlations between different fatigue measures extracted from various assessment methods for workers over the course of a hitch. RMCORR calculated within-subjects correlation coefficients for corresponding repeated measures (Bakdash and Marusich, 2017). Data for fatigue assessments such as subjective measures (KSS, RPE, MF, and FRAME), sleep quality (TST and SE%), and performance-based measures (reaction time, false starts, and lapses) were available for 4 weeks. Heart rate and heart rate variability (pre/post-shift of HR, RMSSD, and LF/HF ratio) were based on the first two weeks of data and thus were not utilized for aim 1.

The standard assumptions of RMCORR are similar to that of Generalized Linear Models, which include linearity, homoscedasticity, and normality of errors, and severe violations could lead to a biased model causing misleading results (Bakdash and Marusich, 2017). Thus, errors were checked for any violations mentioned here. Shapiro-Wilk tests were used to determine the normality of errors, and residual plots were used to determine the remaining violations. All study measures showed the need to transform, thus log transformations were carried out on all measures. Square root transformation was carried out on all FRAME scores and PVT-related false starts given that they included zero as valid values. Statistical significance was tested with alpha = 0.05.

3. Results

3.1. Fatigue over time for each shift schedule

Table 2 lists the repeated measures correlations between various fatigue measures and time on the rig by shift schedules, and Fig. 3 illustrates the changes in the various fatigue measures over the course of the hitch across the three shift types.

3.1.1. Day shifts

For the day shift workers' ($n = 36$) subjective measures, KSS decreased ($rrm = -0.11$, $p < 0.01$), RPE increased ($rrm = 0.08$, $p = 0.03$), FRAME overall score decreased ($rrm = -0.23$, $p < 0.01$), generalized physical fatigue decreased ($rrm = -0.24$, $p < 0.01$), localized physical fatigue decreased ($rrm = -0.14$, $p < 0.01$), cognitive fatigue decreased ($rrm = -0.22$, $p < 0.01$), and sleep-related fatigue decreased ($rrm = -0.11$, $p = 0.03$) significantly over time. For the performance-based measures, reaction time increased ($rrm = 0.10$, $p < 0.01$), significantly over time. For the physiological measures, post-shift heart rate increased ($rrm = 0.12$, $p = 0.02$) and post-shift LF/HF ratio increased ($rrm = 0.12$, $p = 0.02$), significantly over time.

3.1.2. Night shifts

For the night shift workers' ($n = 15$) subjective measures, MF decreased ($rrm = -0.13$, $p = 0.02$), FRAME overall score decreased ($rrm = -0.17$, $p < 0.01$), and generalized physical fatigue decreased ($rrm = -0.29$, $p < 0.01$), significantly over time. For the night shift workers, reaction time increased ($rrm = 0.34$, $p < 0.01$), and number of false starts increased ($rrm = 0.20$, $p < 0.01$), significantly over time. For the physiological measures, post-shift RMSSD increased ($rrm = 0.28$, $p < 0.01$), significantly over time.

3.1.3. Swing shifts

For the swing shift workers' ($n = 19$) subjective measures, MF increased ($rrm = 0.10$, $p = 0.04$) and generalized physical fatigue decreased ($rrm = -0.12$, $p = 0.045$), significantly over time. For the performance-based measures, reaction time increased ($rrm = 0.36$, $p < 0.01$), significantly over time.

Table 2
Repeated measures correlation of fatigue measures over time (all data are based on 4 weeks of data except for physiological which are 2 weeks (last row); * denotes $p < 0.05$; ** denotes $p < 0.01$).

Subjective Measures of Fatigue	KSS	MF	RPE	FRAME overall score	Gen. physical fatigue	Local. physical fatigue	Cognitive fatigue	Sleep-fatigue
Day Shift	−0.11**	0.06**	0.08**	−0.23**	−0.24**	−0.14**	−0.22**	−0.11**
Night Shift	−0.08**	−0.13**	0.03**	−0.17**	−0.29**	0.10**	−0.03**	−0.09**
Swing Shift	0.03**	0.10**	0.07**	−0.10**	−0.12**	0.08**	−0.09**	−0.07**

Performance-based Measure of Fatigue	SE	TST	Reaction Time	FS	Lapses
Day Shift	0.06**	0.00**	0.10**	0.03**	0.01**
Night Shift	0.07**	0.11**	0.34**	0.20**	0.11**
Swing Shift	−0.06**	−0.06**	0.36**	0.08**	0.04**

Physiological Measures of Fatigue	Pre HR	Post HR	Pre RMSSD	Post RMSSD	Pre LF/HF	Post LH/HF
Day Shift	0.03**	0.12**	−0.02**	−0.04**	0.05**	0.12**
Night Shift	−0.09**	0.004*	0.04**	0.28**	0.08**	−0.01**

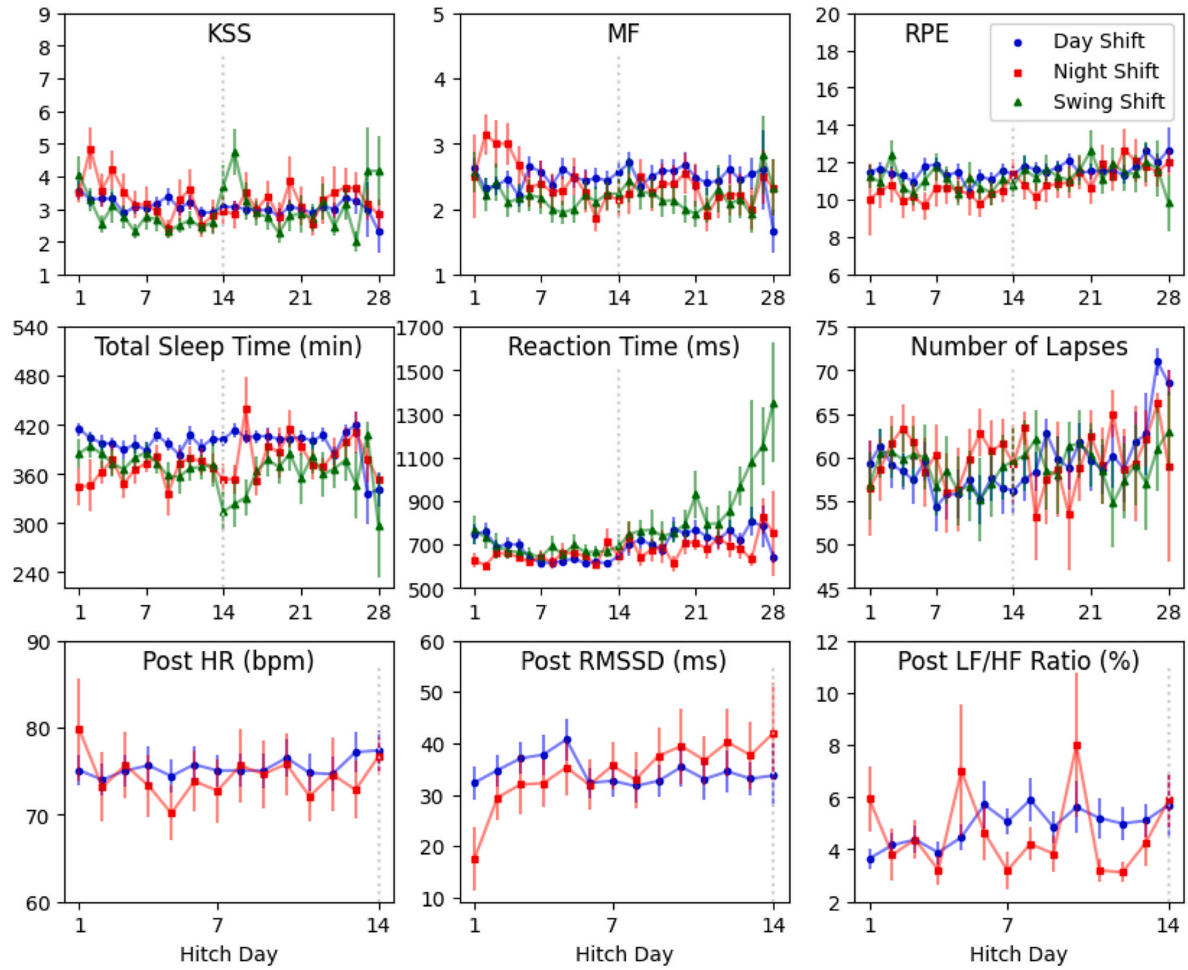

Fig. 3. Daily fatigue measures over time by shift type (day: blue, night: red, swing: green). Dotted vertical gray line represents when the swing occurred for the swing shift workers. Note that physiological data (bottom row) was only collected for the first two weeks. Error bars denote standard error. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3.2. Correlations between fatigue measures

Statistically significant correlations between the different fatigue measures are presented in Table 3. These correlations are based on overall aggregations at the worker-level and pooled across the shift types.

3.2.1. Correlations within each type of measure (subjective, performance, physiological)

KSS, MF, and all FRAME scores (overall and sub-scores) exhibited positive correlations with each other (see Table 3 for correlation coefficients, all $p < 0.01$), while RPE was only positively correlated with the FRAME overall score, and the generalized physical and localized physical fatigue sub-scores (see Table 3 for correlation coefficients, all $p < 0.01$). PVT-based reaction time was found to be positively correlated with the number of false starts and the number of lapses (see Table 3 for correlation coefficients, all $p < 0.01$). Post-shift heart rate had positive relationship with post-shift LF/HF ratio but had negative relationship with pre- and post-shift RMSSD (see Table 3 for correlation coefficients, all $p < 0.03$). RMSSD (pre and post) showed a negative correlation with LF/HF ratio (pre and post), while SE% showed a positive relationship with TST (see Table 3 for correlation coefficients, all $p < 0.01$).

3.2.2. Correlation of subjective measures to performance and physiological measures

RPE was positively correlated with PVT-based reaction time ($r_{rm} = 0.08$, $p < 0.01$) and number of lapses ($r_{rm} = 0.06$, $p = 0.04$). FRAME overall score and the generalized physical fatigue sub-score showed negative relationships with reaction time (see Table 3 for correlation coefficients, $p < 0.03$). KSS showed a negative correlation with post-shift heart rate ($r_{rm} = -0.13$, $p < 0.01$), while MF showed a positive correlation with pre-shift heart rate ($r_{rm} = 0.08$, $p = 0.02$). RPE was positively correlated with post-shift heart rate ($r_{rm} = 0.18$, $p < 0.01$), but negatively correlated with post-shift RMSSD ($r_{rm} = -0.11$, $p < 0.01$). While the FRAME overall score and the generalized physical fatigue sub-score showed positive correlations with pre-shift heart rate, the sleep-related fatigue sub-score showed a negative relationship with post-shift heart rate (see Table 3 for correlation coefficients, all $p < 0.02$). KSS and RPE were negatively correlated with TST, while MF was negatively correlated with SE% (see Table 3 for correlation coefficients, all $p < 0.04$).

3.2.3. Correlations between performance and physiological measures

PVT-based reaction time showed a negative relationship with pre-shift RMSSD ($r_{rm} = -0.10$, $p < 0.01$), while the false start measure showed a negative relationship with post-shift RMSSD ($r_{rm} = -0.08$, $p = 0.04$).

4. Discussion

4.1. Fatigue assessments over time across different shift types

Our results showed that day shift workers' perceived sleepiness

Table 3
Correlations among fatigue measures (all data are based on 4 weeks of data except for with physiological which are 2 weeks; *p < 0.05; **p < 0.01). KSS: Karolinska Sleepiness Scale; MF: mental fatigue; RPE: ratings of perceived exertion; FRAME: Fatigue risk assessment and management in high-risk environments survey; SE: sleep efficiency; TST: total sleep time; HR: heart rate; RMSSD: root mean squared standard deviation; LF: low frequency; HF: high frequency.

Variables	n	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1.KSS	1540	1																		
2.MF	1539	**0.31****	1																	
3.RPE	1544	**0.06***	**0.19****	1																
4.FRAME Overall	1544	**0.43****	**0.38****	**0.16****	1															
5.Gen. Phy Fatigue	1544	**0.35****	**0.35****	**0.18****	**0.77****	1														
6.Loc. Phy Fatigue	1544	**0.17****	**0.18****	**0.14****	**0.54****	**0.41****	1													
7.Cognitive Fatigue	1544	**0.34****	**0.31****	0.06	**0.72****	**0.47****	**0.33****	1												
8.Sleep Fatigue	1544	**0.49****	**0.29****	0.04	**0.73****	**0.47****	**0.30****	**0.59****	1											
9.SE	1463	−0.01	**−0.05***	−0.02	−0.06	−0.06	−0.03	−0.05	−0.06	1										
10.TST	1463	**−0.06***	−0.02	**−0.06***	−0.04	−0.03	−0.03	−0.01	−0.06	**0.34****	1									
11.Reaction Time	1520	−0.01	0.04	**0.08****	**−0.08***	**−0.09***	−0.04	−0.05	−0.02	−0.02	0.01	1								
12.False Starts	1520	0	0.01	0.03	0.01	−0.01	0.02	−0.006	0.03	−0.02	0	**0.09****	1							
13.Lapses	1520	0.02	0.02	**0.06***	−0.01	−0.03	0.04	−0.04	0.002	0.03	0.01	**0.28****	−0.03	1						
14.Pre HR	894	0.03	**0.08***	−0.05	**0.11***	**0.12***	0.04	0.01	0.07	0.05	0.02	0.02	−0	−0	1					
15.Post HR	880	**−0.13****	−0.01	**0.18****	−0.02	0.03	0.03	−0.06	**−0.12***	0.02	0.02	0.002	−0.03	0.06	0.003	1				
16.Pre RMSSD	894	−0.02	−0.04	0.01	−0.03	−0.02	0.05	−0.04	−0.04	0.02	0.05	**−0.10****	0.03	0.01	−0.05*	**−0.08***	1			
17.Post RMSSD	880	0.04	−0.04	**−0.11****	−0.02	−0.06	0.02	0.02	0.01	0.01	−0	0.03	**−0.08***	0.04	−0.02*	**−0.16****	0.02	1		
18.Pre LF/HF	894	0.01	−0.03	−0.03	−0.03	−0.04	−0.07	−0.002	−0.01	−0.01	0.02	0.07	0.04	−0	0.04*	0.06	**−0.39****	−0.01	1	
19.Post LF/HF	880	−0.07	−0.06	0.001	−0.004	0.01	0.05	−0.01	−0.03	−0.07	−0	−0.05	0.04	0.01	−0.04*	**0.09***	0.01	**−0.36****	−0	1

(measured using KSS) decreased over time. In contrast, a previous OGE study reported an increase in day shift workers' perceived sleepiness over a period of 14 days (Riethmeister et al., 2018b). One of the possible reasons behind our unexpected finding may be due to participants' activity before their hitch, e.g., offshore workers prefer driving long durations to ensure arriving just in time to the helipad (Mehta et al., 2019). While this results in them reducing any off-work efforts, such driving preferences often result in sleep deprivation when they arrive on the offshore platforms. Post study, several participants reported that it was not unusual for them to drive all night and arrive at the heliport minutes before taking helicopter to the drillship. This commuting practice is likely to cause sleep deprivation which may have potentially led to high perceived sleepiness at the beginning of their hitch, followed by adaptation over time. Indeed, existing motor vehicle crashes in upstream offshore industry are partially attributed to these driving patterns and preferences (Carvalho, 2020). Workers assigned to the day shifts for the complete course of their stay on the rig reported increases in RPE over time, which is indicative of accumulated physical fatigue. Declines in performance measures and increased in physiological responses over time aligns with physical fatigue manifestation in day shift workers. This is also in agreement with pervious findings that suggest most strenuous work tasks are scheduled for day shift schedules (Frese and Semmer, 1986). Physical fatigue deteriorates performance, resulting in increased reaction time on PVT (Lee et al., 2010), and fatigue causes increase in both heart rate and LF/HF ratio (Escorihuela et al., 2020).

Over the course of the hitch, night shift workers' performance on the PVT, i.e., reaction time and number of false starts, were adversely affected despite stable sleep time and efficiency levels. False starts reflect response inhibition, a critical ability to inhibit unwanted or inappropriate actions, which has shown to deteriorate with increasing mental fatigue (Guo et al., 2018; Kato et al., 2009) and night shiftwork (Anderson and Platten, 2011; Kaliyaperumal et al., 2017). However, for the same group, ratings of mental fatigue and FRAME generalized physical fatigue decreased over time. This performance-perception mismatch was an unexpected finding. This mismatch between performance and perception (objective and subjective measures) may likely be contributed by differences in symptom perceptions versus available cognitive reserves through compensatory neurocognitive mechanisms to achieve task goals (Karthikeyan et al., 2022; Pennebaker and Epstein, 1983; Pennebaker et al., 1982). Prior studies have shown night shiftwork is associated with increased perceptions of sleepiness, mental fatigue, and general fatigue symptomology (Ganesan et al., 2019; Kazemi et al., 2018). Several reasons could likely influence these findings. First, it should be noted that prior studies targeting offshore shiftwork were conducted for durations shorter than those examined in the present study and thus correlations, or lack thereof, of these perceptual measures over time in our study may be impacted by potential circadian adaptation to night shift work (Boudreau et al., 2013). Second, initial sleep deprivation at the beginning of the hitch that we observed in our study may have potentially disrupted workers' circadian rhythm and contributed to the higher initial ratings of mental and physical fatigue thereby influencing perceptual responses. Third, perceptual responses to direct inquiry on fatigue outcomes (e.g., sleepiness or mental fatigue) could have been negatively perceived for job security or social acceptance (i.e., workers fearing to be perceived as the weakest link) (Mehta et al., 2019; Shortz et al., 2019). Nonetheless, that night shift workers did not report increased fatigue over time despite objective declines in cognitive functions has significant implications for choosing appropriate and effective assessments of fatigue in offshore industries.

Workers who were assigned to the swing shifts exhibited decisive signs of fatigue manifestations due to time on hitch, which was also influenced by the circadian disruption of the shift rotations (Fossum et al., 2013). Workers here reported higher mental fatigue scores over time and exhibited longer reaction times on the vigilance and alertness tasks. Typically swing shifts or rotating shifts are associated with disrupted sleep behavior and efficiency (Fossum et al., 2013; Waage et al., 2010), however the repeated measures correlations of these measures with time was not found to be significant in the present study. The lack of significant results for sleep measures in swing shift maybe due to combining data from both day to night shifts and night to day shifts. It was possible that one rotation is worse than the other, but it was not found due to merging data. This also aligns with lower resting heart rate pre-shift by the swing shift workers and lack of correlation of KSS ratings with time. Studies have found that circadian disruption, in the absence of sleep deprivation, have shown to impact attentional control (Facer-Childs et al., 2019). Thus, circadian rhythm disruption, rather than sleep restriction, may have led to greater perceptions of mental fatigue, along with the more robustly-impacted performance measures (Ahn et al., 2016; Niu et al., 2011). These results highlight the specificity of performance-based measures to capture shift-related, rather than sleep loss, impacts on worker fatigue, that also corroborates with perceptual fatigue measures.

4.2. Comparison between different fatigue measurements

All subjective measures were positively correlated with each other, with two exceptions (RPE and FRAME-based cognitive fatigue and sleep-related fatigue sub-scores). However, the correlations between the single-item measures and four types of fatigue measured by FRAME, which is designed specifically for OGE workers, showed positive correlations when measuring the same constructs (e.g., sleep, mental, physical). According to Shortz et al. (2019), the FRAME questionnaire was developed using a qualitative approach based on existing fatigue questionnaires and refined with the involvement of OGE stakeholders and health and safety researchers. As the FRAME questionnaire had never been administered before in field study, this study provides initial convergent validity evidence in a field setting. The results also showed that perceived sleepiness and perceived fatigue (both MF and RPE) were positively correlated. Shen et al. (2006) stated that sleepiness is a state separate from fatigue; however, these two states are interconnected. There is a possibility that workers cannot distinguish between fatigue and sleepiness. Similar to other studies that found mental fatigue negatively impacts physical performance (Van Cutsem et al., 2017), workers' ratings of physical and mental fatigue were positively correlated with one another. As sleep quantity and quality decreased, workers' perceived sleepiness, mental fatigue, and physical fatigue increased. These findings are important, since sleep deprivation is linked to reduced cognitive abilities and vigilance (Dinges et al., 1997; Doran et al., 2001). Consistent with past research, decreases in sleep time were associated with increases in sleepiness (Philip et al., 2012) and poor sleep quality, specifically sleep efficiency, was negatively correlated with mental fatigue (Alapin et al., 2000). Furthermore, the results of this study support the translation of lab-based experimental results to longitudinal studies in offshore settings.

Consistent with Lee et al. (2010), PVT-based metrics were correlated with perceived physical fatigue. However, PVT metrics were not found to be correlated with perceived sleepiness, total sleep time, or mental fatigue. This is in contrast to existing literature that show a strong relationship between PVT and sleepiness (Horne and Burley, 2010). However, the evidence associated with PVT and mental fatigue correlations are mixed (Qi et al., 2019; Smith et al., 2019). Thus, while PVT has been used to capture sleep deprivation (Dinges et al., 1997; Doran et al., 2001), it is likely that sleep behavior or perceptions (captured using actigraphy or KSS in the present study) may be impacted by unique elements of offshore shiftwork. Thus, future studies and/or translation efforts should consider monitoring both sleep behavior (preferably through wearables) and PVT metrics to assess fatigue in offshore workers.

The correlation analyses between the physiological, performance, and perceptual measures showed that heart rate was associated with perceptual responses, while heart rate variability features (i.e., RMSSD) was correlated with performance metrics from the PVT. This is in line with prior literature where, cardioception, i.e., the heart beat perception, has shown to be reliable among adults successfully perceiving their heart rate (Knapp-Kline and Kline, 2005), while heart rate variability has shown to be sensitive to changes in PVT outcomes (Chua et al., 2012). Our study results indicated a negative correlation between workers' perceived sleepiness and their post-shift heart rate, which was consistent with studies reporting a decrease in heart rate following sleep deprivation (Holmes et al., 2002; Vaara et al., 2009). In addition, Boneva et al. (2007) found that fatigue persisted through sleep and led to increased heart rate and decrease in heart rate variability. Similarly, a positive correlation between RPE and post-shift heart rate reported in the present study is in agreement with Borg (1998)'s findings on physical fatigue tracking cardiovascular changes. Myllymäki et al. (2012) reported a similar relationship between RPE and heart rate, as well as a negative correlation between RPE and RMSSD, which corroborates our findings. Based on the results, it is likely that the physiological measures were able to capture both the acute (pre vs post or post on shift 1 to pre on shift 2) and longer-term (~14 days) impacts of fatigue caused by various demands of offshore shiftwork.

Interestingly, while all subjective measures were correlated with each other (e.g., KSS, MF, RPE, FRAME), only the single item self-reports (KSS, MF, RPE) were consistently correlated with objective measures of sleep and PVT. It is likely that the questions from FRAME, which included workers to reflect on their fatigue symptoms as well as the associated impacts on their job performance (e.g., ability to concentrate), may have introduced variability in workers' self-reports (Shortz et al., 2019) owing to numerous reasons, such as perceived threat to employment, inability to project to job performance, or an ability to manage fatigue symptoms through a variety of personal management strategies (Mehta et al., 2019). The single item self-reports are more direct in capturing their perceptions on sleepiness (Åkerstedt and Gillberg, 1990), mental fatigue, and physical fatigue (Borg, 1998), and thus may have lower variability in how workers rated these self-reports. It is not surprising that the physiological measures were largely correlated with the physical exertion question items (e.g., RPE and physical exertion components of FRAME) given that these survey items were created to reflect physiological measures associated with exertion and fatigue levels (Borg, 1998). Given the interesting dynamics between and within (time) the different fatigue measures and recognizing the barriers to periodic fatigue monitoring in offshore environments (Mehta et al., 2019), supplementing short self-reports of fatigue (e.g., KSS, RPE, MF) with a short vigilance test (e.g., PVT) on an electronic device may be a promising practice in capturing cumulative fatigue across different shift types. However, future work on their compliance, perceived usefulness, and acceptance is needed to ensure effective deployment and adoption of this ergonomic practice in offshore shiftwork.

4.3. Study limitations

As a result of operational constraints and concerns for offshore worker safety, there were some unavoidable limitations to our field-based longitudinal study. First, the inability to collect baseline measurements, i.e., pre-hitch measurements, is a critical limitation, as it determines the rate of fatigue manifestation or recovery in subsequent work environments (Riethmeister et al., 2018a), and the impacts of potential multiple jobs during onshore stays by workers. It should be noted that there exist numerous logistical, political, and legal challenges associated with collecting safety and health data from workers in the Gulf of Mexico that limited access to offshore workers beyond the rig environments to quantify types of activities adopted by workers onshore (i.e., between offshore hitches). Future studies that expand on baseline measurements through non-intrusive methods, such as short surveys or commercially off-the-shelf wearables, are needed that can address this limitation. Second, the researchers were not able to stay on the drillships for the full four weeks to collect physiological data. Thus, the analysis of physiological responses is limited to 14 days. Third, because of safety concerns, offshore workers were not allowed to wear heart rate monitors during their shifts; therefore, physiological data were collected before and after shifts. As such, more work is needed to validate these findings using continuous physiological data. Fourth, there was only one female participant in this study. This was expected, as female workers constitute ~3.4% of the offshore workforce (Lo, 2013). This is critical limitation and thus our findings should be cautiously approached to generate recommendations for designing offshore work limits, because fatigue impacts women differently than men (Mehta and Parasuraman, 2014). Lastly, an imbalanced number of participants for each shift type was one of the study's limitations. Since both swing shifts (day to night and night to day) had small sample sizes, fatigue measures were pooled across both swing shifts for the correlation of each fatigue measures over time and across all shift types for the correlations between fatigue measures. As a result, the number of meaningful correlations may have decreased. Therefore, future work is needed with balanced sample sizes for each shift type to conduct correlation analyses by each shift type to examine how fatigue measures change based on time of day (proxy for circadian rhythm).

5. Conclusions

In this longitudinal offshore energy field study, we collected multimodal fatigue assessments from day, night, and swing shift workers during their hitch for four weeks across two different drillships in the Gulf of Mexico. We report that while day shift workers' perceptions of physical fatigue increased as expected, their perceived sleepiness declined over time. Perceived mental fatigue decreased over time for night shift workers but increased for those assigned to the swing shift. Across all shift types (i.e., day, night, and swing), worker reaction times on the PVT increased over time. Several correlations between subjective, physiological, and performance-based measures were consistent with the extant literature on worker fatigue symptoms and manifestations, with higher correlations between the single-item self-reports and the objective measures. The overall findings that fatigue related subjective measures, particularly those that are self-reported, do not always align with objective measures implicate the need for multimodal assessments.

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