Recovery of Cognitive Performance Following Multi-Stressor Military Training

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Objective: This project aimed to assess the impact of an 8-day military training exercise on cognitive performance, and track its recovery in periods of reduced training load and partially restored sleep.

Background: Military personnel often work in challenging multi-stressor environments, where sleep loss is inevitable. Sleep loss can impair multiple cognitive domains, which can have disastrous consequences in military contexts.

Method: A total of 57 male and female soldiers undergoing the Australian Army combat engineer Initial Employment Training course were recruited and tracked over a 16-day study period which included an 8-day field-based military training exercise. Cognitive performance was assessed via a computerised battery at seven time points across four sequential study periods; 1) baseline (PRE), 2) military field training exercise which included total sleep deprivation (EX-FIELD), 3) training exercise at simulated base with restricted sleep opportunities (EX-BASE), and 4) a 3-day recovery period (REC). Subjective load, fatigue, and sleep were evaluated continuously via questionnaire and actigraphy.

Results: Psychomotor speed, reaction time, visual tracking and vigilance were impaired following the EX-FIELD period ($p < 0.05$). The majority of affected measures recovered 2 days following EX-FIELD, being no different in EX-BASE compared to PRE.

Conclusion: The sensitivity of the cognitive tests to sleep restriction, and recovery, indicates they can help assess operational readiness in military personnel. Future studies should explore other indicators of, and strategies to preserve, operational readiness in military personnel.

Application: This study highlights the impact of work-induced fatigue on cognitive performance, and would interest authorities seeking to preserve operational readiness.

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INTRODUCTION

Military personnel are often required to work in challenging multi-stressor environments, which can involve a combination of physical, psychological and cognitive demands, sleep restriction or deprivation, and caloric restriction (Margolis et al., 2014; Nindl et al., 2002). With military occupations often requiring long working hours, night work, short turnarounds between missions (Weeks et al., 2010), and inadequate recovery periods (Hamarsland et al., 2018; Nindl et al., 2007); sleep can be impaired (Bannai & Tamakoshi, 2014; Åkerstedt & Wright, 2009). This can have significant implications for their performance capacity, health and well-being. It is well established that sleep restriction and total sleep deprivation can degrade working memory and attention, visuomotor performance, vigilance (Belenky et al., 2003; Shattuck et al., 2018; Van Dongen et al., 2003), reaction time (Belenky et al., 2003; Lim & Dinges, 2010), and decision making (Harrison & Horne, 2000). Moreover, these effects appear to accumulate over successive days of sleep restriction (Durmer & Dinges, 2005). The capacity to maintain cognitive performance under periods of physical fatigue and psychological stress has great relevance to military personnel and their operational readiness. Fatigue caused by acute and sustained sleep restriction, and therefore prolonged wakefulness, can decrease marksmanship accuracy (Head et al., 2017), impair friend–foe discrimination (Smith et al., 2019), and increase accidents and errors in judgement (Harrison et al., 2017). Up to 80–85% of military accidents may be attributed to decreased cognitive performance (Thomas & Russo, 2007). Therefore, understanding how fatigue-impaired cognition accumulates, and recovers, during military environments can assist with operational risk management to minimise adverse performance outcomes.

Cognitive performance is impaired during and following sustained military operations and simulated combat training in multi-stressor environments (Friedl et al., 2001; Lieberman, Bathalon, Falco, Kramer, et al., 2005; Lieberman et al., 2009). However, it is unclear as to how performance is affected after 80 h of continuous military operations, a relatively common length of deployment, and the recovery time-course of these measures post operation (Vrijkotte et al., 2016). Part of the inconsistency in recovery trajectories may be in part due to the heterogeneity in the reporting of cognitive constructs tested, characteristics of the training group, and training/operational environment. Therefore, kinetics of cognitive performance in a multi-stressor military environment, and the specific cognitive domains that are most vulnerable to deterioration, and fastest to recover, remain unclear. Cognitive domains such as psychomotor speed and executive function, have been touted as potential markers of intolerance to physical training (Dupuy et al., 2010; Nederhof et al., 2006; Saw et al., 2016); however, this concept has not been investigated in a military context. Therefore, an initial assessment of the impact of an 8-day multi-stressor field exercise on cognitive function, a vital component of operational readiness, may be a useful inclusion in a suite of measures for soldier monitoring and management. Furthermore, as adequate rest periods are imperative to restore performance and maintain operational capability, it is necessary to identify the minimum dose of recovery required for a restoration of cognitive abilities, following exposure to occupational stressor(s). The aims of this project were to 1) assess the impact of an 8-day military training exercise on cognitive performance, and 2) track the recovery of these variables in periods of reduced training load and partially restored sleep.

MATERIAL AND METHODS

Participants and design

Participants were Australian Army soldiers undertaking the 18-week Combat Engineer initial employment training (IET) course at the School of Military Engineering (Holsworthy Barracks, NSW). Our 16-day study was divided into four distinct periods which included the final 8-day capstone assessment exercise for this course (Figure 1). In total, 57 soldiers consented (54 men and three women; aged 22.3 ± 3.6 years; body mass: 82.6 ± 12.1 kg, height: 1.79 ± 0.1 m; and body mass index; 25.8 ± 3.4 kg·m^{-2}) to participate. This research complied with the tenets of the Declaration of Helsinki and was approved by the Department of Defence and Veteran's Affairs Human Research Ethics Committee (protocol 021–17). Informed consent was obtained from each participant.

Protocol

To compare cognitive performance between study periods, cognitive data was collected at seven time points; days 2, 4, 6, 8, 10, 12, 14 with each cognitive testing session conducted between 1700 and 2100 h to control for circadian variation. The training exercise was conducted in November 2019. Soldiers were briefed on the investigation on day 0, after which voluntary written informed consent and baseline anthropometric data were collected. Following day 0, soldiers underwent 4 days (days 1–4) of normal training/activities (PRE; Figure 1). Following PRE, soldiers began the 8-day military training exercise (EX) with 4 days living in the field (EX-FIELD; days 5–8), which involved digging trenches, patrols, simulated minefield breaches and responding to contacts. Soldiers were given minimal sleep opportunities, including at least one night of total sleep deprivation, on the first night of EX-FIELD, with the potential for one other 24-h period of sleep deprivation during EX-FIELD. After EX-FIELD, soldiers transitioned to 4 days living at a simulated base (EX-BASE) where they simulated the repelling of enemy attack and completed pickets, with disrupted and restricted sleep during the day and

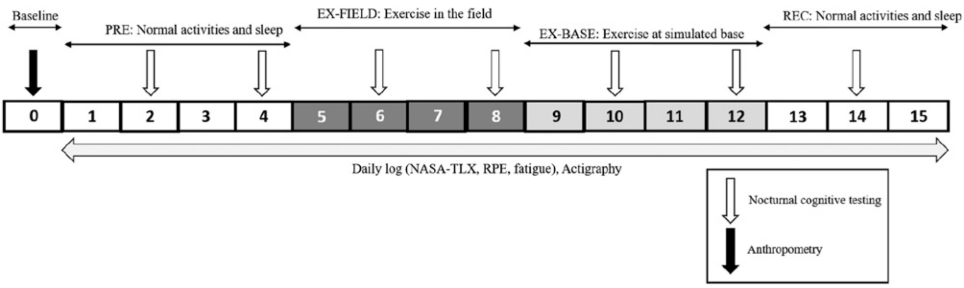

Figure 1. Outline of the 16-day data collection period, comprising four distinct periods.

night (days 9–12). Following this, soldiers returned to their usual accommodation and completed the 3-day recovery data collection phase (REC, days 13–15). During this time, they engaged in light activities (e.g., cleaning, returning equipment) with habitual sleep opportunities. Testing was conducted in soldiers' dormitories for the first and last study periods; other cognitive testing was conducted in the field. Subjective ratings of fatigue, exertion (RPE), cognitive load, and actigraphy for sleep data were collected daily.

Anthropometry

Height was measured to the nearest 0.1 cm and body weight was measured to the nearest 0.01 kg using standard techniques (stadiometer and a metric scale respectively). Body mass index (BMI) was calculated [weight (kg)/height (m^2)].

Cognitive Performance

Neurobehavioral testing was conducted using the automated 'Cognition' test battery from Joggle Research (Joggle Research, Seattle, WA), and the NeuRA Trails application (NeuRA, Randwick, NSW), presented to participants on an electronic tablet (Apple iPad Air; Cupertino, CA, USA). This battery has been validated (Moore, Basner, Nasrini, Hermosillo et al., 2017). Total testing time was approximately 10 minutes to reduce impost on participants and army staff, and the battery can be completed successfully in both online and offline modes. Five tests from the Joggle Cognition battery were administered, to assess cognitive abilities vulnerable to sleep loss and which have relevance for operational performance in military personnel (e.g., working memory, vigilance and reaction time) (Basner et al., 2015; Taylor et al., 2019). In order, tests included the Motor Praxis Task (MPT): psychomotor speed and visual tracking; Visual Object Learning Task (VOLT): working memory and visual object learning; Line Orientation Task (LOT): visuospatial orientation; Digit Symbol Substitution Task (DSST): attention, working memory, complex scanning and visual tracking; Psychomotor Vigilance Task (PVT): psychomotor speed and vigilant attention. Participants completed one practice of each task before test administration. For detailed instructions please refer to (Basner et al., 2015). The 3-min PVT is a valid instrument for measuring reduced alertness due to sleep deprivation, compared to longer 10 min versions (Grant et al., 2017). The main outcomes for DSST, LOT, and VOLT were mean reaction time (RT), accuracy, and standardised efficiency score, which acted as a global performance score for each measure, scored out of 1000. For MPT, mean RT and standardised speed score, for PVT: mean RT, efficiency score, errors (false starts and coincident false starts) and lapses (number of responses longer than 355 ms threshold). The stimuli for the MPT, DSST, LOT and PVT were presented in a random order, VOLT consisted of preconfigured sequences.

The Trail Making Test Part A (visuoperceptual ability/processing speed) involves drawing lines to connect numbered dots in ascending numerical order as quickly as possible while maintaining accuracy (Bowie & Harvey, 2006). Part B (working memory and taskswitching ability) involves connecting dots in ascending order, alternating between numbers and letters, as fast as possible. The number of seconds taken to complete each part of the test is the outcome. The score of Part B minus Part A provides an indication of executive function.

Sleep

Activity monitors (Actigraph GT9-X, Pensacola, FL) were used to assess sleep quantity, worn on the non-dominant wrist 24 h per day during the data collection period, unless contact with water was likely. Participants were not available for data collection on night 15. Due to the aims of this study, physical activity data was not included in analyses. Upon completion of data collection, raw activity counts, measured in one-minute epochs, were uploaded using a device-specific interface unit and analysed using the manufacturer's proprietary software (Actilife v6.13). The Cole–Kripke sleep-wake detection algorithm was used to distinguish sleep and wake periods (Cole et al., 1992). This algorithm has demonstrated 88% agreement (i.e., percentage of sleep and wake epochs correctly identified) when compared with polysomnography (Cole et al., 1992). Participants occasionally undertook daytime naps, and night-time sleep was often broken to perform night duties (e.g., picket/sentry duty). Therefore, to analyse 24 h sleep patterns, sleep duration was aggregated from the end of one night's main sleep until the end of the next night's main sleep. Where total sleep deprivation occurred across a 24 h period, sleep duration was entered as '0'.

Subjective Workload and Fatigue

The following information was recorded each morning upon awakening (between 0700 and 0800 h in participants' accommodation, between 0530 and 0600h in the field). Participants' subjective ratings of fatigue (pre-sleep and post-sleep) were assessed via the Samn–Perelli Fatigue Scale, scored on a seven-point Likert scale (Samn & Perelli, 1982). Developed and validated in occupational settings such as aviation operations, it is reliable and sensitive to the effects of sleep loss at different times of the day. Subjective workload for the preceding 24 h period was measured via the NASA Task Load Index (Hart & Staveland, 1988). The NASA-TLX consists of one question for each of six subscales measuring the levels of mental, physical and temporal demands, performance, effort, and frustration along a continuum from low to high, with an integer value of 0–100 in 5-point increments. This questionnaire shows sensitivity for the assessment of the cognitive demands of a given workload (Hart & Staveland, 1988; Matthews, Reinerman-Jones, Barber, & Abich IV, 2015), and concurrent cognitive and physical demands (DiDomenico & Nussbaum, 2008). The single item Rating of Perceived Exertion (RPE), reported on a scale of 0–10, was used to assess physical effort for the day before (Borg, 1982; Noble et al., 1983).

Statistical Analyses

All statistical analyses were conducted using SPSS v.26.0 (SPSS Inc, Armonk, NY). Data and their residuals were normally distributed. In the first round of analyses, all data were collapsed into three study time periods; PRE, EX (EX-FIELD and EX-BASE training) and REC, using averages for each period. This was done as there was no washout period (i.e., habitual sleep periods) between sleep deprivation (EX-FIELD) and sleep restriction (EX-BASE) phases to separate the effects of each training phase. Effects of the training exercise on cognitive function, sleep and subjective load, and their recovery during REC, were analysed using linear mixed models with random effects, adjusting for participant variability, with time used as a repeated measure, and all models utilising the autoregressive (AR1) covariance matrix. For variables that changed during EX, subsequent analyses using all seven time points were conducted, to determine the immediate impact of sleep deprivation (EX-FIELD) and their response in the following periods (i.e., EX-BASE and REC). To investigate the variance between participant cognitive performance across field training as a result of sleep impairment and restriction, averages of mean RT and efficiency across each of PRE, EX-FIELD, EX-BASE, and REC were calculated, and change data were

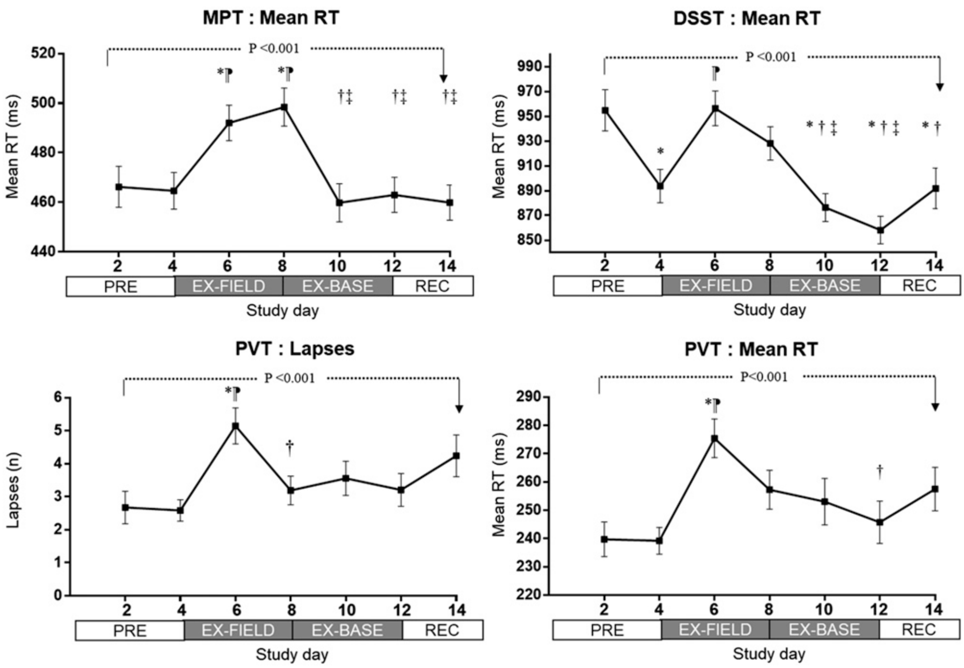

Figure 2. Mean (±SEM) changes in mean reaction time (RT) for Motor Praxis Task (MPT), Digit Symbol Substitution Task (DSST), and Psychomotor Vigilance Task (PVT), and PVT lapses during 16-day study period. $^*p < 0.05$ vs day 2; ⁋ $p < 0.05$ vs day 4; † $p < 0.05$ vs day 6; ‡ $p < 0.05$ vs day 8.

calculated from the difference between scores from these periods. Change data were further divided into 'improved performance' for mean RT and efficiency where changes equated to <0 and ≥0, respectively, and 'impaired performance for mean RT and efficiency where changes equated to ≥0 and <0, respectively. Bonferroni post-hoc estimations adjusted for multiple comparisons. All data are presented as means ± SEM with 95% CI, except demographic data (mean ± SD). The significance level was set at $p < 0.05$.

RESULTS

Cognitive Function

Motor Praxis Task. MPT mean reaction time (RT) was slower during EX, compared to PRE ($p = 0.025$) and REC ($p = 0.008$). MPT mean RT was slower at day 6 compared to days 2, 4, 10, 12, and 14 (all $p \leq 0.029$; Figure 2), and slower at day 8 compared to days 2, 4, 10, 12 and 14 (all $p \leq 0.002$). Speed scores in EX were lower compared to PRE ($p = 0.048$) and REC ($p = 0.006$), and was lower at day 6 compared to days 4, 10, 12 and 14 (all $p \leq 0.028$; Figure 3), and day 8 compared to days 2, 4, 10, 12, and 14 (all $p \leq 0.011$). MPT mean RT and speed score were no different to PRE values by day 10.

Digit Symbol Substitution Task. DSST mean RT was faster during REC than PRE ($p = 0.001$) and EX ($p = 0.028$). DSST mean RT was slower at day 6 compared to days 4, 10, 12 and 14 (all $p < 0.001$; Figure 2) and slower at day 8 compared to days 10 and 12 (both $p \leq 0.001$). DSST mean RT was faster than PRE values by day 10. There was no difference in DSST accuracy across the study period ($p = 0.195$). DSST efficiency was higher during REC compared to PRE and EX (both $p < 0.001$). Efficiency score was higher at day 12 compared to days 2, 6, and 8 ($p \leq 0.032$), and at day 14 compared to days 2 and 8 (both $p \leq 0.032$; Figure 3).

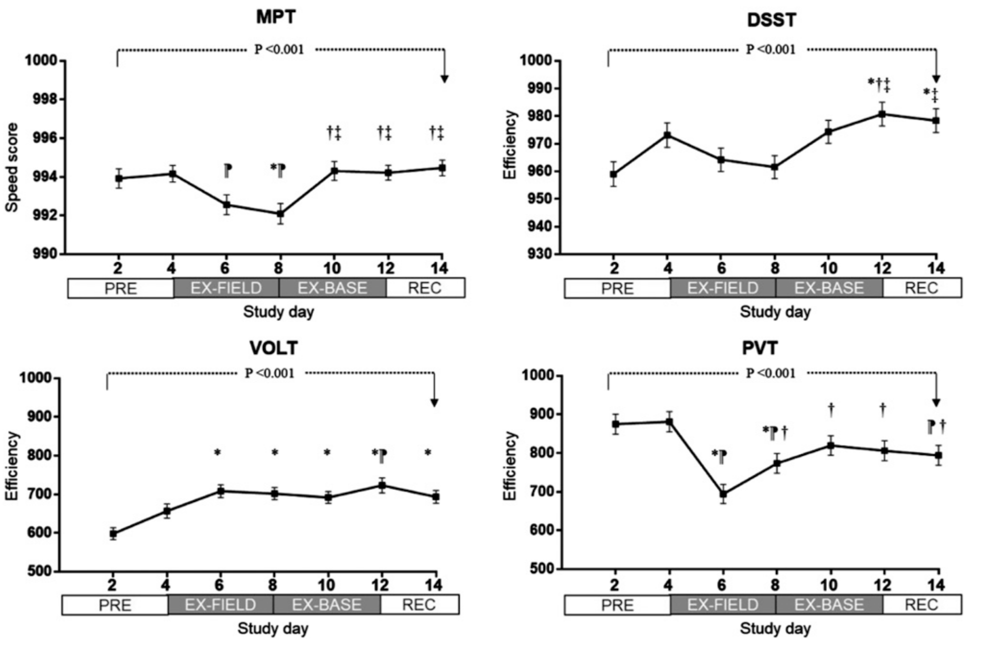

Figure 3. Mean (±SEM) changes in efficiency scores for Motor Praxis Task (MPT), Digit Symbol Substitution Task (DSST), Visual Object Learning Task (VOLT), and Psychomotor Vigilance Task (PVT) during 16-day study period. *$p < 0.05$ vs day 2; ⁋ $p < 0.05$ vs day 4; † $p < 0.05$ vs day 6; ‡ $p < 0.05$ vs day 8

Psychomotor Vigilance Task. Compared to PRE, lapses were higher at EX ($p = 0.001$) and REC ($p = 0.031$). Lapses were higher at day 6 compared to days 2, 4 and 8 (all $p \leq 0.006$; Fig 2). Errors were lower during REC compared to PRE ($p = 0.007$). PVT mean RT was slower at day 6 compared to days 2, 4 and day 12 (all $p \leq 0.027$; Figure 2). PVT mean RT had returned to PRE levels by day 8 (EX-FIELD). PVT efficiency score was lower at EX ($p < 0.001$) and REC ($p = 0.009$), compared to PRE. Efficiency score was lower at day 6 compared to all other days (all $p < 0.018$), and lower at day 8 compared to days 2, 4, and 6 (all $p < 0.018$; Figure 3). PVT efficiency score had returned to PRE levels by day 10.

Visual Object Learning Task. VOLT mean RT was faster at EX and REC compared to PRE (both $p < 0.001$). Accuracy did not change across the study period ($p = 0.070$), however efficiency score increased ($p < 0.001$). Compared to PRE, efficiency was higher at EX ($p < 0.001$) and REC ($p = 0.003$). There were multiple improvements compared to day 2 and day 4 (all $p < 0.005$; Figure 3).

Line Orientation Task. LOT mean RT was faster during REC compared to PRE ($p < 0.001$) and EX ($p = 0.023$), and faster during EX compared to PRE ($p < 0.001$). Accuracy was higher at PRE compared to EX ($p = 0.029$) and REC ($p = 0.010$). Subsequent analyses revealed no changes in accuracy or mean RT between time points. Efficiency did not change across the study period ($p = 0.972$).

Trail Making Test. There was a significant improvement in time to complete Trails-A ($p < 0.001$), Trails-B ($p < 0.001$) and Trails B–A ($p < 0.001$) across the study period (Table 1).

Inter-Individual Variation. The range of cognitive performances for each measure, captured across the study period, is presented in Supplementary Table 1. The proportion of participants with impaired cognitive

TABLE 1: Mean Trail Making Test times to completion for each time point

Trail Making Test	Time to complete task (s)						
	Day 2	Day 4	Day 6	Day 8	Day 10	Day 12	Day 14
Trails-A (s)	21.2 ± 0.4	16.6 ± 0.4*	16.7 ± 0.4*	15.9 ± 0.4*	13.7 ± 0.4*⁋†‡	13.5 ± 0.4*⁋†‡	14.0 ± 0.4*⁋†‡
Trails-B (s)	59.4 ± 1.8	44.9 ± 1.8*	43.5 ± 1.8*	36.9 ± 1.8*⁋†	31.1 ± 1.8*⁋†‡	28.3 ± 1.8*⁋†‡	29.0 ± 1.8*⁋†‡
Trails B-A (s)	38.9 ± 1.8	26.3 ± 1.8*	26.8 ± 1.8*	21.1 ± 1.8*⁋†	17.5 ± 1.8*⁋†	14.8 ± 1.8*⁋†‡	15.2 ± 1.8*⁋†‡

Values are means ± SEM; * 'T1' with 'Day 2', 'T2' with 'Day 4', 'T3' with 'Day 6' and 'T4' with 'Day 8'

performances across the study period is presented in Supplementary Table 2.

Sleep

Participants averaged 5.8 ± 0.1 h (mean ± SEM) sleep during PRE, 3.9 ± 0.1 h sleep during EX (which included 2.2 ± 0.2 h sleep over the 4 days/nights in EX-FIELD, and 5.8 ± 0.1 h sleep over 4 days/nights at EX-BASE), and 5.9 ± 0.1 h during the first two nights of REC. Sleep duration during EX was lower than both PRE and REC ($p < 0.05$), while sleep during EX-FIELD was lower than all periods ($p < 0.05$). From actigraphy data, only one sleep opportunity (of 2 h in length) occurred within 5 hours of an evening cognitive testing session.

Subjective Workload and Fatigue

RPE was higher at EX ($p < 0.001$) and REC ($p < 0.001$) compared to PRE, and lower at REC compared to EX ($p = 0.009$). RPE increased across the study period ($p < 0.001$). Subsequent analysis revealed multiple differences between time points (all $p < 0.045$; Figure 4). RPE was still higher at REC, compared to day 4 of PRE ($p < 0.001$).

Pre-sleep fatigue was higher at EX compared to PRE and REC (both $p < 0.001$). Subsequent analyses revealed multiple significant differences between time points (all $p < 0.015$; Figure 4). Pre-sleep fatigue returned to PRE levels 6 days following EX-FIELD; day 14 within the REC period. Post-sleep fatigue was higher at EX compared to PRE and REC ($p = 0.002$). There were multiple differences between time points (all $p < 0.002$; Figure 4). Post-sleep fatigue returned to PRE levels within 2 days following EX-FIELD.

All six NASA-TLX subscales and the NASA-TLX average changed across the study period (all $p < 0.001$; Table 2). Compared to PRE, NASA-TLX average was higher at EX and REC (both $p < 0.001$) and was lower at REC compared to EX ($p < 0.001$). Multiple differences between timepoints were detected (Figure 4); NASA-TLX average score did not return to PRE levels during REC.

DISCUSSION

The current study investigated the impact of training-induced (simulated operational) fatigue and reduced sleep on cognitive performance, and the recovery of cognitive performance following completion of the training exercise over a 2-day period with habitual sleep opportunities. The main findings were that multiple domains of cognitive function were impaired across simulated operational activities, as soldiers performed worse in tasks assessing psychomotor speed, reaction time, visual scanning/tracking, attention and vigilance, when fatigued. These decrements were detected on night 6, which followed the first night of sleep deprivation (EX-FIELD; night 5), but the majority of affected cognitive performance measures had returned to baseline levels within four nights of this time point (night 10; with a total of ~15 h sleep), despite still conducting nocturnal activities (EX-BASE). The period of simulated operational activities was also associated with increased perceived exertion, fatigue and subjective load.

Decrements in Cognitive Performance During Military Training Exercise

Military personnel must maintain effective cognitive performance in multi-stressor environments, as sub-optimal performance may

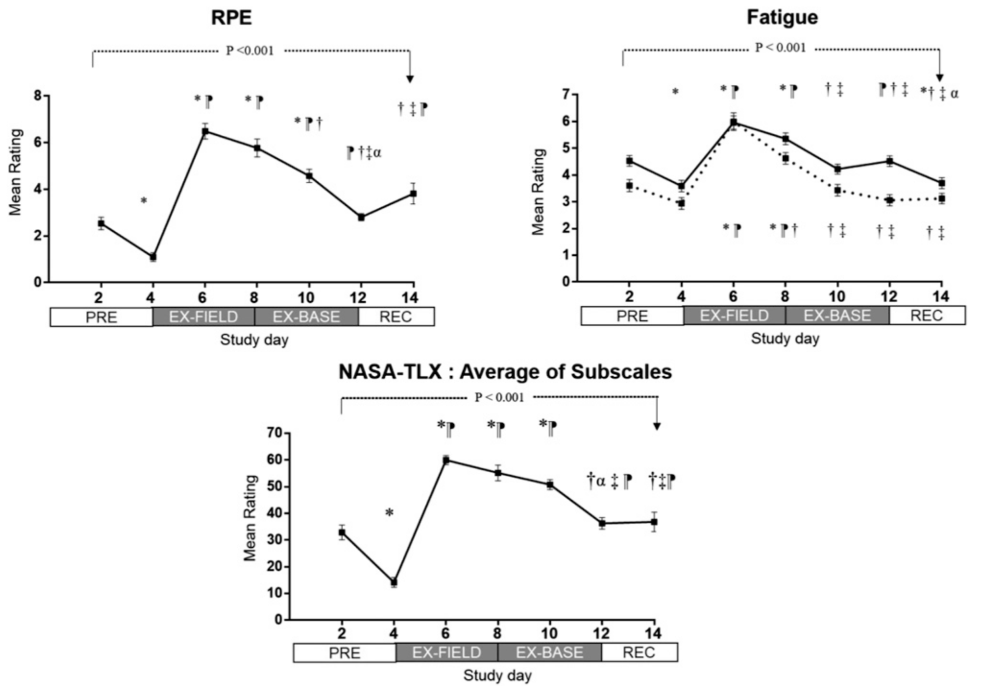

Figure 4. Mean (±SEM) changes in RPE, Pre-sleep fatigue (—) and Post-sleep fatigue (····), and NASA-TLX average of six subscales, during the 16-day study period. * $p < 0.05$ vs day 2; ⁋ $p < 0.05$ vs day 4; † $p < 0.05$ vs day 6; ‡ $p < 0.05$ vs day 8; α $p < 0.05$ vs previous time point.

TABLE 2: Mean NASA-TLX subscale scores for each time point

NASA-TLX Subscale	Subscale Score Day 2	Day 4	Day 6	Day 8	Day 10	Day 12	Day 14
Mental Demand	34.3 ± 3.5	12.5 ± 2.1*	65.5 ± 3.2 *⁋	54.9 ± 3.7*⁋	46.9 ± 2.8 *⁋†	34.3 ± 2.7 ⁋†‡ α	34.3 ± 4.2 ⁋†‡
Physical Demand	32.2 ± 3.3	12.0 ± 2.1*	75.6 ± 2.0*⁋	63.1 ± 3.7*⁋	62.5 ± 3.1*⁋	36.3 ± 2.7 ⁋†‡ α	42.3 ± 4.8 ⁋†‡
Temporal Demand	29.1 ± 3.2	11.2 ± 2.1*	51.9 ± 2.4*⁋	59.5 ± 3.7*⁋	63.2 ± 3.0*⁋	37.9 ± 2.8 ⁋†‡ α	44.3 ± 4.8*⁋‡
Perfection	27.0 ± 3.8	16.8 ± 3.2	35.4 ± 2.9⁋	39.1 ± 3.2 *⁋	28.3 ± 3.6‡ ⁋	25.0 ± 2.9‡	20.5 ± 2.8†‡
Effort	41.5 ± 3.6	17.3 ± 2.8*	76.1 ± 2.2*⁋	66.2 ± 3.2 *⁋	65.0 ± 3.2*⁋	47.7 ± 3.1 ⁋†‡ α	44.4 ± 4.7 ⁋†‡
Frustration	32.8 ± 2.8	14.9 ± 1.9*	54.9 ± 1.7*⁋	48.2 ± 3.0*⁋	38.6 ± 1.9⁋†	35.7 ± 2.2⁋†	32.2 ± 3.6 ⁋†‡

Values are means ± SEM; * ‘T1’ with ‘Day 2’, ‘T2’ with ‘Day 4’, ‘T3’ with ‘Day 6’ and ‘T4’ with ‘Day 8’ α $p < 0.05$ vs previous time point.

compromise mission outcomes (Smith et al., 2019). Our findings indicated that soldiers performed worse in tasks assessing psychomotor speed, reaction time, visual scanning/tracking, and attention (including vigilant attention), following and during a field training exercise involving total sleep deprivation and severe sleep restriction. Performance in tasks involving simple, sustained attention (e.g., vigilance and reaction time) are vulnerable to decline under military operational stress involving high-intensity exercise and stress lasting up to 80 h (Vrijkotte et al., 2016), and lab-based studies involving total sleep deprivation (Alhola & Polo-Kantola, 2007; Lim & Dinges, 2008; Lim & Dinges, 2010; Ołpińska-Lischka et al., 2020). We observed a 7% increase in PVT reaction time between PRE and the training period (EX), with a 15% increase in PVT reaction time specifically within the 48 h period between the end of PRE and the first evening following a 24 h period of total sleep deprivation. These findings align with increases in vigilance task reaction time reported in operational simulations with reduced sleep volume (i.e., 2–3 h per mission) after 49 h (7%, (Lieberman et al., 2006)), and after 53 h in intense heat (22% (Lieberman, Bathalon, Falco, Kramer, et al., 2005)). To contextualise this magnitude, 20% decrements in choice reaction time performance exceed the impairment induced by a blood alcohol concentration of 0.10% (Lieberman et al., 2005; Williamson & Feyer, 2000). Therefore our observed impairment in a related variable may predispose soldiers to misjudgement and increased risk of accidents. We also observed a 11% decrease in a global efficiency score for PVT between baseline and the 8-day exercise period, while lapses increased by 46%. Furthermore, the number of lapses in the first evening following total sleep deprivation was double those recorded during baseline. Importantly, global cognitive impairments may be mediated through decreased alertness and attention through lapses and wake-state instability (drive to fall asleep vs. counteracting need to sustain alertness) (Doran et al., 2001; Dorrian et al., 2005). In operational contexts, relatively brief failures of vigilance, or lapses in concentration, may lower productivity, increase injury risk injury or lead to dire consequences. Performance in PVT and other tasks of sustained, vigilant attention may therefore have utility as predictors of operational readiness (Lim & Dinges, 2008).

The period of total sleep deprivation within EX-FIELD specifically impacted aspects of cognition. Between baseline and testing during EX-FIELD, we detected a 7% increase in reaction time when assessing sensory-motor speed (MPT) and complex scanning and visual tracking (DSST), while there was a 4.3% decrease in accuracy in a spatial orientation task (LOT). The observed decrements in motor skill and visual tracking may be partially ascribed to the fact that most soldiers endured approximately 40 h of wakefulness, from the morning of day 5 to their first sleep opportunity on night 6. Even 17 h of continued wakefulness is associated with declines in motor-skill responses (Dawson & Reid, 1997; Williamson & Feyer, 2000), impaired visual tracking performance (Heaton et al., 2014) and depressed reaction time performance, to levels equivalent or worse than that at a blood alcohol concentration of 0.05% (Williamson & Feyer, 2000). Collectively, our findings support previous research that reaction time and attention can be significantly impaired during simulated military operations. Reaction time is a valuable motor skill required for various military tasks such as recognising potential threats, and piloting manned/unmanned platforms. Therefore, this cognitive ability represents a target of assessment for work readiness, and a basis for decisions on whether countermeasures should be applied to mitigate occupational safety risks (e.g., scheduling breaks in work activities, sleep banking, pharmacologic intervention) (McLellan et al., 2016; Shattuck et al., 2018).

Recovery of Cognitive Performance Following Sleep Loss

The recovery trajectory of cognitive performance after sleep loss in the military setting is still largely unknown, as previous military studies have typically not monitored recovery periods (Vrijkotte et al., 2016). In our study, the recovery period involving reduced physical exertion and mental load, and more sleep than field training altogether, had variable effects on cognitive abilities impaired during EX-FIELD. Given the initial sleep deprivation and subsequent sleep restriction (average 2.2 h for EX-FIELD, 5.8 h for EX-BASE), we expected that cumulative sleep loss would have greater effects on cognitive performance than observed. However, reaction times for MPT and DSST, and efficiency scores for MPT and PVT, returned to baseline levels 2 days following EX-FIELD, within the study period involving restricted sleep (EX-BASE). In contrast, decreases in LOT accuracy, and increases in PVT reaction time and lapses elicited by the severe sleep restriction within EX-FIELD were not different to those experienced in the recovery period, suggesting these domains were still impaired and more sensitive to sleep loss. As most cognitive markers had returned to PRE levels by day 10, this limited data suggests that ~15 h of sleep over 96 h was sufficient to restore most cognitive deficits. Laboratory-based studies have demonstrated that one sleep period of at least 8 h can reverse the adverse effects of up to 55 h of total sleep deprivation on cognition (Adam et al., 2006; Drummond et al., 2006). Furthermore, even a 4 h sleep after a period of 23 h of wakefulness completing simulated military activities, may partially restore cognitive performance (Haslam, 1985). As a point of difference to these studies, our soldiers were subjected to continuous mental and physical exertion across the training exercise, as evident in their consistently elevated ratings of subjective load, physical exertion and fatigue, which might explain the delayed time frame for recovery of some cognitive measures. Our findings therefore suggest that cognitive performance can be partially restored during demanding training exercises, with the provision of increased sleep.

In the current study, sleep bouts were taken opportunistically from days 7 to 12, due to the varying nature of activities completed during the training exercise. Partial restoration of aspects of vigilance, reaction time, and working memory may therefore be possible when sleep can be accumulated through short naps during sustained military operations (Vrijkotte et al., 2016). Moreover, recovery naps may help restore cognitive markers when fatigued from sleep restriction/deprivation (Dutheil et al., 2020; Hartzler, 2014), particularly in operational settings where a 'recovery sleep' is not feasible. Overall, sleep loss seems to be a critical stressor during military training, as the observed cognitive decrements were largely reduced or ameliorated following 4–15 h of sleep accumulated within a 48–96 h period. While restricted sleep opportunities are frequently experienced by military personnel this amount of sleep is not ideal for civilians or soldiers in a chronic context. Moreover, the authors are not suggesting that 15 h of sleep across this period is sufficient for full recovery to occur. Therefore, before we can provide specific recommendations of appropriate recovery durations for military personnel that may be contrary to the current recommendation of a minimum of 7 h of sleep a day in order to sustain optimal performance (Watson, Badr, Belenky et al., 2015), further research is needed. Specifically, to confirm a) what dose is suitable to restore other cognitive measures not tested in our study, b) whether the restoration of cognitive performance corresponds to optimal occupational task performance and c) what the repeated and cumulative effects of sleep restriction (i.e., over multiple deployments) are on cognition, health and well-being following the recovery of these measures to baseline. There was however data (from a sub-analysis) that showed while most participants performed worse in tasks assessing psychomotor speed, reaction time, visual scanning/tracking and attention (including vigilant attention), a smaller percentage of trainees did not demonstrate deterioration between the training periods. Therefore, the potential for inter-individual differences for the impact of sleep loss on cognitive performance, and its recovery, should be further investigated (Van Dongen & Dinges, 2005).

Preservation of Higher Order Cognitive Functioning During Military Training Exercises

Across the study period, we observed improvements in tasks assessing spatial orientation (LOT), spatial learning and memory (VOLT), complex scanning and visual tracking (DSST), and working memory and executive function (TMT). These improvements were not observed in all participants, highlighting inter-individual variability in responses to a multi-stressor training period. Nonetheless, as an initial explanation, changes in higher order cognitive function may be more difficult to detect than basic abilities (Lieberman et al., 2006), while complex tasks may possess novelty which increases participant motivation during total sleep deprivation (Lim & Dinges, 2010). Higher order tasks may also increase attentional effort (Rosa et al., 2020), masking cognitive impairment (Harris et al., 2005), while the utilisation of strategies may preserve performance in tasks such as connecting numbers to letters (TMT-B) or remembering geometric figures (VOLT). Despite improvements in reaction time for these tests, accuracy either decreased (LOT, VOLT) or remained unchanged (DSST). In partial contrast to our findings, a speed-accuracy trade-off has been observed in total sleep deprivation (Tikuisis et al., 2004), and military operations (Lieberman et al., 2006; Smith et al., 2019) whereby performance speed is impaired but accuracy remains unaffected (De Gennaro et al., 2001). Therefore, our participants may have employed different strategies to compensate for fatigue, such as prioritising speed over the accuracy of their response, in maintaining higher order processes (e.g., executive function, working memory), amidst considerable sleep loss and physical exertion.

Subjective Ratings of Well-Being, Load and Fatigue During Military Training Exercise

We observed significant disturbances to subjective load and fatigue across the study, as assessed via NASA-TLX and RPE scales. Ratings of physical demand increased by 96% across the study period, with a two-fold increase apparent between baseline and the field exercise periods (both EX-FIELD and EX-BASE). Mental demand also increased within these periods (57% and 113% respectively). A study involving sleep restriction (2 h sleep/night) over 72 h with soldiers in training also reported significant increases in ratings of physical demand (31%), effort and mental demand (25%) (Smith et al., 2019). However, these soldiers did not undertake any training exercises, which may explain the differences in the magnitude of change between studies. Nonetheless, a combination of increased physical demands over training and a shift in perception with increasing fatigue may partially inform our results. Furthermore, perceived exertion, and all NASA-TLX subscale scores had not returned to pre-training levels by the conclusion of the study period, which may be explained by a continuation of physical and mental tasks during EX-BASE. Soldiers may therefore have still been recovering mentally and physically from the training exercise, despite the apparent recovery of objective cognitive performance. For military exercises involving sustained sleep restriction (up to 8 days), combined with physical and mental stressors, additional recovery time may be required before subsequent missions/training, to ensure optimal physical performance and decreased injury risk (Good et al., 2020; Grier et al., 2020).

Strengths and Limitations

There are several strengths with this study. To our knowledge, this is one of the few studies to evaluate the impact of sleep deprivation on cognitive performance within a multi-stressor environment, *and* track the trajectory of recovery of these measures. Further, the military training exercise conducted was longer than others previously reported (Lieberman, Bathalon, Falco, Kramer, et al., 2005; Lieberman et al., 2006; Vrijkotte et al., 2016), and IET soldiers provide a point of difference to more experienced soldiers. We also used a field-expedient cognitive battery covering domains relevant for military personnel. However, there are limitations which must be considered when interpreting the results. First, 95% of the soldiers in the study were men, and therefore findings may not be generalizable to women in the armed forces. Second, due to the study aims, factors known to influence cognitive performance (e.g., historical sleeping habits, aerobic fitness, nutrition) were not included, but it is acknowledged they may have influenced findings (Walker, 2009; Åberg et al., 2009). Third, the restriction of our cognitive testing within a 2 h period in the evening means that we cannot comment on oscillations in cognitive performance throughout the day, although the consistent timing of testing provides experimental control. Lastly, the consistent improvement in reaction time and efficiency we observed with LOT and VOLT and TMT-B across the study may be partially explained by practice effects. For simple motor response tests such as MPT or PVT, repeated administration does not appear to be subject to learning effects (Lim & Dinges, 2008), with asymptotic performance levels reached after a few administrations. However, for others (e.g., VOLT, TMT-B), practice effects have been seen to continue after 10 or more administrations (Basner et al., 2015; McCaffrey & Westervelt, 1995). While these effects may lead to an underestimation of the degradation of cognitive performance for some tests, the elimination of potential learning effects through repeated test administration was not possible within our study, due to the requirement to minimise the research footprint during the field exercise, which was the final culmination activity in the Combat Engineer course.

In conclusion, 8 days of simulated operational activities impaired cognitive performance related to psychomotor speed, reaction time, visual scanning/tracking, and attention (including vigilant attention), particularly during periods of total sleep deprivation. Most deficits were attenuated after ~15 h of sleep across a 96 h period, or by the end of a dedicated 3-day recovery period following the training exercise. Simple measures of cognitive performance, particularly vigilance and reaction time, may be one useful indicator of soldier readiness in a multi-stressor environment, but decision thresholds will need to accommodate inter-individual differences.

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KEY POINTS

- Multiple domains of cognitive function were impaired across an 8-day military training exercise, including psychomotor speed, reaction time, visual scanning/tracking, attention and vigilance, which were largely attributed to fatigue.
- The majority of affected cognitive measures had returned to baseline levels four nights after a night involving total sleep deprivation (with a total of ~15 h accumulated sleep), despite soldiers still conducting nocturnal activities during these four nights.
- Perceptions of physical exertion, fatigue and training load were higher during the period of simulated operational activities, and these ratings had not returned to pre-training levels by the conclusion of the study period.
- For military exercises involving sustained sleep restriction (up to 8 days), additional recovery time may be required before subsequent missions/training, to ensure optimal performance and decreased injury risk.

AUTHOR'S CONTRIBUTIONS

Study concept and design: all authors; Acquisition of data: Sean Corrigan, Jamie Tait, Luana Main; Analysis and Interpretation of data: Jamie Tait; Drafting of the manuscript: Jamie Tait; Critical revision of the manuscript for important intellectual content: all authors. Each of the authors have read and approved the final manuscript.

ETHICS APPROVAL

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards. This study was approved by the Department of Defence and Veteran's Affairs Human Research Ethics Committee (protocol 021–17).

INFORMED CONSENT

Informed consent was obtained from all individual participants included in the study. Participants consented to the publishing of their data.

DATA AVAILABILITY

Due to the sensitive nature of the work conducted within this manuscript, and the agreement entered into between Deakin University and the Commonwealth of Australia, this data is not available.

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SUPPLEMENTAL MATERIAL

Supplemental material for this article is available online.

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