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“20,000 leagues under the sea”: Sleep, cognitive performance, and self-reported recovery status during a 67-day military submarine mission

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ABSTRACT

Employing a field-based monitoring paradigm, the current study examined day-to-day fluctuations in actigraphy-based sleep recordings, cognitive performance (10-min psychomotor vigilance test; PVT), and self-reported recovery status among 14 submariners throughout a 67-day military mission. Mission averages reflected suboptimal sleep that was of short overall duration (5:46 ± 1:29 h per 24-h day) and relatively low efficiency (82.5 ± 9.9%); suboptimal levels of cognitive performance (PVT mRT = 283 ± 35 ms; PVT response errors = 5.3 ± 4.8); and moderate levels of self-reported recovery. Whilst self-reported recovery status remained stable across mission days, small but consistent day-to-day increases in sleep onset latency and PVT mRT accumulated to reflect meaningful deterioration in sleep and cognitive performance across the entire 67-day mission (i.e., 47% and 16% of the overall mission average, respectively). Future work is required to corroborate the current findings, firmly establish underlying causes, and make evidence-based suggestions for interventions to improve and uphold submariners’ health and performance.

1. Introduction

“The Canadian was clearly at the end of his tether. His energetic personality could not get used to our extended imprisonment. His physiognomy was changing from day to day. His personality was getting gloomier and gloomier. I knew how much he was suffering for I too was feeling homesick. It was nearly seven months since our last news from land.” (Verne, 1828-1905, p. 352). This quote from Jules Verne’s classic novel “*20,000 leagues under the sea*” describes the physical and emotional demands of prolonged submarine travel, long before scientific research on this topic emerged. With military missions lasting anywhere between 30 and 90 days, modern-day submariners often spend long periods at sea – isolated from their natural physical and social environments. Among other things, life on board a submarine entails adjustment to shift work and resting/sleeping in a confined dimly-lit space (Kelly et al., 1999; Paul et al., 2008; Trousselard et al., 2015; Young et al., 2015), facing a wide range of work-related and psychosocial stressors (e.g., work demands; social isolation; Brasher et al., 2010; Brasher et al., 2012), and with limited options to engage in physical activity (Choi et al., 2010). Prolonged exposure to such conditions has been shown to result in a variety of self-reported medical complaints that may arise during missions, such as sleep problems (Horn et al., 2003), as well as significant reductions in body mass (Gasier et al., 2016) and physical fitness (Fothergill and Sims, 2000) that have been recorded upon the completion of missions.

Despite growing understanding of the physical and psychological demands of prolonged submarine missions, robust insight into the temporal development of psychophysiological load effects during missions, thus far, remains unreported (cf. Trousselard et al., 2015). Against this background, the current study examined day-to-day fluctuations in sleep, cognitive performance, and self-reported recovery status, in submariners during a 67-day military mission.

Adequate recovery between periods of work is essential to uphold health, well-being and performance (Geurts & Sonnentag, 2006). This process can be understood from Effort-Recovery theory (Karasek, 1979; Meijman and Mulder, 1998), which basic assumption is that work-related effort results in psychophysiological load effects (e.g.,

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fatigue) from which individuals need to recover on a day-to-day basis. In case of complete recovery, psychophysiological activation levels return to baseline before the next work period is started, and no adverse impact on health, well-being or performance will emerge. However, when recovery is incomplete, and psychophysiological activation levels have not returned to baseline before the next work period is started, load effects will accumulate (McEwen, 1998) and – over time – negative effects on health, well-being and performance will begin to emerge (Kivimaki et al., 2002, 2006).

Sleep is generally considered to be the most important recovery mechanism and essential for restoring energy, replenishing psychophysiological resources, and upholding the immune system (Åkerstedt et al., 2009; Hobson, 2005). In addition, insufficient sleep is consistently related to suboptimal cognitive functioning and performance (see Lowe et al., 2017, for a meta-analysis), especially when the experienced sleep deficit remains persistent over longer periods of time (e.g., multiple days or weeks; Van Dongen et al., 2003). According to the dual-process model of sleep regulation (Borbély, 1982), sleep is regulated by two independent processes; a homeostatic process (process S), which describes how individuals' need for sleep will increase as a function of their time awake, and a circadian process (process C), which is regulated by the endogenous circadian system that requires periodic exposure to light and darkness to establish stable entrainment to a 24 h day (Duffy and Wright, 2005). Whilst sleep is most easily initiated and maintained when both processes align (i.e., homeostatic sleep pressure peaking at circadian nadir), there are several environmental and behavioural factors that may cause interference and, hence, disturb sleep. For example, sleep is most easily initiated in a dark and quiet environment, at regular times from day to day, and in absence of physiological and psychological arousal (Dijk and Archer, 2009;Tang & Harvey, 2004).

Pertinent to the current study, conditions on board a submarine impose several constraints on the optimal regulation of sleep, which potentially challenge preservation of submariner health, well-being, and performance across prolonged military missions. First, submariners work in shifts. Whilst, in theory, isolated circumstances on board a submarine make circadian entrainment to any fixed shift schedule possible (e.g, 6 h on/off), complete adjustment takes time and – as reported by Kelly et al. (1999) – is often not established in practice (but see Young et al., 2015). Circadian disharmony resulting from shift work has been linked to suboptimal sleep (Åkerstedt, 1998), suboptimal recovery between shifts (Radstaak et al., 2014), ill health (Åkerstedt, 1990), and reduced performance (Lamond et al., 2003). Second, light levels are fairly dim throughout submarines (Kelly et al., 1999; Young et al., 2015) and potentially suboptimal in terms of both intensity and wavelength to adequately entrain the circadian system to the imposed work schedule and optimally facilitate sleep (during off-shift hours) and alertness (during on-shift hours; Wams et al., 2017). Third, work on board a military submarine is largely sedentary and the confined physical environment offers limited opportunity to engage in physical activity (Choi et al., 2010). Prolonged physical inactivity is linked to adverse health outcomes (Wen and Wu, 2012) as well as suboptimal sleep (Youngstedt, 2005). Fourth, psychosocial demands imposed on military submariners during missions (e.g., work stress, social isolation; Brasher et al., 2010, 2012) may have adverse effects on sleep and negatively impact mental health and well-being (e.g., rumination, negative affect; cf. Radstaak et al., 2014).

To better understand how prolonged submarine missions impact health, well-being and performance, the current study assessed day-to-day fluctuations in sleep (i.e., actigraphy-based recording), cognitive performance (i.e., psychomotor vigilance task; Dinges and Powell, 1985), and self-reported recovery status (Radstaak et al., 2014) in a sample of military submariners, across a 67-day mission. Previous research in this area is scarce and either focuses on much shorter missions and training voyages (<12 days; e.g., Paul et al., 2008; Young et al., 2015) or only reports data for discrete timepoints (single days) at the start and end of a mission (e.g., Trousselard et al., 2015). Therefore, the aims of the current study were explorative and included; (1) to quantify sleep, cognitive performance, and self-reported recovery status; (2) to examine differences in self-reported recovery status between on- and off-shift hours; and (3) to examine the temporal development of sleep, cognitive performance, and self-reported recovery status from day to day, across the 67-day mission.

2. Methods

The current study was part of a larger project investigating the physiological and psychological demands of military submarine missions. Ethical Approval for the project was obtained from the Surgeon General of the Netherlands Armed Forces.

2.1. Participants

A convenience sample of 14 male crewmembers of a military diesel-electric attack submarine (Walrus Class, The Netherlands Royal Navy; length: 67.7 m; beam: 8.4 m; draft: 6.6 m, total crew: 55 persons, range: 10,000 miles) participated in the study. Participants' mean age was 27.36 years (SD = 3.57) and their mean experience within the naval submarine service was 5.84 years (SD = 4.85). Participants represented a wide range of ranks and on-board roles and responsibilities. During the mission, the majority of participants (i.e., n = 10) worked according to a standard 6-h shift schedule (i.e., 6 h "on"/"off"; cf. Paul et al., 2008; 2010), whilst the remaining four participants either worked 12-h shifts (n = 2; i.e., 12 h "on"/"off") or 2x3-hour shifts (n = 2; i.e., 3 h "on"/"off", followed by 3 h "on call"), in line with their work-related roles and responsibilities (e.g., command, medic, kitchen crew). Regardless of shift condition, sleep opportunity was only provided during "off-shift" and "on call" hours. Prior to participation, all participants completed the Pittsburgh Sleep Quality Index (PSQI; Buysse et al., 1989) and Holland Sleep Disorder Questionnaire (HSDQ; Kerkhof et al., 2013). Participants' mean score on the PSQI was 4.86 (SD = 1.29), with only three participants scoring slightly above cut-off (i.e., >6), indicating that in general participants may be considered reasonably 'good' sleepers. Participants' mean score on the HSDQ was 1.48 (SD = 0.22), with none of the participants scoring above the clinical cut-off (i.e., 2.02), indicating a likely absence of sleep disorders.

2.2. Study design and environment

The current study had a repeated-measures correlational design. Data collection was performed during a military mission that took place between September–December 2016. The total duration of the mission was 67 calendar days. During this period the submarine was submerged continuously, with exception of a forced interruption between days 26 and 31, during which shift schedules (as presented above) were continued but no data could be collected.[1] On board the submarine, lighting is normally very dim (i.e., less than 200 lux and often below 100 lux (Kelly et al., 1999). On-board systems ensure continuous supply of clean, dehumidified air, containing 20–21% oxygen (i.e., comparable to standard outdoor environments). Temperature is variable and depending on outside water temperature and location within the submarine (e.g., cooler in sleep compartments, warmer in engineering rooms) but is normally kept within range of standard indoor living environment

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[1] With regards to research aim 3 (temporal development), the impact of the forced interruption (including incidental exposure to above-surface natural lighting) on day-to-day changes in our sleep, cognitive performance and self-reported recovery indices was verified statistically; indicating no measurable changes with regards to the observed effect estimates (unstandardized beta ('*b*') coefficients). Consequently, the reported analyses encompass the entire 67-days of the mission rather than dividing the data collection period in two separate parts (i.e., 'before' and 'after' the interruption).

temperatures (i.e., 18–24 °C).[2] Although the psychological demand of prolonged military submarine missions is arguably intense (e.g., Brasher et al., 2010; 2012) the work generally is of low physical intensity (i.e., <3 METs; Choi et al., 2010) and – also for the current participants – is mostly performed in seated posture. Resting compartments (visited by crew during off-shift hours) feature a small ‘exercise room’ with (amongst others) a cycle ergometer, thus enabling crew to exercise during their off-shift hours and maintain physical fitness. With exception of the captain and his officers, all crew share a single sleep compartment, where they sleep in small ‘torpedo tube’ bunk beds.

During the mission, communication restrictions prevented direct contact between researchers and participants. Protocol adherence and administration of cognitive tests were supervised by the crew’s Medic. Depending on the variable in question (see “Dependent Variables” section, below), data collection was performed continuously (‘Sleep’), at fixed times during selected off-shift hours (‘Cognitive Performance’), or immediately before and after each shift (covering on-shift and off-shift ‘Mental Load and Recovery’), respectively. Data collection encompassed the entire 67 days of the mission, covering 61 complete 24-h cycles.

2.3. Research materials and dependent variables

2.3.1. Sleep

Sleep was assessed continuously throughout the mission, using validated wrist-worn actigraphs (i.e., Actiwatch Pro, Philips Respironics, Murrysville, USA; De Souza et al., 2003). Participants wore the actiwatch around their non-dominant wrist, except when in contact with water (e.g., when taking a shower). Activity and photonic light were sampled in 60s bins. To facilitate data processing (see below), participants were instructed to press an event marker when (i) attempting to fall asleep; and when (ii) waking up at the end of their sleep period. Variables of interest were total sleep time (TST; in minutes), sleep onset latency (SOL; in minutes), wake after sleep onset (WASO; in minutes), and the ratio between total sleep time and total time spent in bed (i.e., ‘sleep efficiency’ [SE]; in %).

2.3.2. Cognitive performance

Cognitive performance was assessed at fixed times during scheduled off-shift hours, by means of a 10-min Psychomotor Vigilance Task (PVT; Dinges and Powell, 1985). On average, participants performed 6.8 sessions each (SD = 4.1), with an average inter-session interval of 5.8 days (SD = 2.4). The PVT is a computer-based task that measures sustained attention and alertness, is free of practice effects (Basner et al., 2018), and is generally considered the gold-standard in examining effects of fatigue and sleep on cognitive performance (Dinges et al., 1997). Seated behind a laptop (Dell Latitude E5440), participants were instructed to press a button as fast as possible upon appearance of a red target stimulus on an otherwise black screen. Stimuli were always displayed in the centre of the screen. Inter-stimulus intervals were variable and set to range between 2 and 10 s. Reaction times (in ms) were displayed by a scrolling counter in the bottom of the screen and served as immediate feedback upon response. As per standard procedure, reaction times below the anticipation criterion of ≤100 ms were excluded from analysis. Reaction times ≥500 ms were logged as ‘lapses’ and reactions without a stimulus were logged as ‘false alarms’ (errors of commission). Variables of interest were the mean reaction time across all trials (mRT; in milliseconds) and the total number of ‘response errors’ (combined number of lapses and false alarms; Van Dongen et al., 2012; Knufinke et al., 2018).

2.3.3. Self-reported recovery status

Self-reported recovery status was assessed by means of a diary (paper-pencil), which participants completed on a daily basis – immediately after each on- and off-shift block.

The on-shift diary consisted of four sections, which assessed (i) work characteristics (ii) work-related fatigue, (iii) vigor and affect, and (iv) rumination. Following Radstaak et al. (2014), work characteristics and work-related fatigue were measured with selected items from the Questionnaire on the Experience and Evaluation of Work (QEEW; Van Veldhoven and Meijman, 1994; Van Veldhoven et al., 2002). Wording of the items was adjusted to fit the context of the current study. *Work characteristics* (3 items) were measured as follows: “During the past on-shift hours …” [1. “I was busy with my tasks”; 2. “The work was diverse”; and 3. “I could determine how to perform the work myself”]. *Work-related fatigue* (5 items) was measured as follows: “During the last hour of the past on-shift hours, I felt …” [1. “Tired”, 2. “Physically exhausted”; 3. “Fit”; 4. “Weak”; and 5. “Mentally exhausted”]. *Vigor and affect* were measured using the Global Vigor and Affect scale (GVA; Monk, 1989), which includes 8 items that measure how participants feel ‘right now’ (e.g., alert, weary, sleepy, calm, tense, happy, sad). *Rumination* (3 items) was measured with selected items from the QEEW (Van Veldhoven and Meijman, 1994; Van Veldhoven et al., 2002; also see Radstaak et al., 2014). Items included: 1. “I worry about my work”; 2. “I worry about private matters”; and 3. “I can easily detach from work”. In all cases, items were scored on a 10-point scale, ranging from “not at all” (1) to “very much” (10).

The off-shift diary consisted of three sections, which assessed (i) sleep; (ii) vigor and affect; and (iii) rumination. *Sleep* (6 items) was assessed with selected items from the Consensus Sleep Diary (Carney et al., 2012), asking participants to report (a) if they had slept (yes/no); (b) at what time they went sleeping (hr:min); (c) how long they took to fall asleep (min); (d) at what time they woke up to get out of bed; and (e) perceived sleep quality (10-point scale; very bad – excellent). A single item question asking participants to list other activities they had engaged in during the past off-shift hours was added to capture diversity in ‘off-shift activity’. *Vigor and affect* (8 items) and *Rumination* (3 items) were assessed as described above.

2.4. Data processing

All data were sampled at the participant level and categorized according to the day and shift (i.e., on-shift or off-shift) to which they pertained. To facilitate data processing, all data were rectified to ensure that a day was operationalized as a 24-h period that always starts with an on-shift and ends with an off-shift. Depending on the shift condition (i.e., 6-h, 12-h, 2x3-hour), each day contained several on- and off-shifts. The data was processed as follows:

Actigraphy data were analysed using Respironics Actiware 5 (Philips Respironics, Murrysville, USA) in accordance with current guidelines (Ancoli-Israel et al., 2015). First, data were visually inspected to verify proper wearing of the watch and excluded in case the off-wrist sensor indicated detachment. Second, rest intervals were manually set when (i) event markers identified bed- and rise times, or – if event markers were absent – when (ii) light and activity was absent. Diary entries (self-reported bed- and rise times; see above) were used to verify the set rest intervals. Automatic identification of sleep onset and offset was based on the default 10-min immobility parameter. Episodes of sleep/wakefulness were identified using the AW >40 threshold (i.e., epochs were scored as ‘wake’ if activity counts were above 40). TST was derived from the “rest” interval. SOL, WASO and SE were derived from the “sleep” interval (Knufinke et al., 2018).

PVT data were processed as described above.

Diary data were digitized and processed using Microsoft Excel. Data regarding work characteristics and engagement in off-hour activities were used for internal feedback purpose only and were excluded from analyses. Data regarding sleep was used to facilitate analysis of the

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[2] Data from on-board monitoring systems indicate that oxygen supply during the mission was consistently kept within the indicated range (i.e., 20–21%). During the mission, no data was recorded with regards to ambient temperature and lighting levels in sleep and work compartments.

actigraphy data (as described above). Following Radstaak et al. (2014), data regarding work-related fatigue and rumination were reverse-scored where necessary and averaged to arrive at mean category scores that ranged between 1 (low work-related fatigue/rumination) and 10 (high work-related fatigue/rumination). Data regarding vigor and affect were processed following the original procedure detailed by Monk (1989) and subsequently converted to a 10-point scale for ease of interpretation, resulting in distinct scores for vigor and affect that ranged between 1 (low vigor/affect) and 10 (high vigor/affect).

2.5. Statistical analyses

All statistical analyses were conducted in R (version 3.5.0; R Core Team, 2018). In order to explore research *aim 1* (descriptives), means and standard deviations were calculated for all dependent variables. For those variables that were measured during both on- and off-shifts (i.e, self-reported 'vigor', 'affect', and 'rumination'), means and standard deviations were split by shift. Because shifts differed in length between conditions (6 h vs 12 h), sleep variables were calculated such that they always reflect 12 h of off-shift per 24-h day (i.e., two 6 h off-shifts or one 12 h off-shift). To facilitate interpretation, total sleep duration and wake after sleep onset were added up for the two 6-h off-shifts, while sleep onset latency and sleep efficiency were averaged. If a participant had sleep data in only one 6-h off-shift on a given day, the respective data point was excluded from analyses. Given the small sample size and three different shift conditions, means and standard deviations were calculated once for the total sample (n = 14) and once for the largest shift condition (i.e., 6-h shifts, n = 10).

In order to explore research *aim 2* (differences between on- and off-shifts), 'maximal' (Barr et al., 2013) linear mixed-effects models were fitted using the *lmer* function (lme4 package; version 1.1.17; Bates et al., 2015) for those dependent variables that were measured during both on- and off-shifts (i.e., 'vigor', 'affect', 'rumination'). Models predicting each dependent variable included a random per-participant intercept. The within-subject predictor 'shift', was modelled as fixed effect and as random slope, varying across participants. This allowed us to estimate the effect of shift on each dependent variable, while taking the nested data structure into account (measures nested in participants). Due to the small sample size and three different shift conditions, the same models were fitted once for the total sample and once more in our largest shift condition (6-h shifts).

In order to explore research *aim 3* (temporal development), 'maximal' linear mixed-effects models were fitted for all dependent variables. Models predicting each dependent variable included a random per-participant intercept. The within-subject predictor 'day' was modelled as fixed effect and as random slope varying across participants. This allowed estimating the effect of time on each dependent variable over the course of the mission. In all analyses, the variable 'day' was centered. Due to the small sample size and three different shift conditions, each model was fitted once for the total sample and once more for the largest shift condition (6-h shifts).

3. Results

3.1. Aim 1: descriptives

The results associated with research aim 1 can be found in Table 1. As descriptives for the 6-h shift condition were highly comparable to those of the total sample (see Table 1), in-text descriptions concentrate on the total sample only.

3.1.1. Sleep

On average, participants slept 5 ¾ hours during their (combined) off-shifts per 24-h day, showing substantial between-subject variability (i.e., mean TST = 345.60 min; SD = 87.83 min). Sleep onset latencies (SOL) and wake after sleep onset (WASO) averaged around 13.30 min (SD = 15.03) and 26.62 min (SD = 15.25), respectively. Participants' sleep efficiency scores were 82.52% (SD = 9.91%).

3.1.2. Cognitive performance

Participants' mean PVT reaction time across the entire mission averaged around 282.52 ms (SD = 35.26). The average number of response errors (i.e., lapses and errors of commission) was 5.34 (SD = 4.76). As indicated by the standard deviations, both measures showed substantial between-subject variability.

3.1.3. Self-reported recovery status

Upon finishing their on-shift hours, participants generally reported moderate levels of fatigue (M = 4.60; SD = 1.65), moderate levels of vigor (M = 5.04; SD = 1.64), mildly positive affect (M = 6.13; SD = 1.27), and slightly below-average levels of rumination (M = 4.11; SD = 1.52). Mission averages following off-shift hours (i.e., 'vigor', 'affect' and 'rumination' only) revealed a similar picture, with – again – moderate levels of vigor (M = 5.17; SD = 1.52), mildly positive affect (M = 5.99; SD = 1.32), and slightly below-average levels of rumination (M = 4.11; SD = 1.52).

3.2. Aim 2: differences in self-reported recovery status between on-shifts and off-shifts

The results associated with research aim 2 can be found in Table 2 (total sample and 6-h shift).

For both the total sample and the 6-h shift condition, unstandardized effect estimates ('b') indicate very small differences in vigor, affect and rumination, between on- and off-shifts. For example, in the total sample, vigor was estimated to be only 0.03 points higher after the off-shift as compared to after the on-shift (*Note*. All recovery indicators were measured on a scale ranging from 1 to 10). As can be seen in Table 2, 95% confidence intervals are narrow and indicate that these estimates are relatively precise. Based on the small effect estimates and the fact that all confidence intervals included zero, it is concluded that self-reported recovery status did not meaningfully differ between on- and off shift hours. Similar results were observed for the total sample and the

Table 1

Means and standard deviations for all dependent variables (sleep, cognitive performance, self-reported recovery status), split by shift (on-shift and off-shift) in the total sample and the 6-h shift condition only. Measures always reflect a 24-h time window. TST = total sleep time; SOL = sleep onset latency; WASO = wake after sleep onset; SE = Sleep efficiency.

	Total sample (n = 14)		6-h shift (n = 10)	
	On-shift	Off-shift	On-shift	Off-shift
	M (SD)	M (SD)	M (SD)	M (SD)
Sleep				
TST (minutes)		345.60 (87.83)		365.37 (71.75)
SOL (minutes)		13.30 (15.03)		12.70 (12.97)
WASO (minutes)		26.62 (15.25)		28.18 (17.21)
SE (%)		82.52 (9.91)		81.22 (10.76)
Cognitive Performance				
Reaction time (ms)		282.52 (35.26)		283.79 (38.80)
Response errors (#)		5.34 (4.76)		5.75 (4.93)
Self-Reported Recovery				
Fatigue (1–10)	4.60 (1.65)		4.61 (1.77)	
Vigor (1–10)	5.04 (1.64)	5.17 (1.52)	4.94 (1.76)	5.14 (1.63)
Affect (1–10)	6.13 (1.27)	5.99 (1.32)	6.17 (1.27)	6.02 (1.37)
Rumination (1–10)	4.11 (1.52)	4.11 (1.52)	3.97 (1.51)	3.99 (1.53)

Table 2

Unstandardized coefficients (b), standard errors (SE$_{b)}$), and bootstrapped 95% confidence intervals (95% CI) of the statistical models predicting recovery indicators (vigor, affect, rumination) by 'shift' (on-shift vs off-shift) in the total sample and the 6-h shift condition only.

	Total sample (n = 14)			6-h shift (n = 10)		
	b	SE$_b$	95% CI	b	SE$_b$	95% CI
Vigor (1–10)	0.03	0.07	−0.10, 0.17	0.08	0.07	−0.06, 0.22
Affect (1–10)	−0.07	0.05	−0.17, .02	−0.08	0.05	−0.17, 0.01
Rumination (1–10)	0.00	0.02	−0.04, 0.04	0.01	0.03	−0.04, 0.06

6-h shift condition only (see Table 2).

3.3. *Aim 3: temporal development*

The results associated with our research aim 3 can be found in Table 3 (full sample and 6-h shift).

3.3.1. *Sleep*

For both the total sample and the 6-h shift condition, unstandardized effect estimates mostly indicate only very small changes in the measured sleep indicators from day to day (see Table 3). 95% Confidence intervals indicate that these estimates are relatively precise. Paired with the fact that all confidence intervals included zero, it is concluded that – in general – the measured sleep indicators did not meaningfully change as the mission progressed (i.e., it is highly unlikely that in subsequent samples large effects of mission day on these sleep indicators are observed). The only exception is the effect that was observed for SOL. Although the 95% confidence interval just included zero, uncorrected effect estimates indicate that SOL increased by 0.07 min (total sample) and 0.09 min (6-h shift) per day (see Table 3), which – across the entire 67-day mission – equates to a predicted increase in SOL of 4.7 min for the total sample (i.e., 35% of the mission average; see Table 1) and 6 min for the 6-h shift condition (i.e., 47% of the mission average; see Table 1).

Table 3

Unstandardized coefficients, standard errors, and bootstrapped 95% confidence intervals for the statistical models predicting each dependent variable (sleep, cognitive performance, self-reported recovery) across on- and off shifts and by 'day', in the total sample and the 6-h shift condition only.

	Total sample (n = 14)			6-h shift (n = 10)		
	b	SE$_b$	95% CI	b	SE$_b$	95% CI
Sleep						
TST (minutes)	0.16	0.17	−0.18, 0.49	0.10	0.18	−0.24, 0.45
SOL (minutes)	0.07	0.03	0.00, 0.14	0.09	0.04	0.00, 0.14
WASO (minutes)	0.02	0.02	−0.02, 0.06	0.03	0.02	−0.02, 0.07
SE (%)	−0.02	0.02	−0.06, 0.03	−0.04	0.03	−0.09, 0.02
Cognitive Performance						
Reaction time (ms)	0.39	0.23	−0.09, 0.84	0.66	0.24	0.17, 1.15
Response errors (#)	0.05	0.04	−0.03, 0.13	0.08	0.05	−0.02, 0.19
Self-Reported Recovery						
Fatigue (1–10)	0.00	0.00	−0.01, 0.01	0.00	0.01	−0.01, 0.01
Vigor (1–10)	0.00	0.00	−0.01, 0.01	0.00	0.01	−0.01, 0.01
Affect (1–10)	0.00	0.01	−0.01, 0.01	−0.01	0.00	−0.01, 0.00
Rumination (1–10)	0.00	0.00	−0.01, 0.00	0.00	0.03	−0.01, 0.01

3.3.2. *Cognitive performance*

Participants' cognitive performance (PVT reaction times and errors) generally indicated small effect estimates, with most 95% confidence intervals including zero (see Table 3). The only exception is the effect that was observed for PVT reaction times in the 6-h shift condition. Here, the unstandardized effect estimate indicates that participants' reaction times increased by 0.66 ms per day and the 95% confidence interval did not include zero (i.e. 95% CI = 0.17, 1.15; see Table 3). While this effect indicates only a small predicted increase in reaction time per day, across the entire 67-day mission, it equates to a predicted increase in reaction time of 44 ms (i.e., 16% of the mission average; see Table 1).

3.3.3. *Self-reported recovery status*

As appears from Table 3, unstandardized effect estimates indicate a general absence of change in self-reported recovery status over the course of the mission (i.e., with b's $\geq$ 0.00 and $\leq$0.01). Paired with the precise 95% confidence intervals, it is concluded that self-reported recovery status did not meaningfully change as the mission progressed. That is, based on the current results, it is highly unlikely that in subsequent samples, large effects of mission day on these indicators are observed. Comparable results were obtained for the total sample and the 6-h shift condition only.

4. Discussion

The current study investigated day-to-day fluctuations in sleep, cognitive performance, and self-reported recovery status in military submariners, across a 67-day mission. On average, results reflected suboptimal sleep that was of short overall duration and relatively low efficiency; moderate levels of work-related fatigue, vigor, affect and rumination; and moderate levels of cognitive performance (PVT reaction time and error rate). Whilst self-reported recovery status remained stable across shifts and mission days, small day-to-day changes in sleep onset latency and PVT reaction time – especially in the 6-h shift condition – accumulated to reflect potentially meaningful (clinically significant) declines in sleep and cognitive performance across the span of the entire 67-day mission.

With regards to mission averages (i.e., *Aim 1*), results from the current study indicate that submariners may not obtain sufficient amounts of (good quality) sleep during prolonged missions (cf. Kelly et al., 1999). With an average total sleep time of less than 6 h per 24-h cycle (i.e., 5 ¾ hours; see Table 1), observed sleep durations were well below what is generally recommended (i.e., 7–9 h; Watson et al., 2015) and also shorter than previously reported by Trousselard and colleagues (i.e., 6 ¾ hours; cf., Paul et al., 2008; Young et al., 2015). Furthermore, whilst sleep onset latencies and awakenings after sleep onset did not reach atypical levels (i.e., SOL $<$ 30 min; WASO $<$ 60 min), participants' sleep efficiency scores were low (i.e., <90%; cf. Edinger et al., 2004), indicating that sleep should be considered fragmented (see Table 1). These findings were similar across shift conditions and corroborate previous (subjective) reports listing sleep problems as a primary medical complaint among military submariners (Horn et al., 2003). Suboptimal sleep resulting from shift work is not uncommon and has previously been linked to poor sleep hygiene (e.g., circadian misalignment, irregular sleep/wake times, limited sleep opportunity; Åkerstedt 1998; see Paul et al., 2010; Young et al., 2015 for submariner-specific discussions), suboptimal recovery between shifts (Radstaak et al., 2014), ill health (Åkerstedt, 1990) and reduced performance (Lamond et al., 2003). In line with this, mission averages for cognitive performance were modest at best (with PVT mean reaction time = 283 ms and PVT error rate = 5.3; see Table 1) and fell short of values normally observed in repeated administration of the PVT amongst the general population (e.g., Basner et al., 2018) as well as other highly trained populations (e.g., elite athletes; Knufinke et al., 2018) that used the exact same version of the test (i.e., with mean PVT reaction times ranging from 230 to 265 ms, respectively, and error rates $<$ 4). Similarly, values for self-reported recovery status following off-shift hours (i.e., vigor, affect, rumination) largely averaged around the midpoint of the scale, indicating suboptimal levels of vigor and positive affect (Monk, 1989) and mild levels of work and non-work-related rumination (cf. Brasher et al., 2010; 2012; Paul et al., 2008; Trousselard et al., 2015).

Comparing self-reported recovery status between on- and off-shift hours (i.e., *Aim 2*), no clear indication of recovery during off-shift hours was observed. While from an effort-recovery perspective (Karasek, 1979; Meijman and Mulder, 1998) this may reflect that recovery was insufficient (posing risk for accumulated load effects), another explanation for this finding may be that our measures were not sensitive enough. Previous studies, however, have used similar measures and successfully detected differences in self-reported recovery status between shifts and across days (e.g., Radstaak et al., 2014). A notable and important difference between previous research and the current study, however, is the sheer length of the current data collection. After 67 days of daily assessments, contrast with regard to one's perceived recovery status might fade, as individuals get used to the thoughts and feelings associated with suboptimal sleep, work and rest. In other words: everything starts to feel 'normal'. Indeed, a similar effect was reported by Van Dongen et al. (2003), who showed that individuals taking part in a prolonged (14-day) sleep deprivation study – after several days into the study – became indifferent with regards to their subjective levels of alertness whilst objective measures of cognitive performance continued to deteriorate.

Directly speaking to this issue, our analysis of temporal effects (i.e. *Aim 3*) indicated that while self-reported recovery status remained stable across the mission, objective measures of sleep (i.e. sleep onset latency; SOL) and cognitive performance (i.e., PVT reaction times) reflected small but consistent day-to-day declines as the mission progressed (see Table 3). These effects were most pronounced in the 6-h shift condition and – across the entire 67-days of the mission – accumulated to a 6 min increase in SOL (i.e., from 9.7 min to 15.7 min per sleep episode) and a 44 ms increase in average PVT reaction time (i.e., from 262 ms to 306 ms). With regards to current guidelines for healthy sleep (Edinger et al., 2004; Watson et al., 2015) and given the criticality of optimal (cognitive) performance on-board military submarines (e.g., Brasher et al., 2010; 2012; Paul et al., 2008, 2010), these effects should be considered clinically significant. Furthermore, and although 95% confidence intervals urge caution interpreting, the direction of effect for all our other measures of sleep and cognitive performance consistently reflected similar declines (see Table 3); suggesting that observed effects may not be isolated to specific indicators of sleep and performance but, instead, may be widespread.

With 67-days' worth of data collection, the current study is among the first to provide detailed and robust insight in (the temporal development of) sleep, cognitive performance and self-reported recovery status across prolonged military submarine missions. Nevertheless, it is not free of limitations. First, the relatively small sample size ($n = 14$; with 10 participants in the same shift condition) limits interpretation of findings to the current sample and – mostly – the 6-h shift condition. Second, despite being well-accepted in field-based assessments of sleep (Knufinke et al., 2018), wristwatch actigraphy is relatively inaccurate with regards to the detection of sleep onset and offset (Chae et al., 2009; Paquet et al., 2007). Third, work demands during the mission prevented PVT assessments to be conducted on a daily basis and – whilst timing of assessments was kept constant within participants to allow day-to-day comparison (aim 3) – the data collection for cognitive performance should be considered less robust than for our other measures. Fourth, despite being implemented frequently in diary-based assessments of recovery (e.g., Paul et al., 2008; Radstaak et al., 2014), the sheer length of the current data collection (67 days/2–4 assessments per day; depending on shift condition) may have impacted the extent to which findings continue to provide an adequate representation of between-shift and day-to-day fluctuations in self-reported recovery status.

Importantly, the current study was exploratory and – as such – it is imperative that future hypothesis-testing studies are conducted to replicate the current findings. Doing so, future studies should take above-mentioned limitations into account and, in addition, may conduct targeted examinations of (a) the specific work conditions that drive observed effects; and (b) potential interrelations between measures. For example, looking at future interventions to improve sleep and performance in military submariners, it is important to examine the extent to which observed declines are driven by shift condition (Paul et al., 2008, 2010), suboptimal ambient lighting (e.g., Kelly et al., 1999; Young et al., 2015), a prolonged lack of physical activity (Choi et al., 2010) and/or sustained psychosocial stress (Brasher et al., 2010, 2012); as well as the extent to which observed declines in performance may be driven by associated day-to-day declines in sleep (Knufinke et al., 2018) and/or sustained sleep deprivation (Lowe et al., 2017; Van Dongen et al., 2003). The small sample size, unequal division of participants across shift conditions, and other limitations with regards to the study design (as presented above), prevented such analyses in the current study. Furthermore, given the wide range of medical complaints reported by military submariners (Horn et al., 2003) – and knowing that sufficient good quality sleep is of vital importance to uphold the immune system and maintain health in general (Åkerstedt et al., 2009; Hobson, 2005) – it is imperative that future studies are conducted to extend the current findings by also considering other aspects of health and recovery (e.g., physiological; nutritional; metabolical; e. g, Gasier et al., 2016).

5. Conclusions

In conclusion, findings of the current study extend previous reports on sleep, health and performance of military submariners (e.g., Brasher et al., 2010; 2012; Choi et al., 2010; Horn et al., 2003; Kelly et al., 1999, Paul et al., 2008; 2010; Trousselard et al., 2015; Young et al., 2015) and – based on 67 days of data collection – provide robust and objective evidence to suggest (1) that sleep during prolonged military submarine missions is fragmented and of short duration; and (2) that small but consistent day-to-day increases in sleep onset latency and PVT reaction times may accumulate to reflect clinically significant deterioration in sleep and cognitive performance across the span of an entire mission. Future work is required to corroborate the current findings, firmly establish underlying causes, and make evidence-based suggestions for interventions to improve and uphold submariners' sleep and performance.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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