Cruisin' for a Snoozin': the role of sleep in resilience to simulated military operational stress

by

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Submitted to the Graduate Faculty of the

School of Health and Rehabilitation Sciences in partial fulfillment

of the requirements for the degree of

Doctor of Philosophy

University of Pittsburgh

2021

UNIVERSITY OF PITTSBURGH

SCHOOL OF HEALTH AND REHABILITATION SCIENCES

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November 19, 2021

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BACKGROUND: Military personnel must maintain high levels of operational performance despite exposure to sleep loss, caloric restriction, physical exertion and high cognitive loads. These operational stressors may influence sleep, operational performance and perception-action coupling performance. Sleep prior to exposure to operational stressors may mitigate the effects of such stressors.

PURPOSE: 1) Examine trait-like aspects of sleep parameters across exposure to simulated military operational stress (SMOS); 2) Examine the impact of baseline sleep on operationally-relevant performance outcomes; 3) Examine the effects of SMOS on perception-action coupling; 4) Examine different aspects of neurobehavioral resilience and differences in baseline sleep between resilient and vulnerable participants

METHODS: 69 active-duty and reserve status military personnel completed a 5-day SMOS protocol that included two days of sleep restriction and disruption. Participants completed assessments of subjective alertness, vigilance, perception-action coupling, marksmanship and physical performance throughout the protocol. 1) Intra-class correlations across different sleep opportunities were calculated for EEG sleep parameters. 2) Habitual and baseline sleep parameters were regressed on marksmanship and physical performance outcomes. 3) Effects of SMOS and time-of-day on perception-action coupling were examined. 4) Participants were classified as resilient or vulnerable using a 2-step decision-making approach that included performance during sleep disruption and change in performance from baseline of different neurobehavioral (alertness, vigilance and perception-action coupling) assessments.

RESULTS: 1) Absolute spectral activity during non-rapid eye movement sleep was stable and robust across variable sleep opportunities during the SMOS protocol (ICC > .6). 2) Baseline aerobic fitness, daytime sleepiness and slow wave activity predicted physical performance but not marksmanship. 3) Perception-action coupling was maintained during typical waking hours (18:00 and 22:00) but deteriorated across days at 04:00. 4) Subjective measures of alertness, and behavioral measures of vigilance and perception-action coupling reflect distinct aspects of neurobehavioral resilience.

CONCLUSION: Individual differences in sleep are maintained across exposure to SMOS, demonstrating the trait-like nature of sleep. Differences in baseline sleep may have implications for operationally-relevant aspects of physical performance and for neurobehavioral resilience. Lastly, perception-action coupling performance is sensitive to the combined effects of SMOS and time-of-day and reflects a distinct aspect of performance from vigilance.

Table of Contents

List of Tables

List of Figures

Preface

Of the many sentences in this document, the sentences in this section are perhaps the most important. Thankfully, they've basically written themselves these past four years. I received more support to get me to this point than I could have ever imagined; there are so many people to thank who helped me throughout this process.

First, I must thank Dr. Dave Thorp and Dr. Brian Higginson who mentored me throughout my time at Gonzaga University. Dr. Thorp not only encouraged my efforts to (successfully) turn the Human Physiology building into a mini-golf course but also provided ever-patient and occasionally sarcastic guidance that led me to first work in a sleep lab and to pursue graduate school and, ultimately, a doctorate degree. I also owe many thanks to the labs I've had the privilege of working in during my time in Pittsburgh: the Neuromuscular Research Laboratory (NMRL), the Military Sleep Tactics and Resilience Research Team (MSTARRT) and the Psychiatry and Neuroscience Laboratory (PyNeL). All the students, research assistants, coordinators, faculty and staff across these labs have made this research possible and have made these past four years enjoyable. I especially want to thank Dr. Caleb Johnson, Dr. Shawn Eagle, Dr. Anne Beethe, Ian Allen, Dennis Dever, Felix Proessl, Maria Canino, Nicole Sekel, Alaska Beck, Leslie Jabloner and my cohort. To my cohort: Dr. Meaghan Beckner, Dr. Will(iam) Conkright, Dr. Kellen Krajewski, and Dr. Aaron Sinnott, it's been a pleasure going through this process with you and I couldn't imagine doing this with another group of people. I wish you all the best going forward. I also want to thank my past and present MSTARRT (Maggie Sphar, Hassan Khan, Megan Wolfson, Jenna Parrish, Wallace) and PyNeL (Sabine Janssen, Rachel Kaskie, Marlee Renard, Ahmad Mayeli, Gonzalo Quinones) co-workers for their support and for making testing my favorite place to be.

I must also thank members of the Sleep and Behavioral Neuroscience Center who assisted in collecting much of the data presented in this work and who taught me much about sleep and running studies. Justin Williams, thank you not only for your help administering tasks and keeping participants awake but also for your endless Googling of dad jokes and fun facts to help pass the time. Dan Limpert, thank you for letting me pick your brain about sleep scoring and for always having a stash of candy. Eric Miller, the fastest wire-up in Western Psych, thank you for keeping us on time even when we were running late and for all of the coffee, conversations and guidance. To David Cashmere, I've appreciated your support and attention to detail to ensure data was collected and processed properly.

The Sleep and Circadian Science T32 seminars have also had a huge impact on my training and on my time in Pittsburgh. To all of the past and present trainees thank you for all of your guidance and support throughout the years. In particular, I want to thank the writing group (Eunjin Lee Tracy, Michelle Stepan and Amy Hartman) for providing accountability during this final stretch. I also must thank Linda Willrich, Dan Buysse and Tica Hall for all of the work they do to organize and lead the T32. It's been quite the past year and I appreciate the time you've taken to discuss my boxes and arrows despite everything that was going on.

To my committee, I really can't thank you enough. Dr. Qi Mi, thank you for your willingness to always talk about different statistical approaches to address a research question without losing the question in the process. Dr. Shawn Flanagan, I appreciate your enthusiasm for research and your attention to detail especially in writing. To Dr. Fabio Ferrarelli, Dr. Anne Germain and Dr. Chris Connaboy, I couldn't imagine a better advising team; there is no group I would rather have my back. Dr. Ferrarelli, thank you for always taking the time to talk through statistical analyses and data and for walking me through your thought process; I have learned so

much from our discussions. Don't tell anyone, but I actually appreciate your dad jokes. Dr. Germain, thank you for your unwavering support: from lab Hawaiian shirts (even though you thought they were ugly) to talking through different analyses to reminding me that I am my harshest critic. Thank you for always making time to talk and for always checking on Dog and Wally. Dr. Connaboy, thank you for your support since day -1, I really can't thank you enough for all you've done for me throughout my time at Pitt. You encouraged me to stay in Pittsburgh and to pursue studying sleep, both of which worked out pretty well. Thank you for your constant guidance and encouragement and for letting me borrow your nerf guns. My writing breaks over these final weeks were generally nerf gun inspired.

There are countless other people who have provided moral support throughout this process. My various roommates: Regina Stump, Jordan Lane, Skylar Cottrell, Cecile Garfunkel, Matt Stanziola, Matt Farago (honorary) and Rachel Stanziola have provided many study breaks needed to maintain some semblance of work-life balance. Rachel, thank you for being my hype man, street badminton opponent and collaborator on all of our non-work-related projects, no matter how ridiculous they may sound when we say them out loud. With that, I must also thank Social at Bakery Square (Chris Kuhn and Ben Burke) and our neighbors (especially Michael Bonidie and Nora Bates) who were/are the most frequent victims/most outspoken supporters of our various endeavors from fake axe-throwing leagues to pop-up ice cream shops and everything in between. Lastly, I need to thank my family for all of their support and understanding throughout this process and for withstanding the less than riveting phone calls and substantial delays in text responses. A huge thank you to my siblings (Charlie and Sam LaGoy; Christina and Dylan Campbell), sister-in-law (Kaylee Morris), niece/nephews (Cora and Eliot Campbell), stepmom (Amanda Maffei)

and parents (Patty and Peter LaGoy), I can't put into words how much I love and appreciate you all. And with that, hashtaggozags.

1.0 Introduction

The importance of sleep to individual well-being and performance has recently gained increased appreciation in the military. Healthy sleep was identified as essential for ensuring resilience and readiness in the National Defense Authorization Act for fiscal year 2015[1] and, along with nutrition and physical activity, was identified as an essential component of health in the Army Medicine's Performance Triad[2]. More recently, the Government Accountability Office released a report highlighting the importance of addressing sleep loss and fatigue in Naval Surface Fleet personnel while also highlighting that current work demands and staffing shortages compromise the ability to obtain sufficient sleep[3]. The recent emphasis on sleep stems from the high prevalence of insufficient and disturbed sleep in military personnel, the increased appreciation for the importance of sleep to health and performance and from recent sleep loss-related accidents that, unfortunately, clearly demonstrated the operational and safety implications of insufficient sleep[3–8]. Still, operational demands often compromise the ability of military personnel to obtain sufficient sleep. The high pace, around-the-clock and unpredictable nature of operational settings contribute to abbreviated sleep opportunities occurring at different times-of-day[5,9]. These non-traditional sleep schedules that do not align with intrinsic circadian rhythms may further compromise sleep by increasing sleep fragmentation and decreasing sleep quality[10].

Sleep is a multifaceted biological process that contributes to mental and physical health, recovery and performance[11,12]. Chronic poor sleep can contribute to negative mental and physical health outcomes including increasing risk of posttraumatic stress disorder, musculoskeletal injury, cardiovascular disease, diabetes and all-cause mortality[5,13–16]. Additionally, acute exposure to insufficient sleep, such as during sleep deprivation or restriction, can compromise performance and safety[17–19]. One night of poor sleep can decrease mood[20,21], compromise cognitive and physical performance[17,19,22–24], impair muscle recovery[25–27] and negatively affect metabolic function[28–30]. In military personnel[5,10,31] who must perform at a high level despite short and poor quality sleep, sleep loss-related decrements can have pronounced effects on job-related performance[32,33].

Not only do operational demands impact the ability of military personnel to obtain sufficient sleep, but these demands may influence sleep architecture, having implications for the functional role of sleep. Sleep is a dynamic process that varies between and within nights. Within a single night, sleep cycles through different stages: non-rapid eye movement (NREM; see Appendix A for a complete list of abbreviations) stage 1 (N1), stage 2 (N2), stage 3 or slow wave sleep (SWS) and rapid-eye movement (REM) sleep. SWS, a marker of homeostatic sleep need, occurs primarily during the first half of the night when the homeostatic drive for sleep is high. SWS is characterized by slow wave activity (SWA; 0.5 – 4 Hz) and collectively, these aspects of sleep may relate to cognitive and visuomotor performance[34–36]. Conversely, N2 and REM sleep occur primarily during the second half of the night as the homeostatic drive for sleep dissipates and are more strongly influenced by circadian processes[37–39]. Between nights, sleep architecture (the timing and duration of sleep stages) can vary based on homeostatic sleep need and circadian influences related to sleep timing. For example, extended wakefulness during total sleep deprivation protocols increases the homeostatic drive for sleep which contributes to subsequent increases in SWS[37]. Sleep loss and variable sleep schedules in operational settings may therefore impact sleep architecture. However, substantial inter-individual differences in sleep exist which may impact how an individual's sleep responds to operational settings[40,41]. Inter-individual differences in the build-up and decay of homeostatic sleep pressure are stable across repeated bouts of sleep deprivation[42]. Whether this trait-like behavior of sleep is stable across operationally-relevant sleep manipulations is unknown. Further, whether this trait-like behavior is consistent across individuals with different baseline characteristics known to influence sleep, such as trauma exposure and resilience is unknown[43,44]. Military personnel in the field are exposed to sleep loss, circadian challenges, caloric restriction, high cognitive load and physical exertion. These stressors collectively referred to as military operational stress can have a pronounced impact on the sleep of military personnel throughout training and deployment. Inter-individual differences in sleep may reflect inter-individual differences in responses to exposure to operational stress.

Exposure to military operational stress, in the field and simulated in laboratory settings, can also compromise cognitive and physical performance[18,45]. Sleep loss, caloric restriction, cognitive load and physical exertion individually have decremental effects on performance. Additionally, decrements in mood, vigilance, working memory, reasoning, marksmanship and physical performance are observed following periods of field training with prolonged exposure to operational stressors[45–48]. Field studies provide valuable information about the real-world implications of military operational stress, but the lack of experimental control in such environments makes it difficult to quantify the magnitude of specific stressors. Simulated military operational stress (SMOS) protocols impose similar stressors on individuals and provide greater experimental control. Such protocols have also revealed decrements in cognitive and physical performance similar to those experienced in training environments[49]. Collectively these findings demonstrate decremental effects of military operational stress, in field and laboratory settings, on neurobehavioral function (mood, vigilance), cognitive function (working memory, reasoning) and operational performance (marksmanship, physical performance)[18,45,49,50]. Still, the impact of operational stress on the ability to adapt to changing environmental conditions or tasks demands, an essential aspect of operating with dynamic and unpredictable operational settings, remains unknown. Perception-action coupling, the ability to efficiently and accurately execute motor responses coupled to perception information, allows an individual to respond to changes within their environment[51,52]. Impaired perception-action coupling could impact how individuals maneuver through and respond to their environment, thereby increasing behavioral risk and compromising operational efficiency[51,53]. Therefore, examining perception-action coupling within military operational stress scenarios is an essential future direction of study. Perception-action coupling may be compromised by physical exertion[54] and sleep loss[55,56] but it is unknown whether cumulative exposure to military operational stressors influences perception-action coupling. It is further unknown if perception-action coupling is influenced by time-of-day, as essential research question given the around-the-clock nature of military operational settings[5]. Lastly, examining the relationship between perception-action coupling (a functionally-relevant measure of alertness) and more widely used measures of neurobehavioral function would provide additional insight into the effects of operational stress on military personnel.

In response to sleep loss, robust inter-individual differences exist in mood, neurobehavioral performance, cognitive performance and operationally-relevant aspects of performance[57–59]. Similarly, individuals may display different levels of neurobehavioral resilience or vulnerability to military operational stress; individuals who demonstrate more neurobehavioral resilience to stress exposure may be able to maintain high levels of performance despite stress exposure while more vulnerable individuals may experience a dramatic deterioration of performance, alertness and mood These differences may reflect trait-related differences in neurobehavioral resilience or vulnerability to sleep loss[60]. Given the functional importance of sleep, sleep may contribute to neurobehavioral resilience to military operational stress. In particular, prior sleep history may impact the susceptibility of an individual to sleep loss. Further, sleep throughout the SMOS exposure may impact an individual’s ability to adapt or recover from the SMOS exposure. To what extent inter-individual differences in sleep contribute to inter-individual differences in operational and neurobehavioral resilience is unknown.

1.1 Definition of the problem

In the field, military personnel are exposed to military operational stress which includes sleep loss, caloric restriction, physical exertion and high cognitive load. Exposure to military operational stress can impact the sleep and performance of military personnel. It is unknown to what extent the trait-like behavior of sleep is maintained throughout military operational stress and to what extent these stable inter-individual differences in sleep may predict inter-individual differences in resilience on neurobehavioral and operational performance outcomes. Further, the extent to which baseline characteristics, such as trauma exposure and psychological resilience may impact the response of sleep through exposure to operational stress. The purpose of the present dissertation is to examine the role of sleep on resilience during a SMOS protocol that included sleep restriction and disruption, caloric restriction, daily physical exertion and a high cognitive load.

1.2 Specific Aims

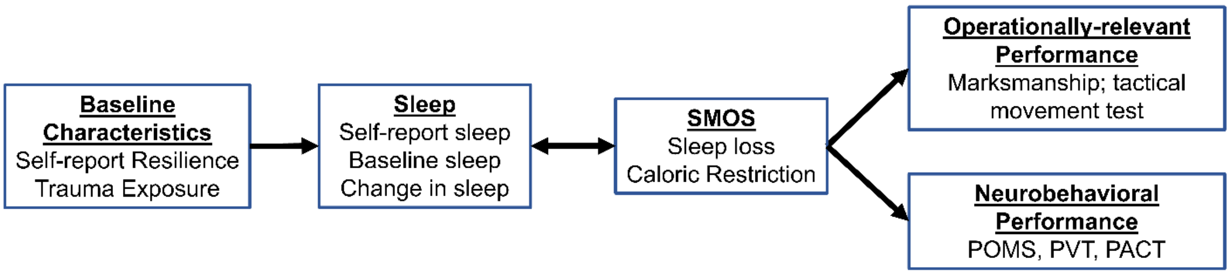

Figure 1: Conceptual model of dissertation aims

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1.2.1 Aim 1

To determine the effects of SMOS on the stability and robustness of objectively-measured sleep parameters and to examine the effects of baseline characteristics, specifically self-reported resilience and trauma history, on the stability and robustness of sleep across SMOS exposure.

Hypothesis 1a: SWS, and absolute and relative NREM spectral activity will demonstrate stable and robust trait-like behavior across the SMOS protocol while measures of sleep architecture will be less stable across the protocol.

Hypothesis 1b: Trauma exposure and self-report resilience will impact the stability of sleep measures during SMOS. Participants with high trauma exposure and low resilience will demonstrate lower sleep stability than participants with low trauma exposure and high resilience.

1.2.2 Aim 2

To determine whether habitual (PSQI), baseline (night 1 EEG measures) and changes in sleep (change in EEG measures from night 1) influence resilience to SMOS (sleep loss and caloric restriction) as assessed using operationally-relevant tasks (marksmanship and physical performance).

Hypothesis 2a: PSQI scores, baseline SWA, and baseline REM will predict performance on marksmanship and physical performance outcomes on days 2, 3 and 4.

Hypothesis 2b: Changes in SWA and REM from baseline to nights 2, 3 and 4 will predict performance on marksmanship and physical performance on days 2, 3 and 4.

1.2.3 Aim 3

To determine the effects of SMOS on perception-action coupling performance across different times of day (04:00, 18:00, 22:00).

Hypothesis 3a: Affordance actualization efficiency and affordance perception accuracy will deteriorate across increased exposure to simulated military operational stress.

Hypothesis 3b: Affordance actualization efficiency and affordance perception accuracy will be worse at 04:00 than at 18:00 or 22:00.

1.2.4 Aim 4

To determine whether subjective and objective measures of alertness (Profile of Mood States, POMS; Psychomotor Vigilance Task, PVT; and Perception-action Coupling Task, PACT) reflect distinct aspects of neurobehavioral resilience and to quantify differences in habitual (PSQI, ISI, ESS) and baseline sleep (SWS, REM and SWA) between resilient and vulnerable participants across different neurobehavioral measures.

Hypothesis 4a. Subjective and objective measures of alertness will reflect distinct aspects of neurobehavioral resilience. Limited overlap will be observed between functional measures of alertness that capture vigilance (PVT) and perception-action coupling performance (PACT).

Hypothesis 4b. Participants with high neurobehavioral resilience, as defined by POMS, PVT and PACT will have better habitual sleep quality (lower PSQI scores) and higher baseline SWA than individuals with low neurobehavioral resilience. Resilient and vulnerable groups will not differ in other sleep architecture parameters.

2.0 Review of the Literature

2.1 Sleep and Military Operational Stress

Military operational stress includes sleep loss, caloric restriction, high cognitive load and physical exertion. Insufficient sleep is highly prevalent across different branches and operational settings. Military personnel often get less than 7 hours of sleep, report poor sleep quality and report getting disrupted sleep[32,61–65]. For example, while approximately 33% of American adults get insufficient sleep weekly, 57% of Naval personnel reported obtaining insufficient sleep (less than 7 hours per night) when surveyed mid-deployment[66]. Of note, more prior deployments and longer deployment duration both predicted worse sleep in these Naval personnel, independent of age and military rank demonstrating the decremental effect of cumulative exposure to operational settings may have on sleep[66]. The sleep of military personnel is compromised by operational demands which can limit sleep opportunity duration and impact sleep opportunity timing[5]. Operational work schedules often require extended shifts (> 12 hours) that curtail or may interrupt sleep opportunities. Similarly, around-the-clock operations necessitate that some military personnel will be sleeping during the day, when the circadian drive for sleep is low. As such, the quality of sleep at this time may be lower than that would be obtained during overnight sleep. Additional environmental factors, such as shared bunk space, ambient light and noise related to around-the-clock operations can also further compromise sleep in operational settings[64,67]. Insufficient sleep in operational settings has a decremental effect on military personnel; more sleep complaints in operational settings predict decreased well-being[68,69] and increased sleepiness[62], fatigue, musculoskeletal injury[14,62] and operational risk[32,33,70].

Further, military personnel often operate at a caloric deficit in the field due to the combined effects of caloric restriction and high physical demands of training and deployment[71]. Caloric intake may be restricted in the field due to limited food ability and space limitations related to carrying food[71]. This caloric restriction can then be compounded by physical demands that exceed those typically experienced by civilian populations. Across different roles, operations, and branches military personnel expend upwards of 3000 kcal per day[71,72]. The caloric deficit caused by this high energy expenditure and limited caloric intake can have substantial implications on physiological function, mood, cognitive performance and physical performance, within operational settings[71–73]. Importantly, the above-mentioned stressors act simultaneously on military personnel to impact their performance and safety within operational settings.

2.2 Sleep

2.2.1 Sleep stages and features

Sleep can be measured subjectively using questionnaires, behaviorally using actigraphy or objectively using polysomnography (PSG) and neuroimaging. PSG is the gold standard means of assessing sleep and includes electroencephalography (EEG), electrooculography (EOG) and electromyography (EMG)[74]. Sleep stages (NREM N1, N2, SWS and REM) can be defined by particular PSG signatures which reflect the different characteristics of each sleep stage[74]. Additional information regarding sleep can be provided by examining the spectral profile of the PSG record through quantitative EEG[75]. Power spectral analysis provides information about EEG activity during NREM and REM sleep in the delta (0.5 – 4 Hz), theta (4 – 8 Hz), alpha (8 – 12 Hz), sigma (12 – 16 Hz) and beta (16 – 32 Hz) ranges. Delta activity can also be referred to as slow wave activity (SWA). Collectively, information about sleep stages and the spectral composition of sleep provides a comprehensive picture of an individual's sleep.

Light sleep includes N1 and N2. N1 sleep is the lightest stage of sleep occurring predominantly during sleep-wake transitions (~6% of total sleep time)[74,76]. Much of N1 sleep consists of alpha (8 – 12 Hz) activity particularly in occipital regions. N2 sleep is the most prominent sleep stage throughout the night (~50% of total sleep time)[76]. In particular, N2 sleep occurs predominantly during the second half of the night. N2 sleep is defined by two EEG features: K-complexes and sleep spindles. K-complexes are high amplitude, low-frequency waves that occur spontaneously or can be elicited by sensory stimulation and input[77,78]. In response to ambient noise, or other environmental sensory stimuli, k-complexes may reflect sensory gating occurring between the cortex and thalamus allowing individuals to maintain sleep despite such disturbances[77]. Sleep spindles, which occur predominately during N2 and to a lesser extent SWS, are short duration (0.5 – 3 s), high-frequency bursts (~9 – 16 Hz) of activity that are generated in the thalamus and modulated by cortico-thalamic inputs[79,80]. Spindles contribute to both, cognitive and sensorimotor function[81–84], potentially through use-dependent reactivation of specific neural pathways and by contributing to synaptic potentiation. Disrupted spindle activity predicts poor cognitive function and compromised visuomotor function[85]. Further, higher local spindle density predicts greater offline motor learning and increasing spindle density through transcranial alternating current stimulation during sleep leads to improved sensorimotor performance[86–88]. Spindles are further divided into slow (~9 – 12 Hz) and fast (~12 – 16 Hz) spindles which have distinct topographical distributions, occur during different sleep stages and at different times of night[80,89]. Slow spindles are coupled with slow waves and therefore occur predominately in frontocentral brain regions during the first half of the night[89]. Their functional role is not well defined but they may influence perceptual capabilities and sensorimotor function by contributing to visual discrimination performance [89,90]. Increased slow sigma activity in occipital regions, overlying the visual cortex, predicted better visual discrimination performance[90] but this finding was not found across similar studies[91]. Fast spindles appear predominantly in parietocentral brain regions during the second half of the night[80,89] and are associated with motor aspects of sensorimotor performance including motor learning[92,93] and visuomotor performance[94,95].

SWS is considered deep sleep and occupies ~15-20% of the night in adults with normal sleep but decreases with aging[76]. SWS is defined by the presence of slow waves, low frequency (0.5 – 4 Hz), high amplitude (> 0.75 μV) waveforms that typically present most prominently in frontal EEG channels and propagate posteriorly[96,97]. As such SWS consists largely of SWA. Slow oscillations are generated from the synchronized hyperpolarization and depolarization of cortical neurons which result in alternating periods of coordinated increased firing and cessation of firing; this rhythmicity allows slow oscillations to coordinate activity across different brain regions[79]. Slow wave slope and amplitude reflect the strength and synchrony of synaptic firing, respectively[98–100]. The up slope occurs during depolarization and periods of coordinated firing while the down slope occurs during hyperpolarization and periods of neuronal silence.

SWS, SWA, and slow wave features reflect homeostatic sleep need and contribute to use-dependent plasticity (although the mechanisms of this contribution are debated[101–104]). SWS, SWA and slow wave slope and amplitude increase following periods of extended wakefulness and decrease exponentially throughout the night as the homeostatic drive for sleep decreases (see Section 2.2.2 below). As decreased synaptic strength, marked by cortical excitability, is associated with changes in slow wave parameters, synaptic depotentiation and the maintenance of synaptic homeostasis have been proposed as essential functions of SWS[101,105,106]. Further, SWS, SWA and slow wave features change in a use-dependent manner between nights suggestive of roles in cognitive and sensorimotor function[105,107]. Following a period of learning or skill-acquisition, SWA, slow wave slope and slow wave amplitude increase in task-specific regions[35,36,108,109]. SWA increased over sensorimotor regions following practice of visuomotor tasks[36,110,111] but decreased over sensorimotor regions following arm immobilization[112]. Further, the causal relationship between SWS and cognitive and sensorimotor function has been demonstrated through SWS/SWA enhancement and depression studies[113–118]. SWS enhancement through auditory[119–122] and transcranial direct current stimulation[34,123–126] stimulation phase-locked to the up slope of slow waves, has consistently resulted in improved declarative memory (but see [127,128]). Additionally, SWA depression, through auditory tones, compromised perceptual learning[129] and visuomotor adaptation[110]. Together, these findings suggest a causal role of SWA in sensorimotor adaptation and learning. Slow waves may also coordinate function across different brain regions through coupling with sleep spindles and hippocampal sharp wave ripples (80 – 100 Hz oscillatory features from the CA1 hippocampal region)[102,130]. Coupling strength between slow waves and spindles may contribute to cognitive function[131–133], but a role in sensorimotor or physical function has not been found[134]. Altogether SWS plays an important restorative function, contributes to the maintenance of synaptic homeostasis and relates to different aspects of performance that may be relevant to military personnel.

REM sleep displays distinct EEG activity patterns from NREM sleep and plays different, but complementary, functional roles. Mixed frequency, low amplitude EEG activity, muscle atonia (measured from the submentalis), and rapid eye movements characterize REM sleep which occurs predominantly during the second half of the night in the early morning hours[74]. Upregulation of plasticity promoting factors and the occurrence of ponto-geniculo-occipital (PGO) waves also characterize REM sleep and the transition from NREM to REM[104,135]. REM sleep plays several important functions: emotional memory consolidation[135,136], sensorimotor development[137,138], sensory renormalization[139,140] and learning of novel information[139,141]. The importance of REM sleep to emotional memory consolidation has long been hypothesized due to the role of disrupted REM sleep in psychiatric disorders such as PTSD[142]. More recently, improved emotional memory consolidation was found to be predicted by more REM theta activity[135]. Further, sensorimotor development and the early integration of the sensory and motor systems occurs during REM sleep[137,138]. To what extent REM sleep contributes to sensorimotor function during adulthood is unknown although more time in REM sleep predicted better motor control performance[143] (but see [144]).

REM sleep may also impact cognitive and sensorimotor performance through targeted depotentiation. Following exposure to novel information or places, hippocampal neurons fire at peaks of REM theta oscillations, promoting synaptic potentiation[104]. Following repeated exposures to this same information, the relevant hippocampal neurons instead fire at the troughs of REM theta oscillations promoting synaptic depotentiation; information that has been learned and transferred to the cortex no longer needs to be stored in the hippocampus[104]. Sensory renormalization may occur through similar means of REM-related synaptic depotentiation[104,139,145]. Visual and perceptual discrimination abilities deteriorate throughout wakefulness, even without severe wake extension[146]. This deterioration may be related to synaptic strengthening that occurs throughout wakefulness which increases the signal to noise ratio[101]. If REM sleep contributes to depotentiation of these spurious synaptic connections, then REM may help to renormalize and restore these sensory discrimination abilities. Perceptual discrimination was restored following naps that contained both SWS and REM, but not after naps that only contained SWS lending support to the importance of REM sleep in sensory renormalization[140]. Further, in monkeys trained on a somatosensory task, the receptive fields of the trained fingers were only normalized in monkeys that experienced both SWS and REM, demonstrating that REM sleep is needed for depotentiation in these sensory areas of the brain[139]. Whether the restoration of visual discrimination abilities through REM has implications for target identification relevant for marksmanship in operational settings is an intriguing possibility.

2.2.2 Sleep-wake regulation

Sleep is predominantly regulated by 2 processes: a homeostatic sleep process (process S) and a circadian process (process C)[37,147]. In brief, as the duration of wakefulness increases throughout the day, the homeostatic drive for sleep increases exponentially. Initially, the circadian drive for wakefulness also increases throughout the day to oppose this increase in homeostatic sleep drive and maintain wakefulness. As the day processes and habitual bedtime is approached, the circadian drive for wakefulness decreases thus promoting sleep. Conversely, when as individual is asleep, the homeostatic drive for sleep decreases throughout the night. Again, the circadian drive for wakefulness acts counter to the homeostatic drive for sleep and decreases throughout the night to help maintain sleep. As typical wake time approaches in the morning, the circadian drive for wakefulness increases to promote waking. Homeostatic and circadian processes work interactively to promote consolidated sleep and wake periods throughout the day[37,39]. This combined regulation of sleep impacts the macro- and micro-architecture of sleep and has implications that extend to other aspects of health, performance and function.

Sleep stages and features are sensitive to homeostatic and circadian processes. Most prominently, SWS and SWA have been characterized as indexes of homeostatic sleep drive[37]. SWA occurs primarily during the first half of the night, when homeostatic sleep drive is high and dissipates throughout the night across multiple sleep cycles in accordance with reduced homeostatic sleep pressure. Further, SWA increases following periods of extended wakefulness which increase homeostatic sleep drive. While the original 2-process model was conceptualized based on global sleep and wakefulness, there is now greater appreciation for local and use-dependent aspects of sleep and wakefulness[37,148]. As mentioned above, SWA increases in a use-dependent manner following periods of increased cognitive or physical engagement which reflects local homeostatic regulation of sleep[149,150]. Given that military operational stress involves sleep loss, high cognitive load and physical exertion, increases in SWA would be expected[149,151]. To what extent individual differences in SWA throughout exposure to operational stress impact resilience or recovery from the stress in unknown. SWA may serve as a marker of resilience and an ability to recover quickly from the stress scenario or it may serve as a marker of increased sleep need and greater vulnerability to the stress[152,153]. Further work is needed to examine beneficial and maladaptive responses to military operational stress and how these responses manifest themselves in SWA.

Operational settings may also impact the timing of sleep. While some work has suggested a circadian influence of SWS[154], the circadian system has a more pronounced influence on REM sleep due to indirect projections from the suprachiasmatic nucleus (SCN) to REM-promoting brain stem regions[39]. The SCN is the central pacemaker that coordinates circadian processes throughout the body. To what extent circadian regulation of sleep impacts different aspects of sleep within operational settings in unclear.

2.2.3 Interindividual stability of sleep

While sleep manipulations result in significant changes in sleep, differences between individuals are consistently greater than the magnitude of changes within individuals. These inter-individual differences in sleep have been characterized as having 'trait-like' behavior due to: 1) their genetic underpinnings[155,156]; 2) their stability across multiple nights of normal sleep[40,157,158]; and 3) the robustness of these differences across experimental manipulations[157–159]. While not consistent across all sleep architecture measures, SWS and NREM spectral activity demonstrate high levels of stability across multiple nights of normal sleep and before and after a night of total sleep deprivation[40,60,155,157,160,161]. This stability has been observed regardless of age[157,162] and in both healthy sleepers and individuals with insomnia[40].

Sleep spindles in particular have been classified as 'the fingerprint' of sleep[41,155]. There are pronounced individual differences in sleep spindles that are in part genetically-determined and are robust across a variety of sleep manipulations[41,155]. Specifically, high stability in a spectral range encompassing slow and fast spindles (8 – 15 Hz) was observed across 6 nights including an adaptation night, baseline night, night of sleep disruption, 2 nights of SWS deprivation and a recovery night[41]. A recent study has expanded these findings to demonstrate that the specific frequency profile, topographical distribution and phase-coupling with slow waves are also unique to an individual[80,134].

SWA and spectral activity across all frequency bands also demonstrate trait-like behavior across normal sleep and before and after total sleep deprivation[40,157], although few studies have examined the stability of high frequency activity[40]. SWS displays substantial stability (ICC > .6) across a variety of sleep manipulations: multiple nights of normal sleep[157,158], before and after nights of total sleep deprivation[157,159], across nighttime naps[158], and across variation in sleep timing[159]. Additionally, homeostatic responses to sleep, as indexed by SWA, are also stable across repeated bouts of total sleep deprivation[42]. The rate and topographical progression of SWA dissipation is stable within individuals[42,163,164]. An intriguing possibility is that individuals with rapid dissipation of SWA may be better able to adapt to operational environments. The rapid dissipation of SWA may reflect more efficient recovery from the prior day enabling individuals to be more resilient to sleep loss.

While the trait-like nature of sleep has been widely demonstrated, several gaps remain. First, while the stability of spectral sleep parameters and sleep spindles persists across nights of normal sleep, whether this stability persists across more variable sleep opportunities remains less clear. Two studies have demonstrated that SWS remains stable across different sleep durations (40-minute, 5-hour, 8-hour) and timing (night vs day), but it is unclear how other sleep parameters behave under such conditions[158,159]. Further, in groups of adolescents exposed to different sleep conditions (5-hour, 9-hour), NREM SWA and fast sigma spectral activity were less stable in the sleep restriction group (5-hour) than the control group (9-hour), but stability across the different sleep conditions was not examined within a single group[165]. Understanding how sleep varies within and between individuals across simulated military operational stress may not only provide greater insight into the robust trait-like nature of sleep but may also inform how sleep relates to resilience and adaptability during such exposures. Two intriguing possibilities exist: 1) trait differences in sleep may relate to trait differences in resilience across different tasks; or 2) differences in how sleep adapts during operational stress may relate to differences in adaptability and resilience to the stress scenario. A second critical gap is in understanding how baseline characteristics may impact the trait-like nature of sleep. Relevant to military personnel would be examining the effects of trauma exposure and psychological resilience on sleep stability. Trauma exposure and low psychological resilience are both related to sleep quality[43,44]. Whether high resilience may mitigate decremental effects of trauma exposure on sleep is unknown.

2.3 Performance during military operational stress

In addition to impacting sleep, military operational stress can impact operational performance. Exposure to individual stressors (e.g., sleep loss, caloric restriction, cognitive load, physical exertion) can compromise operationally-relevant aspects of performance including marksmanship and physical performance. Further, operational stress, in field and laboratory settings, has pronounced effects on cognitive and neurobehavioral aspects of performance that underlie operational performance. Given the focus of the study aims, the effects of operational stress on cognitive performance are not reviewed here (but see [50,166]). Assessment of neurobehavioral aspects of performance provides additional insight into how operational stress impacts specific components of operational performance, thereby identifying potential intervention targets. Further, given the short duration and portable nature of neurobehavioral assessments, these tests can be used in the field to monitor fatigue, predict at-risk performance and plan intervention administration.

2.3.1 Impact of military operational stress on operational performance

Marksmanship: Marksmanship, an essential aspect of military performance, is a complex sensorimotor task that involves, among other functions, reaction time, visual discrimination and tracking, perceptual attunement and perception-action coupling[167,168]. As such, operational stress may alter marksmanship by affecting any one of a number of underlying cognitive and sensorimotor processes[111,169]. Deficits in marksmanship accuracy have been observed with increased cognitive load during and prior to the marksmanship task[170,171] and following physical exertion[172]. Further, operational stress and sleep loss may have decremental effects on marksmanship accuracy and reaction time[46,170,173,174], although effects have been inconsistently reported[48,175,176]. Marksmanship accuracy decreased while shot distribution variability increased following 73-hours of Hell Week in 62 Navy SEALs who obtained approximately 1-hour of sleep at the time of marksmanship testing[46]. Conversely, marksmanship accuracy was maintained across 72-hours of SMOS in 10 male Soldiers that involved severe sleep loss (total sleep time ~ 3.6 hours) and caloric restriction (caloric intake ~ 1600 kcal)[48]. The inconsistency between studies may be related to differences in study populations, marksmanship protocols and severity of the operational stress exposure. In military populations, marksmanship is a well-learned task; military personnel may be able to maintain overall marksmanship accuracy despite exposure to operational stressors due to the habitual nature of the task. Examining the distribution of shots has been proposed as a more sensitive marker of marksmanship performance, especially in well-trained individuals[177].

Physical Performance Outcomes: Military operational stress may compromise physical performance, thereby impacting overall operational efficiency, although findings across different domains of physical performance are inconsistent[18,178]. Performance of submaximal, muscular and aerobic endurance tasks is impaired by military operational stress and sleep loss while anaerobic performance may be less affected[48,179–182]. During a simulated combat exercise, five nights of sleep restricted to 5-hours resulted in higher (slower) 2-mile run times in 34 infantry Soldiers as part of a simulated combat exercise, but these same individuals were able to maintain performance on a Wingate test assessing lower-body anaerobic capacity[180]. Caloric restriction may also contribute to compromised physical performance in operational settings[71]. During a 5-night sleep restriction protocol, male Soldiers in control (3200 kcal/day) and high (4200 kcal/day) caloric intake groups were able to maintain aerobic endurance while the performance of Soldiers in the low caloric intake group (1800 kcal/day) deteriorated[181]. Similar decrements in aerobic endurance were observed following 96-hour continuous operations in individuals consuming reduced calories, but again endurance was maintained across the stress exposure in moderate and high caloric intake groups [181]. Decrements to other aspects of physical performance including power and muscular strength are also observed[180,183,184] but findings are inconsistent[179,183].

2.3.2 Impact of military operational stress on alertness/neurobehavioral performance

Subjective Measures of Alertness: Similar to the effects of isolated sleep loss[20], subjective feelings of alertness and mood are particularly sensitive to operational stress[45,62,185]. Subjective alertness includes sleepiness, fatigue and vigor which reflect similar but separate constructs. Sleepiness relates to biological sleep need and is defined as sleep propensity or drowsiness while fatigue is defined as weariness or exhaustion after periods of pronounced effort[186]. Sleepiness and fatigue, while weakly correlated, do not necessarily overlap; individuals with high sleepiness do not necessarily also present with high fatigue and vis-a-versa[186]. It is unclear to what underlying mechanisms may relate to differences in sleepiness or fatigue or to what extent sleepiness and fatigue impact performance differently.

High sleepiness, high fatigue and low vigor are prevalent in operational settings[62,186]. Underway aboard an aircraft carrier, 32% of Naval personnel surveyed reported excessive daytime sleepiness on the Epworth Sleepiness Scale (ESS > 10), a questionnaire used to identify clinically-meaningful levels of sleepiness[62]. Sleepiness and fatigue increase while vigor decreases across chronic and acute exposures to military operational stress in field and laboratory settings[9,45,47–49,62,187]. Fatigue, measured on the POMS, increased by 465.8% and 148.3% across a 73-hour combat training exercise in 31 Army Rangers and across 73-hours of Hell Week in 16 Navy SEALs respectively[45]. In the same two samples, vigor decreased by 75.2% (Army Rangers) and 53.0% (Navy SEALs). Of note, the Navy SEALs started with a higher fatigue and lower vigor than the Army Rangers. Army Rangers obtained approximately 3 hours of sleep while Navy SEALs obtained approximately 1 hour of sleep across the operational exposures which involved nearly continuous cognitive and physical tasks; information about caloric intake was not provided[45]. Similar deficits in POMS fatigue and vigor were observed during a 84-hour SMOS protocol involving 6-hours of disrupted sleep, continuous military-specific tasks and caloric restriction in 13 individuals[49].

High prevalence of decreased alertness, excessive sleepiness and fatigue in operational settings may contribute to additional decrements in performance that have implications for operational efficiency and safety[62,188]. High daytime sleepiness aboard a Naval surface warfare ship was correlated with shorter sleep duration and was related to complaints of musculoskeletal injuries that limited normal activities [62]. In a separate sample of 69 Naval crewmembers underway, high daytime sleepiness predicted worse performance on the PVT[188].

Behavioral Measures of Alertness: Military operational stress also has a substantial effect on behavioral measures of alertness which typically include an assessment of reaction time and vigilance. The psychomotor vigilance test (PVT), a 10-minute assessment of sustained attention and reaction time, is the gold standard measure used to assess changes in alertness and vigilance in the sleep field and is sensitive to total sleep deprivation, sleep restriction and variation in habitual sleep duration[19,189–193]. Sleep loss results in slowed reaction times, more lapses and more variability in reaction times thought to reflect greater state instability[190,191,193,194]. Additionally, the PVT is sensitive to variations in circadian timing, of particular relevance to military personnel conducting around-the-clock operations[195–197]. PVT performance is worse, indicative of lower alertness, overnight when the circadian drive for wakefulness is low. Sleep loss-related decrements in PVT performance, and alertness, may be related to reduced activation in frontal brain regions and greater instability in default mode activity[198,199]. Increased local sleep (including local-sleep like occurrences of slow waves during wakefulness) and more neuronal silent periods may also contribute to reduced PVT performance and lapses of attention[200,201].

Given the sensitivity of the PVT to sleep loss and time-of-day, and the relevance of these factors to operational settings, many studies examining the effects of operational stress on performance capabilities in real world settings have used the PVT to assess performance[63,188]. While the effects of sleep loss on alertness assessed with the PVT have been consistent, decrements related to operational stress have been less consistently reported. In 20 Special Operations personnel completing simulated nighttime operations, with sleep restricted to 4-hours each afternoon, PVT performance was worse during overnight hours consistent with sleep loss literature[176]. Conversely, limited decrements in PVT performance were found for experienced mariners during 28 days at sea[202] and for experienced submariners during 67 days at sea[65]. Further, circadian-related variation in the PVT was not observed in the mariners[202]. Interestingly, minimal changes in mood and subjective sleepiness were also observed in the submariners despite high prevalence of short and fragmented sleep[65].

Perception-Action Coupling: An essential aspect of neurobehavioral performance not captured by traditional assessments, is the ability to adapt to changing task demands and environmental characteristics. Operational efficiency requires not only the ability to adapt quickly, captured by reaction time measures such as the PVT, but also the ability to react appropriately. Specifically, while the PVT is a sensitive measure of an individual's ability to attend to a stable environment and respond quickly, it does not capture an individual's ability to respond to changing environmental conditions or task demands. quantifies the ability of individuals to adapt to their environment.

Perception-action coupling refers to the ability to perceive task-relevant information about the environment and to couple this information with an appropriate and efficient motor response which enables individuals to 'read and react' to changing action possibilities within their environment[51,52,203]. These action possibilities, which depend on individual capabilities, environmental characteristics and the interaction between the individual and their environment are affordances[204]. Perception-action coupling relies on accurate perception of affordances and efficient actualization of affordances. If individuals do not accurately perceive afforded behavior, they may attempt action that is not possible or not attempt action that is possible. Further, if individuals do not react in an efficient manner, they may not respond until after the afforded behavior is no longer available. Either of the aforementioned outcomes may increase behavioral risk and impact the ability of an individual to successfully and safely operate within their environment[53,205]. Improved perception-action coupling abilities may contribute to operational efficiency and movement behaviors. Further, assessment of perception-action coupling in operational settings may provide a more functional assessment of alertness that includes a behavioral endpoint.

No studies to our knowledge have empirically examined the effects of military operational stress on perception-action coupling and affordance-based behaviors. Differences in state impact perception-action coupling; altered affordance-based behaviors have been related to increased anxiety[206,207], physical fatigue[208], prior concussion[209,210], load carriage[167,211,212], and sleep loss[55,56,213]. Of relevance to military operational stress, total sleep deprivation resulted in compromised affordance perception accuracy[55,56] and affordance actualization efficiency[55]. Only two studies, to my knowledge, have directly investigated the effects of sleep loss on affordance behaviors. One study used a tablet-based assessment where participants were required to make perceptual judgements regarding whether a series of virtual balls fit through a series of virtual holes and were required to adapt their motor behavior accordingly. Both, affordance perception accuracy and actualization efficiency were compromised following a night of total sleep deprivation. The second study required participants to make perceptual judgments regarding whether they could step over an obstacle of different heights. Affordance perception was compromised following sleep loss even though action capabilities (and therefore affordances) did not change. Perception-action coupling is compromised by sleep loss and other individual stressors common to operational settings. Still, it remains unknown how perception-action coupling is affected by operational stressors and to what extent perception-action coupling tasks capture distinct elements of neurobehavioral function to more traditional assessments of neurobehavioral and sensorimotor function.

While a limited number of studies have directly examined perception-action coupling and affordance-based behaviors, the effects of sleep loss and operational stress on other aspects of sensorimotor function have been more widely studied. Sleep loss-related deficits in other aspects of sensorimotor function provide further evidence that perception-action coupling may be compromised in operational settings where sleep is disrupted. Total sleep deprivation compromises visual discrimination[146,214], oculomotor function[215,216] and saccadic reaction time[217] which may influence the ability to visually track movement within the environment and attune to or discriminate task-relevant features of the environment. Sleep restriction (4-hour sleep opportunities) also compromises visuomotor tracking[218]. Additionally, both total sleep deprivation[219,220] and sleep restriction (4 hours of sleep for 3 days)[221] compromised postural control and movement coordination suggesting a reduced ability to execute appropriate movement patterns following sleep loss. Further in military personnel, 32 hours of total sleep deprivation during training and transitioning from day to night-shift work also compromised static and dynamic postural stability respectively[222,223]. Training environments involving sleep loss, caloric restriction and physical exertion also compromise aspects of coordination and sensorimotor function[183,184,224]. Altered perception-action coupling may underlie sleep loss-related decrements in operational tasks requiring coordination and the ability to react within dynamic environments. While perception-action coupling has not been directly examined in operational settings, collectively these findings demonstrate that perception-action coupling may be impaired by operational stress. Understanding to what extent operational stress impacts perception-action coupling is essential to understanding the demands placed on military personnel in the field. There is a recognized need to examine the effects of sleep loss and operational stress on the ability to react quickly and appropriately to unexpected perturbations[10,31,225,226]; examining perception-action coupling and affordance-based behaviors during exposure to operational stress would address this need.

2.4 Resilience to sleep loss and operational stress

2.4.1 Inter-individual differences in responses to sleep loss and operational stress

The severity of sleep loss-related decrements in mood, alertness and performance varies considerably between individuals; some individuals are resilient and better able to maintain performance despite sleep loss than other individuals[227]. Inter-individual differences in resilience are consistent across different sleep loss manipulations, and are observed across different tasks and assessments. Subjective measures of mood, alertness and sleepiness, behavioral measures of alertness, and simple and higher order cognitive measures demonstrate reliable inter-individual differences in response to sleep loss[57,59,228–230]. Of note, operationally-relevant tasks such as postural stability and operating a flight simulator may also demonstrate inter-individual differences in response to sleep loss[58,222]. The trait-like nature of functional resilience across different tasks highlights the potential utility of neurobehavioral assessments to identify resilient individuals and predict future performance based on past exposure to operational stress.

Importantly, functional resilience, quantified through inter-individual differences, varies across different tasks and based on different definitions of resilience. Individuals who are able to maintain performance on the PVT do not necessarily also maintain performance on a working memory task or maintain high levels of subjective alertness[57,153,228]. In addition to using different tasks to examine resilience, studies have defined neurobehavioral resilience differently. Some studies have examined overall performance during periods of stress exposure while others have examined change in measures from baseline. A recent series of studies concluded that across different neurobehavioral assessments using absolute performance and change in performance identify different individuals as resilient; these two approaches are not interchangeable[231–233]. Ensuring safe and effective performance during exposure to military operational stress relies on both, high overall performance and limited change in performance from baseline (high stability of performance despite stress exposure). Therefore, when examining neurobehavioral resilience to military operational stress, it is important to 1) define neurobehavioral using appropriate neurobehavioral tasks; 2) consider absolute performance; and 3) consider changes in performance from baseline.

Reliable inter-individual differences in response to sleep loss demonstrate the potential trait-like nature of behavioral responses to sleep loss. Identifying individuals who are resilient (able to maintain mood/performance) to sleep loss may be important to ensuring operational efficiency and safety. Further, understanding and monitoring how a particular individual responds to stress may inform the administration of individualized countermeasures (e.g., caffeine[234–236], strategic napping[31]) to mitigate decremental effects of sleep loss and operational stress.

2.4.2 Influence of sleep on resilience

Sleep plays an essential role in the restoration, maintenance and enhancement of performance across days. Further, sleep changes in a use-dependent manner and in response to operational stressors such as extended wakefulness[37,101]. While state-related changes in sleep occur, sleep also displays stable inter-individual differences in SWS and NREM spectral activity that are said to be trait-like[60]. Altogether, these aspects of sleep make it a potential marker of contributor to resilience in operational settings.

Sleep prior to exposure to sleep loss can mitigate the decremental effects of sleep loss on performance. Sleep extension and prophylactic naps prior to sleep loss are common strategies used to counteract decremental effects of future sleep loss[187,237,238]. Sleep extension has beneficial effects on alertness[238–240], cognitive performance and athletic performance[238,241], which likely depends on perception-action coupling[209,242]. Following sleep extension, PVT performance and basketball shooting accuracy, a skill that requires perception-action coupling, improved[238]. The Army has recently released guidance encouraging prophylactic naps, which have demonstrated an ability to partially mitigate the decremental effects of total sleep deprivation during 52-hours of continuous operations[187]. Sleep prior to operational stress exposure may influence performance on neurobehavioral aspects of performance relevant for military personnel.

Whether sleep during the operational stress exposure can protect against performance decrements remains less clear but has been suggested as a countermeasure to mitigate decremental effects of sleep loss on operational performance[31,243]. Naps occurring early, 8- and 16-hours into

56-hours of sleep deprivation were more effective at protecting against the sleep loss-related impairments in alertness, assessed using the PVT[244]. Importantly, naps 30-, 42-, and 54-hours into the protocol also mitigated some of the decremental effects of sleep loss, but to a lesser extent[244]. Other studies have also demonstrated beneficial effects of naps during periods of sleep deprivation on measures of alertness[245–248], although findings are mixed[249]. Sleep inertia, which becomes more severe following sleep loss, contributes to the inconsistent findings[250,251]. Sleep inertia refers to the feeling of grogginess and reduced alertness upon awakening[250]. Still, while sleep inertia may occur immediately upon waking from naps longer than 30-minutes, beneficial effects of the naps on alertness and performance may last longer than 2-hours[246,252]. The beneficial effects of sleep may also vary across different tasks. A 30-minute nap following 51-hours of sustained operations involving military-specific tasks resulted in higher sleepiness and lower motivation but enhanced physical performance[249]. Physical performance may benefit from sleep during operational stress exposure[249,253]. Overall, after accounting for potential effects of sleep inertia, sleep during exposure to operational stress or sleep loss may mitigate decremental effects of the stress exposure on operationally-relevant and neurobehavioral aspects of performance although it is unclear how marksmanship or perception-action coupling may be impacted. Collectively these findings suggest that both, sleep prior to and during exposure to military operational stress may contribute to resilience across different aspects of performance.

3.0 Methods

3.1 Experimental Design

Data collected as part of a larger 5-day cross-sectional study identifying predictors of cognitive resilience to SMOS was used to address dissertation aims. To examine the effects of SMOS on sleep and performance, within-participant comparisons were made across the 5-study days. To examine the impact of inter-individual differences in baseline characteristics on sleep and of inter-individual differences in sleep on performance, between-participant comparisons were made.

3.2 Study Participants

Study participants were active duty and reserve-status military personnel determined to be fit for deployment. Participants were recruited through word of mouth, briefs and fliers. Interested individuals contacted the study team and complete a telephone screening to determine study eligibility. Inclusion criteria were as follows: 1) 18-41 years of age; 2) active duty or recently separated (< 2 years); 3) medically eligible for deployment; 4) successfully have completed branch-specific annual physical fitness test; 5) able to complete marksmanship qualification with a M4/M16.

Exclusion criteria were as follows: 1) on injury profile or a current musculoskeletal injury that limited their ability to maneuver with a load; 2) taking any medications that influence sleep, hormone concentrations or cognitive function (e.g., hypnotics, benzodiazepines, antidepressants, anxiolytics, antipsychotics, decongestants and sedating antihistamines, beta blockers, corticosteroids, non-birth control related hormonal treatment); 3) current or recent history of concussion or traumatic brain injury; 4) currently breastfeeding or pregnant; 5) current nightshift work 6) high-risk of sleep apnea (STOPBANG > 4[254] or apnea-hypopnea index > 15 assessed using standard polysomnography during the first study night); 7) screen for alcohol use disorder (AUDIT > 16)[255]; 8) endorse severe, untreated, or recent treatment for a psychotic disorder including schizophrenia or bipolar disorder; 9) recent hospitalization for severe depression, suicidal thoughts or attempts; and 10) recent drug abuse, including heroin and cocaine. After signing informed consent at intake, participants were withdrawn from the study if they failed a urine drug screen or breathalyzer. All study procedures were approved by the University of Pittsburgh IRB and Department of Defense Human Research Protection Office.

3.3 Study Procedures

The SMOS protocol consisted of 5-consecutive days and nights completed in cohorts of up to four participants. Participants will arrive to the Neuromuscular Research Laboratory at approximately 18:00 the night prior to beginning testing to complete informed consent, and baseline psychological and sleep history questionnaires. Participants were then be transported to the Sleep and Behavioral Neuroscience Center to complete an adaptation night of sleep which included an 8-hour sleep opportunity (23:00 – 07:00) and apnea-screen. Familiarization (Day 0) and baseline (Day 1) testing occurred the next two days. Participants received 100% of their estimated caloric need on each day and received an 8-hour sleep opportunity (23:00 – 07:00) on the night prior to Day 1. Caloric need was estimated using the total daily energy expenditure for an active individual determined from body composition testing via air displacement plethysmography (Bod Pod Body Composition System; Life Measurement Instruments, Concord, CA) on the morning of Day 0[256]. Body fat estimates from the BodPod are reliable (CV range 1.7 - 4.1%) and are valid when compared with hydrostatic weighing (mean differences of -4.0 – 1.9%)[257]. Caloric restriction and sleep restriction and disruption, additional operational stressors, were introduced on Days 2 and 3. Caloric intake was restricted to 50% of estimated caloric need and participants received two 2-hour sleep opportunities each day (01:00 – 03:00, 05:00 – 07:00). Participants then received a recovery bout of sleep (23:00 – 07:00) before the final day of testing (Day 4).

Across all study days, participants completed extensive cognitive, physical and military-specific testing. Briefly, participants completed various cognitive test batteries, simulated marksmanship protocol (EST 3000), tactical movement test (TMT), sensorimotor test battery, and a military-specific decision-making assessment (Figure 2). Morning and sleep disruption testing began ~2 hours and 40 minutes after lights on to minimize potential effects of sleep inertia[250].

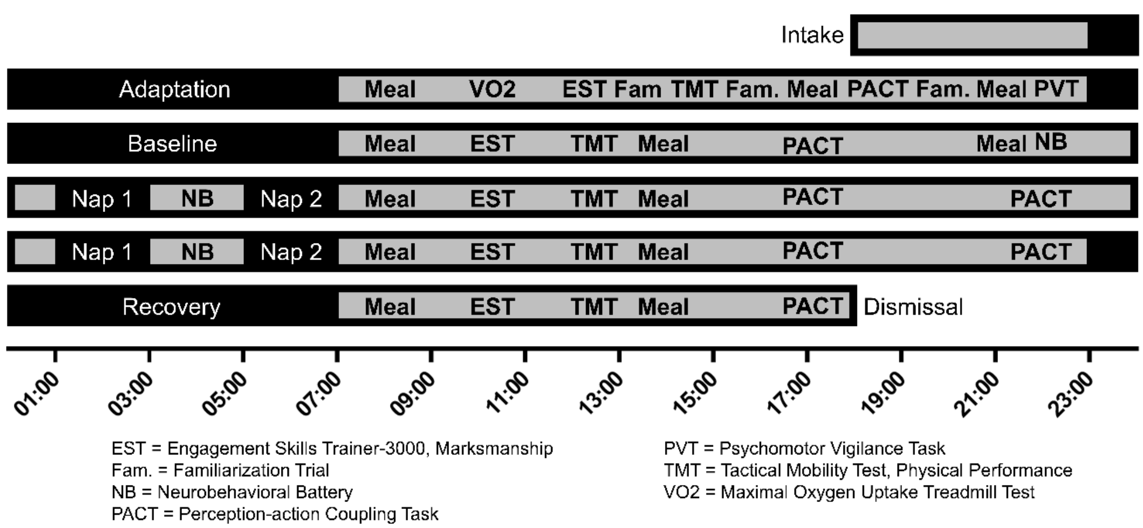


Figure 2: Overall study protocol

3.4 Study Measures

3.4.1 Baseline Questionnaires

Pittsburgh Sleep Quality Index (PSQI): The PSQI is a 19-item questionnaire that assesses 6 components of sleep: overall sleep quality, sleep latency, sleep duration, sleep efficiency, sleep disturbance, sleep medication use, and daytime dysfunction[258]. Component scores are summed to create a global PSQI score which provides an overall measure of sleep quality and ranges from 0 – 21 with higher scores indicating worse sleep quality. PSQI scores > 4 typically reflect poor sleep quality although a cut-off score of 10 may be more clinically-relevant in military populations[259]. PSQI has demonstrated high internal consistency (Cronbach's α = .83). A high proportion of military personnel meet criteria for 'poor sleep' on the PSQI which has demonstrated health, safety and operational implications[68–70,222,260].

Insomnia Severity Index (ISI): The ISI is a 7-item questionnaire that quantifies the severity of insomnia symptoms over the past 2 weeks[261]. Items address difficulty initiating sleep, difficulty maintaining sleep, difficulty awakening, sleep satisfaction, daytime dysfunction, daytime impairment, and sleep-related distress. Participants rated the presence of these impairments on a 5-point Likert scale with higher scores indicating greater insomnia severity (range 0 – 28). The ISI demonstrates good internal consistency (Cronbach's α > .70) and high concurrent and content validity[262].

Epworth Sleepiness Scale (ESS): The ESS is an 8-item questionnaire that quantifies habitual daytime sleepiness[263]. Participants rated how likely they would be to fall asleep during 8 typical activities on a 4-point Likert scale ranging from 0 (never) to 3 (high chance of falling asleep). Higher scores indicate more daytime sleepiness and scores greater than 10 reflect excessive daytime sleepiness. The ESS demonstrates high internal consistency (Cronbach's α > .70) and is sensitive to treatment interventions designed to influence daytime sleepiness[264].

Trauma History Questionnaire (THQ): The THQ is a 24-item questionnaire that quantifies the number of traumatic events an individual experiences in their lifetime[265]. The THQ also captures information regarding the traumatic event type and the age of exposure to traumatic events.

Connor Davidson Resilience Scale: The Connor Davidson Resilience Scale (CD-RISC) is a 25-item questionnaire that provides a subjective measure of resilience[266]. Participants rated 25-items on a 5-point Likert scale ranging from "not true at all" to "true nearly all the time" based on how well they felt the item described them.

3.4.2 Marksmanship

Marksmanship testing was completed using the Engagement Skills Trainer 3000 (EST-3000), a computer-based marksmanship training system that simulates live fire scenarios. A custom EST-3000 protocol was developed for the study. Participants were familiarized with the marksmanship protocol on day 0 but this session was not be used in the analysis. The marksmanship testing was completed at approximately 09:30 on days 1-4. Prior to marksmanship testing, participants completed one short (~25 min) cognitive test battery, but no physical testing occurred before the marksmanship protocol. There were four components of the marksmanship assessment: zeroing, qualification, varied distance and moving target. Zeroing was the calibration phase of the assessment, ensuring that the weapon was firing properly and accurately. Marksmanship sessions where participants were unable to zero their weapon were not used for analysis. Qualification consisted of three firing positions conducted in a standardized order. Participants fired 20 shots from a prone supported (using sandbags), 10 shots from a prone unsupported and 10 shots from a kneeling position. Targets during qualification were set at distances of 100, 150, 200 and 300m. Following qualification, participants completed the varied distance scenario. The varied distance scenario was completed in the prone unsupported position and included 180 targets presented left and right of center at distances of 50, 100, 150, 200, 250 and 300m. Each target was displayed for 3 seconds and 2-3 seconds separated the presentation of each target. The final scenario completed was the moving target scenario which was also completed in the prone unsupported position. During the scenario, 80 targets were presented at distances of 50, 100, 150 and 200m and these targets moved horizontally across the screen at a speed of 3.5 miles per hour. Primary outcomes were accuracy from the varied distance and moving target scenarios.

3.4.3 Tactical Mobility Test (TMT)

The TMT was an operationally-relevant physical test battery that consisted of multiple events: unloaded and loaded vertical jumps, water can carry, fire and movement drill with a casualty drag, unloaded and loaded 300-meter shuttle run, and a 4-mile ruck march. TMT testing started at approximately 12:00 in a climate-controlled, indoor sports facility at the University of Pittsburgh with participants wearing their service-specific duty uniform and boots. In the case of blisters, participants were allowed to wear running shoes.

The battery began with 5 unloaded and loaded vertical countermovement jumps completed with each foot on a force plate approximately shoulder width apart. Participants were instructed to complete 5 jumps consecutively in each condition; as soon as they landed the prior jump they immediately exploded into the next jump until 5 jumps had been completed. Participants then completed the water can carry task which required them to walk as far as they could around a short course in 2 minutes while holding a 20-kg water can in each hand and while wearing 12-kg of external load consisting of an Army Combat Helmet, body armor and model weapon. Next participants completed the fire and movement followed immediately by the casualty drag. Wearing the same 12-kg load, participants first completed the fire and movement drill. Participants started in a prone unsupported position and moved between a series of 16 cones placed 6.6 meters apart. At each cone participants adopted a kneeling or prone position for 5-seconds in a 2:1 pattern alternating between cones. Immediately upon completing the last kneeling position, participants sprinted to the starting area of the casualty drag and dragged a 91-kg Rescue Randy dummy 20 meters. A 3-minute rest period was provided following completion of the casualty drag. Participants then completed the 300-meter unloaded and loaded (16-kg vest with weight evenly distributed anterior and posteriorly) shuttle run with a 3-min rest between conditions. Participants completed 10 30-meter sprints continuously, touching an end line with their hand at each turn. Participants then repeated the vertical jump assessment before being provided a 10-minute rest period. Participants then completed the 4-mile ruck march in 2 phases: a 2-mile phase at a pace of 6.0 km/hr and a 2-mile phase at their best pace. A brief 30-second rest period was provided between the 2 phases. Both phases were completed with a 16-kg load consisting of an Army Combat Helmet, model weapon and ruck sack. Upon completion of the ruck march, participants again completed the vertical jump assessment.

3.4.4 Profile of Mood States (POMS)

The POMS is a 65-item questionnaire that assesses six mood domains: vigor, tension, depression, anger, fatigue, and difficulty concentrating[267]. Higher scores reflect greater mood disturbances except for the vigor subscale where higher scores reflect higher vigor or alertness. A total mood disturbance score is also determined from the combination of the different component scores after vigor has been reverse scored. POMS was completed at 09:00 (Days 0 – 4), 22:00

(Days 0 – 3) and 03:45 (Days 2 and 3). The POMS is sensitive to operational stress[47,73] and has demonstrated robust trait-like behavior during total sleep deprivation and acute sleep restriction protocols[228].

3.4.5 Perception-Action Coupling Task (PACT)

PACT is a tablet-based assessment of affordance perception and actualization that lasts approximately 15 minutes (384 trials), which is sensitive to one night of total sleep deprivation [55] and prior concussion history[210]. PACT was completed 10 times throughout the protocol: 18:00 (Days 0 – 4), 22:00 (Days 1 – 3) and 04:00 (Days 2 – 3). During PACT a series of virtual balls and apertures of varying sizes are presented on the tablet. Participants must make perceptual judgements as to the relative fit between the ball and aperture. Participants begin with the index finger of their dominant hand placed on a standardized starting position on the tablet screen (home button). Upon the appearance of the ball and aperture pairing, participants lift their finger off the home button and move it to the virtual joystick used to complete a response. If the ball is judged to be smaller than the aperture, participants swipe the virtual joystick towards the top of the tablet, which moves the ball towards the aperture. If the ball is judged to be larger than the aperture, participants swipe the joystick down towards the bottom of the tablet, which moves the ball away from the aperture. After completing a response, participants move their index finger back to the home button and await the next trial. Participants are instructed to respond quickly and accurately. Performance on PACT has demonstrated intra-individual stability after 1 familiarization trial, which will be completed on Day 0 of the proposed study[268].

The relative size of the ball and aperture equates to one of 8 possible ratios: 0.2, 0.4, 0.6, 0.8, 1.2, 1.4, 1.6, and 1.8. Ratios less than 1.0 reflect trials where the ball can fit through the aperture; the affordance of the ball passing through the aperture is available. Conversely, ratios greater than 1.0 reflect trials where the ball cannot fit through the aperture; the affordance of the ball passing through the aperture is not available, this action is unafforded.

Primary outcomes of interest for PACT can be divided into affordance actualization efficiency and affordance perception accuracy measures. Affordance actualization efficiency measures include response time (RT; the time to complete a response), reaction time (RXT; the time from presentation of the ball-aperture pairing to when the finger is lifted off the home button), movement time (MT; the time from lifting the finger off the home button to when the joystick is touched), and initiation time (IT; the time to complete a response using the joystick). Affordance perception accuracy measures include the total number of correct responses, incorrect responses and lapses (trials without completed responses).

3.4.6 PVT

A computer-based version of the 10-minute PVT (PC-PVT 2.0[269]) was completed 4 times across the protocol: Day 0 and 1 (22:00); and Day 2 and 3 (03:45). Participants were seated upright at the computer and completed responses with their dominant hand. A white fixation cross appeared centered on the screen against a black background. At randomly spaced intervals (interstimulus interval = 1 – 10 seconds), red numbers appeared on the screen counting up from 0. Participants responded by clicking the mouse key on the laptop as quickly as possible after seeing the numbers appear. Primary outcomes of interest included reaction time (RXT) of the slowest 10% of trials and RXT of the fastest 10% of trials[190].

3.4.7 Sleep parameters

Participants shared sleeping rooms with their study cohort and slept on cots to increase the ecological validity of the study. Sleep was monitored each night (Compumedics Grael 4K

PSG:EEG amplifiers, Charlotte, NC) using a standard American Academy of Sleep Medicine recommended montage (F3, F4, C3, C4, O1, O2, M1, M2), including bilateral electrooculographic electrodes on the outer canthi, three electromyographic electrodes on the submentalis, ground and reference electrodes.

3.5 Data Reduction

3.5.1 Sleep Data

Registered sleep technicians performed sleep staging in 30-second epochs according to established guidelines[74]. Sleep architecture outcomes of interest included total sleep time (TST), sleep efficiency (SE; percent of time in bed spent asleep), wake after sleep onset (WASO; minutes of time spent awake from sleep onset to lights on) and the percent of total sleep time spent in N1, N2, SWS and REM sleep.

For quantitative EEG outcomes, raw EEG data was digitized at 256 Hz and high-pass (0.3 Hz), low-pass (30 Hz) and notch (60 Hz) filters were applied. Signals were then converted to our legacy binary format for automated processing. EEG data was decimated to 128 Hz and band-limited to 64 Hz. A Fast Fourier Transform was performed after a Hamming window was applied to non-overlapping 4-second epochs[270]. Validated algorithms removed 4-second epochs contaminated with muscle (26.25 – 32 Hz) and ocular artifacts using moving window thresholds[271,272]. Lastly, artifact identification was confirmed with visual inspection. Spectral activity in bands from 0.5 – 32 Hz was quantified with power spectral analysis. Outcomes of interest included NREM absolute spectral activity and relative spectral activity (absolute spectral activity normalized using total absolute power) in delta (0.5 – 4 Hz), theta (4 – 8 Hz), alpha (8 –

12 Hz), sigma (12 – 16 Hz) and beta (16 – 32 Hz) frequency bands at the C3 and F3 electrode derivations. NREM total absolute power (0.5 – 32 Hz) was also examined.

3.5.2 Operational outcomes: EST-3000 and TMT

Composite scores were used to examine operational performance outcomes. For marksmanship, average accuracy was calculated across the varied distance and moving target scenarios. Higher average accuracy was considered to reflect better overall marksmanship performance. For physical performance, Z-score transformations were used to create composite scores across the different TMT outcomes, excluding vertical jump performance which will be presented in detail elsewhere. TMT task z-scores were summed, except for the water can carry which was subtracted to create a single composite TMT score. The z-score for the water can carry was subtracted to ensure consistency in how z-scores were interpreted. Lower composite TMT scores indicated better TMT performance. Z-score transformations were performed to ensure that all outcomes were on the same scale when creating composite scores.

To examine change in operational performance across SMOS, absolute change in marksmanship accuracy and physical performance were used as outcomes of interest. For physical performance, absolute change was calculated for each TMT task before being converted to z-scores and then summed to again create a composite measure of physical performance change.

3.6 Statistical Analysis

For all dissertation aims, means and standard deviations were calculated and reported for descriptive variables. Additionally, the breakdown of the sample based on racial identity, ethnic identity, and military service branch were also described. Normality was assessed using Shapiro-Wilks tests and outliers were defined as values greater than 3 SD away from the mean. Appropriate transformations were made if normality is violated.

3.6.1 Aim 1

Statistical analyses were completed in SPSS (Version 25, IBM). To address aim 1, the stability and robustness of inter-individual differences in sleep parameters was assessed using intraclass correlation coefficients (ICC) determined with 2-way mixed model ANOVA with absolute agreement for single measures. 95% confidence intervals were calculated[273]. Stability of sleep parameters during SMOS were examined by calculating separate ICC values across 8-hour sleep opportunities (nights 1 and 4; 23:00 – 07:00), across early naps (nights 2 and 3; 01:00 – 03:00) and across late naps (nights 2 and 3; 05:00 – 07:00). Robustness of sleep parameter stability across sleep opportunities of different durations and timing was examined by calculating separate ICC values across all 2-hour sleep opportunities (early and late naps on nights 2 and 3) and across all sleep opportunities (nights 1 through 4). The influence of resilience and trauma on sleep stability during SMOS was examined by creating 4 groups using median splits of CD-RISC and THQ trauma exposure outcomes. ICC values and 95% confidence intervals were calculated for each group: low trauma, high resilience; low trauma, low resilience; high trauma, high resilience; and high trauma, low resilience. ICC values were interpreted using established guidelines: slight (0.0 – 0.2), fair (0.2 – 0.4), moderate (0.4 – 0.6), substantial (0.6 – 0.8) and almost perfect (0.8 – 1.0)[274]. When 95% confidence intervals did not overlap, differences in ICC values between sleep opportunities and groups were considered significant.

3.6.2 Aim 2

To examine the influence of habitual sleep and baseline sleep prior to SMOS on marksmanship (EST) and physical performance (TMT), lasso regressions were performed to identify informative predictors of operationally-relevant outcomes. Lasso regressions were also performed to examine the influence of habitual sleep and baseline sleep on change in marksmanship and physical performance during exposure to SMOS. Several exploratory analyses were then performed based on findings from the primary analyses. First, lasso-identified predictors were included in multiple regressions to examine whether they predicted specific TMT tasks. Second, lasso regressions were performed to examine whether habitual and baseline sleep predicted average RPE after TMT tasks. Lastly, repeated measures ANOVA were performed to examine differences in sleep across SMOS between high and low TMT performers classified using a baseline split of TMT performance.

3.6.3 Aim 3

PACT RT measures were reciprocally transformed and ACC measures were log-transformed due to violations of normality of the standardized residuals. Separate linear mixed effects models (*lmer* function from the *lmerTest* package in R Version 4.0.3) were performed for all PACT outcomes using a restricted maximum likelihood approach[275]. Fixed effects included time-of-day (04:00, 18:00, 22:00) and study day (D1-3) and the interaction between time and day. Maximal random effects (participant, time-of-day and day) were included when possible. If models failed to converge, random intercept models were performed[276]. Unstructured random effects covariance structures were used. Age was controlled for in all models. To examine the combined effects of time-of-day and day on PACT outcomes, pairwise comparisons with Tukey adjustments for multiple comparisons were performed when interaction effects were significant (*emmeans* package)[277,278]. If the interaction effect was not significant, main effects from the additive model were examined via pairwise comparisons with Tukey adjustments for multiple comparisons Denominator degrees of freedom were determined using the Kenward-Rogers method.

3.6.4 Aim 4

Participants were defined as resilient or vulnerable based on POMS Vigor and Fatigue, PVT FAST and SLOW; and PACT 1/RT, lapses and incorrect responses. A 2-step decision making approach was used to classify participants as resilient or vulnerable. Resilient individuals demonstrated high alertness (mood/performance) across the two sleep disruption nights and minimal deterioration in alertness from baseline during the two sleep disruption periods. Vulnerable participants demonstrated low alertness across the two sleep disruption nights and marked deterioration in alertness from baseline during the two sleep disruption periods. Agreement between resilient groups classified using different neurobehavioral measures was examined using percent agreement and Cohen's kappa coefficient. Lastly, differences in baseline factors, baseline sleep and sleep throughout SMOS were examined between resilience groups across each neurobehavioral measure.

4.0 Aim 1: Stability and robustness of sleep across sleep opportunity manipulations during simulated military operational stress

Abstract

Study Objectives: Within-subject stability of certain sleep features across multiple nights is thought to reflect the trait-like behavior of sleep. However, to be considered a trait, a parameter must be both stable and robust. Here, we examined the stability (i.e., across the same sleep opportunity periods) and robustness (i.e., across sleep opportunity periods that varied in duration and timing) of different sleep parameters.

Methods: Sixty-eight military personnel (14 W) spent 5 nights in the sleep laboratory during a simulated military operational stress protocol. After an adaptation night, participants had an 8-hour sleep opportunity (23:00–07:00) followed by 2 consecutive nights of sleep restriction and disruption which included two 2-hour sleep opportunities (01:00–03:00; 05:00–07:00) and, lastly, another 8-hour sleep opportunity (23:00–07:00). Intra-class correlation coefficients were calculated to examine differences in stability and robustness across different sleep parameters.

Results: Sleep architecture parameters were less stable and robust than absolute and relative spectral activity parameters. Further, relative spectral activity parameters were less robust than absolute spectral activity. Absolute alpha and sigma activity demonstrated the highest levels of stability that were also robust across sleep opportunities of varying duration and timing.

Conclusions: Stability and robustness varied across different sleep parameters, but absolute NREM alpha and sigma activity demonstrated robust trait-like behavior across variable sleep opportunities. Reduced stability of other sleep architecture and spectral parameters during

shorter sleep episodes as well as across different sleep opportunities has important implications for study design and interpretation.

Disclosure: This work has been accepted for publication at the journal SLEEP with publishing by Oxford Press

4.1 Introduction

Sleep is an essential biologic function, influenced by individual differences in response to gene-environmental factors and variability in underpinning brain structures[155,279,280]. However, while some sleep parameters, including stage 1 (N1), stage 2 (N2), and rapid eye movement (REM) sleep vary substantially from night to night[40], other sleep features are highly stable across multiple nights[40,60,160]. Slow wave sleep (SWS) duration and non-rapid eye movement (NREM) spectral activity, including in the sigma range (12-16 Hz) which is characterized by sleep spindles, display high levels of stability across several nights regardless of age[40,41,80,155,162]. Based on these findings, it is suggested that high within-subject stability of certain sleep features may reflect the trait-like behavior of sleep[60]. Characterizing trait-like sleep features may therefore provide greater insight into individual differences in these features across different sleep opportunities and into which sleep features may be more sensitive to changes in sleep opportunities.

To be considered a trait-like characteristic, a sleep parameter must not only be stable, but this stability must also be robust to (i.e., remain high despite) different experimental manipulations such as total sleep deprivation, which impact subsequent sleep[60]. High stability of inter-individual differences in SWS and NREM spectral activity, including alpha (8 – 12 Hz) and sigma activity, have been observed before and after total sleep deprivation[155,157,161]. Tucker and colleagues reported a substantial stability of SWS duration and NREM delta (0.5 – 4 Hz) activity across multiple baseline and recovery nights following 36 hours of total sleep deprivation[157]. High stability of the spectral profile of NREM sleep and of the homeostatic build-up and dissipation of sleep are also observed across repeated bouts of total sleep deprivation[42,161]. Still, few studies have systematically examined the robustness of inter-individual differences in sleep parameters across sleep opportunities of different durations or across different times of day[41,158,159,165]. Specifically, one study showed that NREM sleep power in the 8 – 15.5 Hz range, which includes alpha and sigma activity, was stable across different sleep conditions that included different sleep disruption paradigms[41]. Two studies demonstrated stability of SWS during nighttime naps and 5-hour daytime sleep opportunities but did not report spectral activity[158,159]. Lastly, a final study reported that in groups of adolescents exposed to sleep opportunities of different durations (1-hour, 5-hour, 9-hour sleep opportunities), NREM delta activity and fast sigma spectral activity were less stable in the sleep restriction group than in a control group exposed to multiple nights of 9-hour sleep opportunities[165]. However, the latter study did not examine the robustness of sleep power spectra within the same group across different sleep opportunities and neither study examined both sleep architecture and sleep EEG spectral activity parameters across varying sleep opportunities. This gap is relevant, given that sleep opportunities vary across nights, especially in certain professions (e.g., medical professionals[243], pilots[31], military personnel[5]). For example, unpredictable and around-the-clock work demands combined with other operational factors (see[64] for review), can cause substantial variation in the duration and timing of sleep opportunities for deployed military personnel. Sleep may be further impacted by the high cognitive and physical demands characteristic of operational settings[281,282]. Of note, experimental paradigms have been developed to characterize the impact of simulated military operational stress (SMOS) on military personnel in a laboratory environment. Examining the robustness of sleep stability during SMOS can provide greater insight into the trait-like nature of sleep and into the impact of these stressors on military personnel and related professions characterized by varying sleep opportunities.

Operational stressors do not impact all individuals to the same extent. As such the impact of SMOS on sleep may vary between individuals. Understanding whether baseline psychological characteristics such as trauma history and resilience, which are relevant for military personnel, impact the stability and robustness of sleep would provide additional insight into factors that may influence how different military personnel respond to SMOS. Individuals with post-traumatic stress disorder (PTSD) have reduced night-to-night stability in sleep, as measured with sleep diaries and actigraphy, when compared with healthy sleepers or individuals with insomnia[283,284]. Further, history of trauma exposure, even without subsequent development of PTSD, can have persistent effects on sleep[43,285]. As shown in a sample of military veterans, childhood trauma exposure is associated with REM sleep fragmentation even when accounting for adult trauma exposure[285]. Still, there remain gaps in our understanding of the relationship between trauma exposure and sleep stability.

The relationship between psychological resilience, which may impact how an individual responds to trauma exposure, and sleep stability is also unknown. Higher resilience, the ability to adapt to challenging circumstances, may mitigate decremental effects of trauma exposure on the psychological well-being of individuals and reduce the likelihood of developing PTSD[286]. Further, higher resilience is associated with higher sleep quality and less sleep complaints[44,287]. Yet, the relationship between resilience and other aspects of sleep including the trait-like nature of sleep is unknown. Further, the combined effects of trauma exposure and resilience on the trait-like behavior of sleep are not fully understood. The ability of high resilience to mitigate decremental effects of trauma exposure on sleep is an intriguing possibility. It seems therefore appropriate to understand how these two facets interact and influence sleep-wake cycles. Exploring these relationships would inform future research efforts aimed at examining factors contributing to resilience or vulnerability to PTSD.

In the current study, we examined the stability and robustness of sleep characteristics, including sleep architecture and sleep EEG spectral activity parameters, across a 5-day SMOS protocol, as well as relationships between trauma history, resilience, and sleep. Our primary aim was to examine trait-like features of sleep across sleep opportunities of different durations (8 vs 2-hours) and timing (lights out at 01:00 vs 05:00). The SMOS protocol included 3 types of sleep opportunities: typical nighttime sleep (8-hours from 23:00 – 07:00), an early night-nap (01:00 – 05:00) and a subsequent late-night nap (05:00 – 07:00), which allowed us to examine the stability and the robustness of the stability of different sleep parameters. Further, participants completed several cognitive and physical tasks each day allowing us to examine the stability and robustness of sleep parameters to high cognitive and physical demands. We hypothesized that SWS, absolute spectral activity and relative spectral activity would demonstrate high stability that would be robust across different sleep opportunities, while remaining sleep architecture parameters (sleep efficiency, N1, N2 and REM sleep) would be less stable. A secondary aim was to explore the influence of trauma history and resilience on sleep stability. We hypothesized that sleep would be less stable in less resilient participants exposed to more trauma compared to more resilient participants exposed to less trauma.

4.2 Methods

4.2.1 Participants

Active-duty, Reserve, and National Guard military personnel aged 18-41 years old who were eligible for deployment, had successfully completed their annual branch-specific fitness test, and stated an ability to complete a marksmanship qualification assessment with a M4 or M16 rifles were included in the study. Potential participants were excluded if they: 1) were on an injury profile or had a current musculoskeletal injury that limited running, jumping or load carriage; 2) took medications that influence sleep, cognition, physical performance or hormone concentrations including hypnotics, benzodiazepines, antidepressants, anxiolytics, antipsychotics, decongestants and sedating antihistamines, beta blockers, corticosteroids, non-birth control related hormonal treatment; 3) currently or recently had a concussion or traumatic brain injury; 4) were working overnight shifts; 5) were breastfeeding or pregnant; 6) were at high-risk of sleep apnea (STOPBANG > 4[254] or apnea-hypopnea index > 15 assessed using standard polysomnography during the first study night); 7) screened positive for alcohol use disorder (AUDIT > 16)[255]; 8); had severe, untreated, or recent treatment for schizophrenia, bipolar disorder or another psychotic disorder; 9) were hospitalized in the past three months for severe depression, suicidal thoughts or attempts; and/or 10) used drugs of abuse, including heroin and cocaine, in the past three months. Written informed consent was obtained at intake. Participants could be later withdrawn from the study if they failed a breathalyzer or urine drug screen. All study protocols were approved by the University of Pittsburgh Institutional Review Board and Department of Defense Human Research Protection Office.

4.2.2 Protocol

Cohorts of up to four participants at a time completed the 5-day SMOS as part of a larger study examining cognitive resilience in military personnel. Participants arrived at the laboratory at 18:00 on the day prior to testing to complete baseline demographic and psychological questionnaires. During each day, participants completed extensive physical and cognitive testing from approximately 08:30 – 22:45 (Figure 3)[166,288]. Cognitive test batteries assessed a wide range of cognitive domains including vigilance, working memory, visuomotor function, emotion recognition, and decision-making among others[166]. Testing also included a simulated marksmanship protocol, and physical test battery of military-specific tasks including a loaded 4-mile ruck march (see[288] for a full description of the physical test battery). On day 0, participants were familiarized to study tasks and completed baseline testing of physical capabilities and body composition (Bod Pod Body Composition System; Life Measurement Instruments, Concord, CA). Baseline testing of study tasks was completed on day 1. Participants received 100% of their caloric need based on estimated daily energy expenditure on days 0 and 1, and had 8-hour sleep opportunities from 23:00 – 07:00 on nights 0 and 1. Additional operational stressors were introduced on days 2 and 3; caloric intake was restricted to 50% estimated caloric need and sleep was restricted and disrupted on both nights. Participants had two 2-hour sleep opportunities from 01:00 – 03:00 (Nap 1) and 05:00 – 07:00 (Nap 2). Participants completed additional cognitive testing from 03:45 – 04:45 on these nights. Finally, participants had an 8-hour sleep opportunity from 23:00 – 07:00 which served as a recovery night prior to the last day of the study (Figure 1). Light levels in the morning and at night, when participants were at the sleep lab, were under 150 lux. Lights were turned off and participants did not have access to their phones during sleep opportunities. Participants were allowed free time between testing and were allowed to engage in activities that maintained an even-keeled environment (i.e., read, use their phones, talk to other participants or staff). Trained research staff continuously monitored participants throughout the 5-day protocol to ensure participants stayed awake and maintained an even-keeled environment.

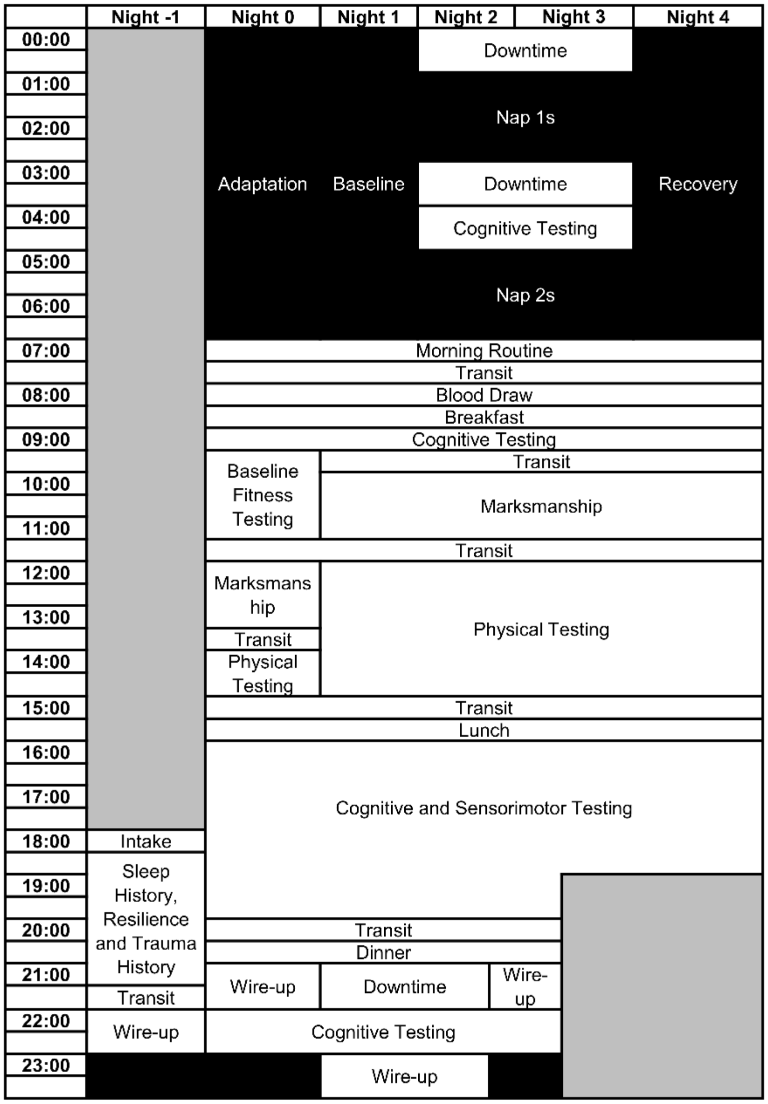


Figure 3: Outline of study protocol

4.2.3 Study Questionnaires

Baseline psychological and demographic questionnaires included assessments of sleep complaints, resilience, and trauma exposure. To quantify sleep and sleep-related complaints of participants, the Pittsburgh Sleep Quality Index (PSQI)[258], Insomnia Severity Index (ISI)[262] and

Epworth Sleepiness Scale (ESS)[264] were administered. The PSQI quantifies self-reported sleep quality and disturbances from the prior 30 days. The ISI quantifies insomnia-specific sleep complaints. The ESS quantifies daytime sleepiness-related complaints. Resilience was measured using the Connor Davidson Resilience Inventory Scale (CD-RISC), a 25-item inventory that requires participants to rate how well they feel a prompt describes them on a 5-point Likert scale from "not true at all" to "true nearly all the time"[266]. Higher scores indicate higher levels of resilience. The Trauma History Questionnaire (THQ) is a 24-item questionnaire that quantifies the number of traumatic events an individual experiences in their lifetime[265].

4.2.4 Sleep Data Collection and Processing

Sleep was monitored with standard polysomnography each night (Compumedics Grael 4K PSG:EEG amplifiers, Charlotte, NC). To increase ecological validity, participants slept on cots in shared suites (2-conjoined rooms) with their study cohort (1 – 4 participants). Males and females slept in separate suites. A standard American Academy of Sleep Medicine recommended montage was used which included bilateral frontal (F3/4), central (C3/4) and occipital (O1/2) EEG electrodes referenced to linked mastoids (M1/2), bilateral electrooculographic electrodes on the outer canthi, three electromyographic electrodes on the submentalis, ground and reference electrodes. Sleep staging was performed for 30-second epochs according to established criteria[74]. Sleep architecture outcomes of interest included sleep efficiency (SE; percent of time in bed spent asleep), and the percent of total sleep time spent in N1, N2, SWS and REM sleep.

Raw EEG data were digitized at 256 Hz and filtered between 0.3–30 Hz with a notch filter also applied at 60 Hz. Signals were then converted to our legacy binary format for automated processing. EEG data were then decimated to 128 Hz and band-limited to 64 Hz. A Hamming window was applied to non-overlapping 4-second epochs and a Fast Fourier Transform was performed[270]. The signals were then processed with validated algorithms to remove 4-second epochs contaminated with muscle (26.25 – 32 Hz) and ocular artifacts[271,272]. Lastly, signals were visually reviewed to confirm appropriate artifact identification. Power spectral analysis quantified spectral activity in bands from 0.5 – 32 Hz. Outcomes of interest included NREM absolute spectral activity and relative spectral activity (absolute spectral activity normalized using total absolute power) in delta (0.5 – 4 Hz), theta (4 – 8 Hz), alpha (8 – 12 Hz), sigma (12 – 16 Hz) and beta (16 – 32 Hz) frequency bands at the C3 and F3 electrode derivations. NREM total absolute power (0.5 – 32 Hz) was also examined. When data was not available for C3 or F3 due to artifact, C4 and F4 results were used (4 total nights from 2 participants; < 1% of data).

4.2.5 Statistical Analysis

All statistical analysis was completed in SPSS (Version 25, IBM). Shapiro-Wilk tests were used to assess for normality. Due to violations of normality, absolute and relative spectral activity were log-transformed. To examine the stability of sleep across the SMOS exposure, multiple intra-class correlation coefficient (ICC) values were calculated; 2-way mixed model ANOVA with absolute agreement for single measures were performed and 95% confidence intervals were calculated[273]. To examine stability of sleep parameters across sleep opportunities of similar duration and timing, separate ICC values were calculated across both 8-hour sleep opportunities (nights 1 and 4; 23:00 – 07:00), across both nap 1s (nights 2 and 3; 01:00 – 03:00) and across both nap 2s (nights 2 and 3; 05:00 – 07:00). To further examine robustness of sleep parameter stability across sleep opportunities of different durations and timing, separate ICC values were calculated across all 2-hour sleep opportunities (naps 1 and 2 on nights 2 and 3) and across all sleep opportunities (nights 1 through 4). We examined differences in ICC values across different sleep opportunity comparisons within each sleep parameter; ICC values were considered significantly different from one another when 95% confidence intervals did not overlap.

To examine the influence of resilience and trauma exposure on sleep stability, the sample was divided into four groups with high and low levels of trauma exposure and resilience using the median split for each parameter. Thirty-four participants were defined as having high resilience (CD-RISC > 83) and 34 were defined as having low resilience (CD-RISC ≤ 83). Twenty-nine participants were defined as having low (2 or less traumatic events) trauma exposure and 33 participants were defined as having high (3 or more traumatic events) trauma exposure. Six participants did not complete the THQ as the questionnaire was added after data collection had started. The low trauma, high resilience group contained 16 participants, the low trauma, low resilience group contained 13 participants, the high trauma, high resilience group contained 16 participants and the high trauma, low resilience group contained 17 participants. ICC values and 95% confidence intervals were calculated for the four groups: low trauma, high resilience; low trauma, low resilience; high trauma, high resilience; and high trauma, low resilience. ICC values were interpreted according to established guidelines: slight (0.0 – 0.2), fair (0.2 – 0.4), moderate (0.4 – 0.6), substantial (0.6 – 0.8) and almost perfect (0.8 – 1.0)[274]. ICC values were considered significantly different between groups when 95% confidence intervals did not overlap. Study data are available upon reasonable request.

4.3 Results

4.3.1 Participant characteristics

Sixty-eight active duty and reserve status military personnel (54 men, 14 women) completed the SMOS protocols and were included in analyses. One woman was an outlier for sleep spectral data across all electrode derivations (> 3 standard error away from the mean) and was excluded from analyses. Participants were 26.2 ± 5.4 years old, and predominantly from the Army (Table 1). The racial and ethnic breakdown of the sample is similar to that of the military (Table 1)[289]. Participants were largely healthy sleepers who reported normal sleep (PSQI = 3.9 ± 2.4, range 0 - 13), minimal insomnia symptoms (ISI = 4.5 ± 3.6, range 0 - 13) and minimal daytime sleepiness (ESS = 5.4 ± 2.2, range 1 - 11). Twenty-four participants were classified as poor sleepers based on a PSQI cut-off of 5, but only one was classified as a poor sleeper based on the suggested military-specific PSQI cut-off of 10[259]. Based on a standard cut-off of 5, good and poor sleepers only differed in sleep stability of 8-hour relative sigma activity (Figure S1). Participants demonstrated high resilience (CD-RISC = 83.1 ± 10.6) and high trauma exposure (3.8 ± 3.3 lifetime traumatic events) relative to civilian populations, a finding similar to other military populations[286,290]. Sleep architecture across SMOS is presented in Table 2.

Table 1: Descriptive information of study participants

Category		Count (%)
Military Branch	Army	59 (86.8)
	Marines	6 (8.8)
	Air Force	3 (4.4)
Racial Identity	White	46 (67.6)
	Black or African American	15 (22.0)
	Multiracial	2 (2.9)
	Asian	2 (2.9)
	Undisclosed	3 (4.4)
Ethnic Identity	Not Hispanic/Latino descent	59 (86.8)
	Hispanic/Latino descent	9 (13.2)

Table 2: Sleep architecture across a simulated military operational stress protocol

	Baseline		Night 2				Night 3				Recovery	
			Nap 1		Nap 2		Nap 1		Nap 2			
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
TST (min)	446.4	18.9	113.5	6.2	112.0	6.2	115.1	3.6	114.9	4.8	453.2	19.3
SE (%)	92.9	3.9	93.8	5.1	92.7	5.1	95.3	2.7	95.1	3.9	94.2	4.1
N1 (%)	6.9	4.2	5.0	3.1	7.9	4.5	3.9	2.9	5.1	4.2	4.9	2.8
N2 (%)	52.2	6.7	41.6	15.4	42.7	12.5	35.9	13.1	40.7	12.1	52.5	7.2
SWS (%)	14.7	6.7	38.6	16.7	9.6	9.5	42.4	15.0	13.7	12.2	16.5	7.3
REM (%)	26.2	4.5	14.7	7.3	39.8	10.2	17.7	8.9	40.6	10.4	25.9	4.2

TST = Total sleep time; SE = sleep efficiency; N1 = stage 1 sleep; N2 = stage 2 sleep; SWS = slow wave sleep; REM = rapid-eye movement sleep

4.3.2 Stability and robustness of sleep parameters across SMOS exposure

Across most sleep architecture parameters, fair to moderate levels of stability were observed (Figure 4A). ICC values for similar sleep opportunities (8-hour, nap 1 and nap 2) reflected the stability of sleep parameters, while ICC values for combined sleep opportunities (2-hour and all) reflected robustness of sleep parameter stability to variation in sleep timing and duration, respectively. ICC values were slightly higher for similar sleep opportunities than for combined sleep opportunities, but these differences were not significant for SE, N1 or REM (confidence intervals overlapped). For N2, the ICC across 8-hour sleep opportunities (ICC = .649; CI = .487 - .768) was significantly higher than the ICC for all sleep opportunities (ICC = .302; CI = .175 - .441). Further, SWS demonstrated almost perfect (ICC = .867; CI = .723 - .930) stability for the 8-hour sleep opportunities, but ICC values were significantly lower (ICC = .173 - .510; CI upper limits = .667; see Appendix B, Table 15 for individual ranges) across the other sleep opportunities.

Compared to ICC values for sleep architecture, ICC values for absolute spectral activity at C3 were higher across all frequency bands and sleep opportunities (Figure 4B). Almost perfect levels of stability were observed across all frequency bands for the 8-hour sleep opportunities (ICC = .847 - .972). Further, levels of stability for alpha (ICC = .882 - .972) and sigma (ICC = .827 - .959) activity were almost perfect for each sleep opportunity combination, thus reflecting robustness to variation in sleep timing and duration. The stability of delta, theta and beta activity ranged from substantial to almost perfect for similar sleep opportunities (ICC = .640 - .948), but this stability was less robust across varying sleep opportunities: 2-hour sleep opportunities and all sleep opportunities (ICC = .514 - .790). Similarly, total absolute power (Appendix B Table 15) demonstrated almost perfect stability (ICC = .931; CI = .891 - .957) for the 8-hour sleep opportunities, substantial stability for nap 2 (ICC = .784; CI = .636 - .870) and moderate stability for nap 1, 2-hour sleep opportunities and all sleep opportunities (ICC = .473 - .592; CI ranges = .265 - .729).

For relative spectral activity at C3, stability across similar sleep opportunities was comparable with absolute spectral activity stability for 8-hour sleep opportunities and nap 1 but lower for nap 2 (Figure 4C). Specifically, ICC values were almost perfect for the 8-hour sleep opportunities across all frequency bands (ICC = .821 - .950), almost perfect for nap 1 across all frequency bands (ICC = .821 - .902), except beta for which ICC values were substantial (ICC = .795). Conversely, ICC values for nap 2 ranged from moderate to substantial across all frequency bands (ICC = .457 - .664; CI upper limits $\leq$ .779) demonstrating significantly lower stability than 8-hour sleep opportunities for each frequency band (CI lower limits $\geq$ .801) and significantly lower stability than nap 1 for delta (nap 1 ICC = .821, CI .723 - .886; nap 2 ICC = .457, CI = .246 - .626), theta (nap 1 ICC = .902, CI = .795 - .948; nap 2 ICC = .584, CI = .404 - .722), and sigma bands (nap 1 ICC .831, CI = .734 - .894; nap 2 ICC = .507, CI .302 - .666). Further, relative spectral activity stability was lower than absolute spectral activity stability for 2-hour sleep and all sleep opportunities, with ICC values ranging from moderate to substantial across all frequency bands (ICC = .446 - .745), thus demonstrating less robustness across sleep opportunities of different timing and durations (Figure 4C). Specifically, ICC values were significantly lower for 2-hour (CI upper limits $\leq$ .769) than 8-hour sleep opportunities (CI lower limits $\geq$ .801) for each frequency band and were significantly lower for 2-hour sleep opportunities than nap 1 for delta (2-hour ICC = .448, CI = .222 - .630), theta (2-hour ICC = .593, CI = .292 - .769), and sigma activity (2-hour ICC = .446, CI = .161 - .656). ICC values were also significantly lower for all sleep opportunities than 8-hour sleep opportunities for each frequency band (delta: all ICC = .574, CI = .398 - .712;

8-hour ICC = .926, CI = .880 - .954; theta: all ICC = .690, CI = .496 - .812; 8-hour ICC = .929, CI = .858 - .961; alpha: all ICC = .745, CI = .616 - .835; 8-hour ICC = .950, CI = .921 - .969; sigma: all ICC = .544, CI = .317 - .709; 8-hour ICC = .910, CI = .859 - .944; beta: all ICC = .608, CI = .439 - .737; 8-hour ICC .874, CI = .801 - .921) and were significantly lower for all sleep opportunities than nap 1 for delta (nap 1 ICC = .821, CI = .723 - .886) and theta activity (nap 1 ICC = .902, CI = .795 - .948). ICC values for absolute and relative spectral activity were consistent across C3 and F3. For ease of interpretation, C3 findings are presented here, but F3 results are in Appendix B.3.

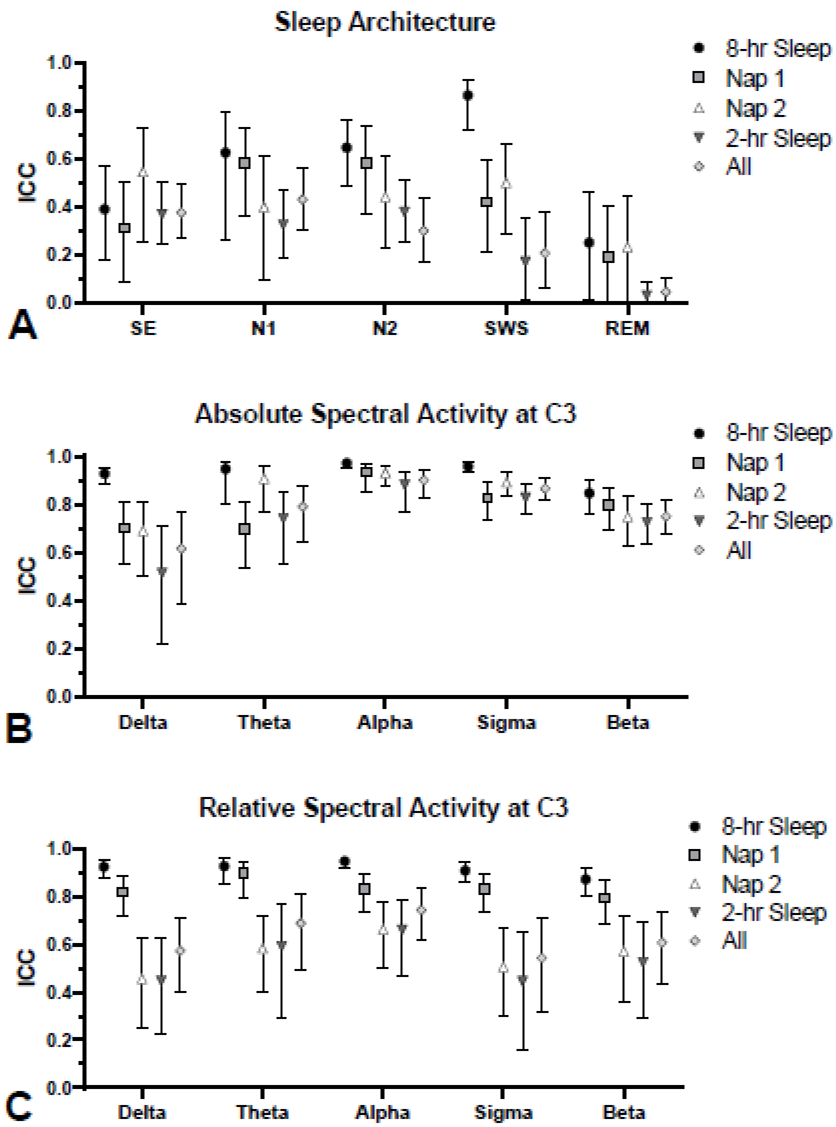


Figure 4. Stability and robustness of sleep parameters across exposure to simulated military operational stress

4.3.3 Impact of resilience and trauma history on the trait-like stability of sleep across SMOS

Groups did not differ in sleep complaints on the ESS or ISI, but the high trauma, low resilience group had significantly higher PSQI scores than the high trauma, high resilience group

(Table 3; *p* > .05). As groups differed in PSQI scores and age, we conducted post hoc exploratory analyses examining sleep stability differences related to PSQI scores and age which are presented in the supplemental materials (Appendix B.2 and B.5 respectively). No differences in sleep architecture were observed between groups (Appendix B.1).

For the 8-hour sleep opportunities (Figure 5A), no significant differences in ICC values were found for any sleep parameters between groups. For nap 1 absolute delta activity (Figure 5B), both the low trauma, high resilience (ICC = .951, CI = .865 - .982) and high trauma, high resilience groups (ICC = .936, CI = .801 - .978) had significantly higher ICC values than both the low trauma, low resilience (ICC = .416, CI = -.141 - .784) and high trauma, low resilience groups (ICC = .488, CI = -.006 - .787). The low trauma, high resilience group, but not the high trauma, high resilience group, also had a significantly higher ICC value (ICC = .947, .828 - .982) for nap 1 absolute theta activity than both the low trauma, low resilience (ICC = .266, CI = -.249 - .698 and high trauma and low resilience groups (ICC = .572, CI = .107 - .828). For nap 2 relative sigma activity (Figure 5C), the high trauma, low resilience group (ICC = .149, .CI = -.378 - .594) had a significantly lower ICC than the high trauma, high resilience group (ICC = .855, CI .637 - .947). No significant differences between groups were found for any sleep parameters across 2-hour or all sleep opportunities (Appendix B.1).

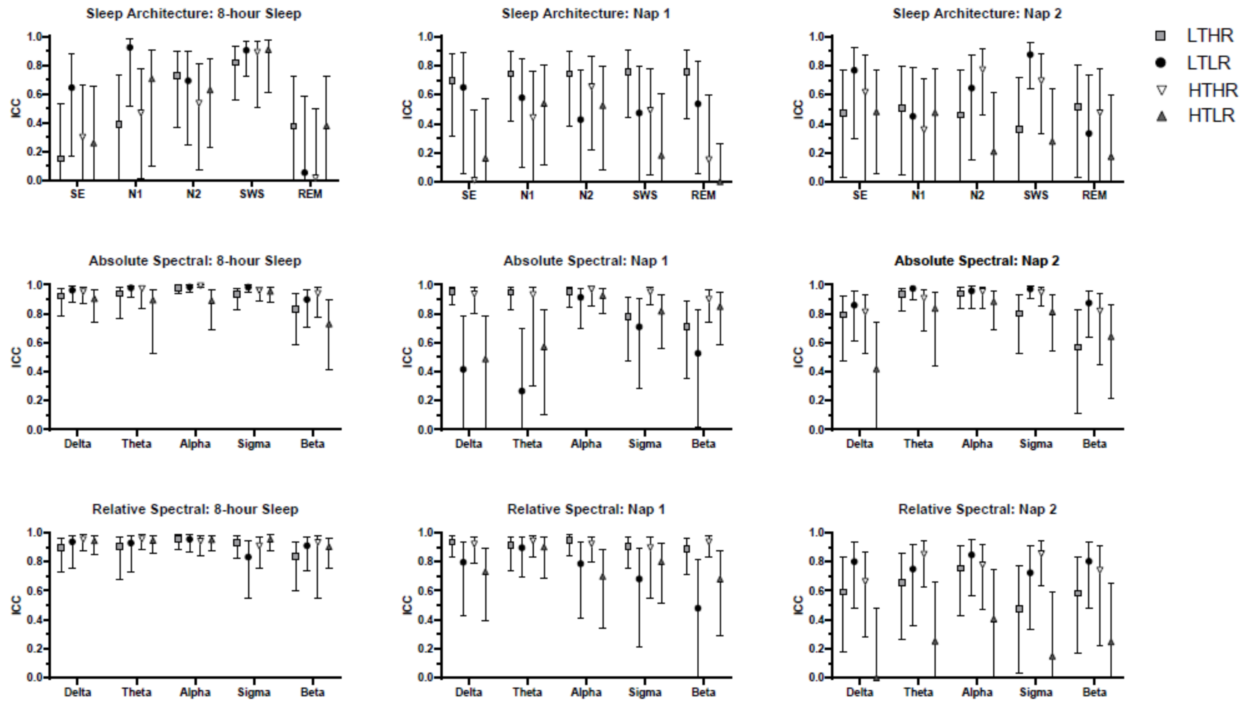


Figure 5. Stability of sleep parameters across simulated military operational stress in trauma and resilience groups

Table 3. Differences in baseline sleep complaints in different trauma exposure and resilience groups

	LTHR		LTLR		HTHR		HTLR		F	*p*	η_P^2
	Mean	SD	Mean	SD	Mean	SD	Mean	SD			
Trauma	1.3	0.8	1.1	0.6	6.1	2.5	6.3	3.3	27.255	<.001	.585
Resilience	91.4	4.9	75.7	6.7	91.9	5.1	72.7	6.7	47.437	<.001	.710
Age	22.7	2.9	26.5	4.8	30.1	5.9	25.6	5.2	6.224	.001	.244
ESS	5.3	2.1	6.5	2.6	4.8	2.3	5.3	1.9	1.410	.249	.068
ISI	3.0	3.0	5.3	3.1	3.8	3.3	5.6	4.1	2.101	.110	.098
PSQI	3.3	1.9	3.8	1.5	2.9	2.3	5.2	2.9	3.153	.032	.140

LTHR = low trauma, high resilience; LTLR = low trauma, low resilience; HTHR = high trauma, high resilience; HTLR = high trauma, low resilience; ESS = Epworth Sleepiness Scale; ISI = Insomnia Severity Index; PSQI = Pittsburgh Sleep Quality Index; SD = standard deviation

4.4 Discussion

In this study with military personnel, we characterized both the stability of electrophysiological sleep parameters across a 5-day SMOS protocol, that included different sleep opportunities, and trait-like behavior (i.e., stability and robustness) of these sleep parameters. We also characterized the effects of trauma exposure and resilience on this trait-like behavior. A key finding from this study was high stability of absolute NREM alpha and sigma activity that was robust across variable sleep opportunities. Other sleep parameters, including SWS, absolute and relative delta, theta and beta spectral activity demonstrated high stability across 8-hour sleep opportunities, but this stability was less robust across different sleep opportunities. In terms of differences in the stability of sleep parameters in participants with different levels of trauma exposure and resilience, the results showed that absolute NREM delta and relative NREM spectral activity during short sleep opportunities were less stable in individuals with high trauma exposure and low self-reported resilience. Altogether, the present findings suggest the robust, trait-like nature of absolute NREM alpha and sigma spectral activity across different sleep conditions and the potential impact of trauma and resilience on these and other sleep characteristics.

The sleep schedule used in the present study allowed us to characterize the trait-like aspects of sleep architecture and sleep EEG spectral activity parameters across sleep opportunities that differed in duration, timing and cumulative SMOS exposure (including high cognitive and physical load). Sleep architecture parameters, especially REM sleep, did not demonstrate stable or robust trait-like behavior across the SMOS exposure, while only SWS was stable across the 8-hour sleep opportunities (ICC = .867). High stability of SWS in the current study extends findings from prior work[40,157] by demonstrating that high stability persists across acute sleep manipulations as well as across periods with increased cognitive and physical load accumulated through the SMOS protocol. Although a prior study has demonstrated high stability of SWS across nighttime naps[158], here we found lower stability during 2-hour naps early and late in the night which may be related to the difference in nap duration (2-hours vs. 40-minutes) and the additional operational stressors (cognitive and physical load, caloric restriction) participants were exposed to in the present study. Similar to SWS, absolute NREM delta activity demonstrated almost perfect stability across the 8-hour sleep opportunities, but this stability was lower across the 2-hour opportunities. The finding that both SWS and NREM delta activity were less stable across short sleep opportunities suggests that these deep sleep parameters are sensitive to changes in state and may reflect individual differences in resilience or susceptibility to SMOS. Individual vulnerability to sleep loss varies across individuals and differences in this vulnerability may have been further exacerbated by the extensive cognitive and physical testing that the participants completed throughout the study. A reduced robustness of SWS and delta activity across SMOS may reflect such vulnerability, especially when sleep opportunities are shorter (i.e., 2-hour naps). In contrast, across a full night of sleep (i.e., 8-hours), differences in homeostatic sleep need may be less apparent as individuals obtain sufficient SWS and delta activity. Future studies are needed to examine whether the reduced stability observed across an acute SMOS protocol has long term implications across the more chronic exposures experienced by military personnel; long-term disruption to sleep stability within an individual could conceivably have implications for overall sleep, physical and mental health.

Conversely, absolute theta and beta activity were highly stable across 8-hour, nap 1, and nap 2 sleep opportunities. Few studies have reported on the stability of NREM beta activity, although, one study found lower stability (ICC $< .6$) in this frequency range in healthy sleepers compared to individuals with insomnia[40]. The authors hypothesized that, in healthy sleepers, NREM beta activity was more sensitive to changes in state than spectral activity in other frequency bands[40], which is contrary to the high stability observed in the current study. Differences in study demands, specifically the greater cognitive and physical demands and younger study sample in the current study may have contributed to differences in study findings. Absolute theta and beta activity were also robust across varying sleep opportunities, albeit less so than absolute NREM alpha and sigma activity. Specifically, the stability of absolute NREM alpha and sigma activity remained high across similar sleep opportunities and was robust to variations in sleep opportunity duration and timing across increasing SMOS exposure; that is, high stability was maintained despite changes in circadian and homeostatic factors and pronounced cognitive and physical load, which can all influence sleep. The robust trait-like behavior of absolute NREM alpha and sigma activity throughout the SMOS protocol lends further support to prior studies characterizing activity in these frequency bands, and sleep spindles (which occur across these frequency ranges), as the "fingerprint" of sleep[41,80,155]. Future studies should examine whether chronic exposure to operational stress impacts the robust trait-like stability of alpha and sigma activity. Chronic exposure to operational stress and shiftwork has decremental effects on health and sleep. Whether alpha and sigma activity remain stable and whether the reduced stability of delta activity is further exacerbated by chronic exposure to operational stress would provide additional insight into the relationship between sleep stability and vulnerability to stress. Additionally, the relationship between sleep stability and the decremental effects of chronic stress on sleep could be examined. Altogether, the higher stability of absolute spectral activity, as compared to sleep architecture, demonstrates the need to examine quantitative EEG measures when studying sleep in settings with variable sleep opportunities as is often the case in field studies, including those with operational populations.

The current study also established that differences in sleep timing influenced the stability of NREM relative spectral activity, and that NREM relative spectral activity parameters showed reduced stability and robustness across sleep opportunities when compared to absolute spectral activity. Lower stability of relative spectral activity during nap 2 compared to nap 1 may be related to greater sensitivity to consecutive days of SMOS during the second half of the night and to circadian-related variation in sleep parameters. Absolute delta and theta activity, which decrease throughout the night as homeostatic sleep pressure dissipates, were less robust to varying sleep opportunities than other absolute spectral bands. Importantly, absolute delta and theta activity contribute most to total absolute power. Lower stability and robustness of total absolute power and absolute delta and theta activity across different sleep opportunities was therefore likely magnified in the relative spectral parameters. Furthermore, given that relative spectral activity is calculated by normalizing the absolute spectral activity within a specific frequency range to the total absolute power, reduced stability within a specific frequency range and across total absolute power can both contribute to reduced stability in relative spectral activity. Therefore, when examining relative spectral activity across a sleep manipulation protocol, the impact of the manipulation on broadband and frequency-specific absolute power should be accounted for carefully.

Another novel aspect of the current study was the examination of sleep stability in participants with different levels of resilience and trauma exposure. Regardless of trauma exposure, participants with low resilience had less stable sleep than participants with high resilience during the nap 1 sleep opportunities. Further, participants with high trauma history, in addition to low resilience, demonstrated less stable sleep across nap 1 and 2 sleep opportunities. Altogether, these findings suggest that high resilience may protect the sleep of individuals exposed to trauma. Further, these findings suggest that low resilience may be related to lower stability in sleep and that trauma may exacerbate this decreased stability. It's important to mention that among participants with high trauma exposure, less resilient participants had worse habitual sleep quality on the PSQI than more resilient participants. This raises the intriguing possibility that decreased sleep stability may contribute to worse habitual sleep especially in individuals with lower psychological resilience and a history of more trauma exposure. To build upon these findings demonstrating links between resilience, trauma exposure and disrupted sleep, future studies should be replicated in larger samples and across normal sleep conditions to assess whether higher variability is characteristic of the low resilience groups or occurred in response to the SMOS protocol. Second, relationships between resilience, trauma exposure and sleep stability demonstrated in the present study should be explored in clinical populations. For example, understanding the relationships between these parameters in individuals with PTSD may have important implications to characterize the role of sleep disturbances in the neurobiology and clinical manifestation of PTSD, and is likely to have implications for developing novel interventions and improving treatment outcomes.

Although the current study provided a comprehensive examination of the short-term stability and robustness of sleep architecture and NREM spectral activity, there are several limitations that should be addressed in future studies. First, the study sample was composed of military personnel who self-selected to participate in a study about resilience. Therefore, care must be taken when interpreting these findings as it is unclear to what extent they may generalize to the broader population. Second, while here we established that some sleep parameters display trait-like behavior across acute exposure to sleep restriction and disruption, we were not able to examine chronic effects of exposure to SMOS and disrupted sleep, relevant for military personnel and others working in professions characterized by disrupted sleep including medical professionals, fire-fighters and pilots. Future work should examine whether trait-like behavior persists across chronic sleep restriction. Third, the current study provided a limited examination of circadian influences on the stability of sleep EEG parameters. We examined the combined effects of homeostatic sleep pressure and circadian timing on sleep stability within a night of sleep but did not examine the independent effects of time-of-day (as could be examined in forced desynchrony or constant routine protocols) or the effects of sleeping during periods of high circadian drive for wakefulness (during typical waking hours) on sleep stability. While one study has examined stability of SWS across daytime naps, a more comprehensive examination of the effects of variable sleep timing on sleep stability across spectral sleep parameters is needed. Lastly, the EEG montage used in the present study provided limited spatial resolution of spectral activity, which could be enhanced in future studies by performing high-density sleep EEG recordings.

In conclusion, in the present study we established that absolute NREM spectral activity, especially in the alpha and sigma range, had stable and robust trait-like behavior across a wide variety of sleep opportunities. Lower robustness of absolute delta and theta activity and of relative spectral activity across shorter sleep opportunities must be considered when designing studies, and interpreting results from studies that include brief sleep opportunities. For individuals who have inconsistent sleep schedules, these findings highlight that certain sleep features may be more sensitive to changes in sleep periods while others likely remain more consistent across different sleep opportunities. For example, to obtain stable estimates of SWS or absolute delta activity that are representative of an individual's sleep, data from multiple short sleep opportunities may be needed. Further, variability in sleep parameters during SMOS seems to be influenced by resilience and prior trauma exposure, suggesting that future research should further examine the causal relationships between these variables, including their possible implications in the development of sleep or psychiatric disorders.

5.0 Aim 2: Daytime sleepiness and slow wave activity predict worse physical performance in military personnel

Abstract

Military personnel must maintain marksmanship and physical performance despite exposure to operational stressors such as sleep loss, caloric restriction and high cognitive load. Habitual sleep quality may relate to baseline differences in fitness that impact physical performance within operational settings. Slow wave sleep, in particular, may relate to individual differences in body composition and fitness although findings are inconsistent and it is unclear whether findings extend to operational settings. Further, sleep and specific sleep features may contribute to recovery of marksmanship and physical performance across days. We examined the role of individual differences in baseline sleep on baseline marksmanship and physical performance and on the change in marksmanship and physical performance through exposure to simulated military operational stress. Active-duty and reserve status military personnel completed a 5-day SMOS protocol during which they completed a tactical mobility test and marksmanship protocol daily. Sleep questionnaires were administered at intake and sleep was monitored each night with polysomnography. Lasso regressions were used to identify meaningful predictors of marksmanship and physical performance at baseline and of change in marksmanship and physical performance across SMOS. Sleep was not related to marksmanship performance but better aerobic fitness, lower daytime sleepiness and lower slow wave activity (0.5 – 4 Hz) predicted better baseline physical performance. Collectively, higher daytime sleepiness and slow wave activity may reflect more chronic exposure to insufficient sleep and higher baseline sleep need which may have contributed to compromised physical performance.

5.1 Introduction

Increasing evidence demonstrates an active role of sleep in regulating physical performance. Longer sleep duration and better sleep quality contribute to improved anaerobic, aerobic and skilled performance[237,238,291–296]. For example, better habitual sleep quality reported on the Pittsburgh Sleep Quality Index (PSQI) predicts better performance on a maximal effort incremental cycling test[297]. Further, multiple nights of sleep extension contribute to better motor coordination, muscular endurance, sprints times and lower-limb power[238,298]. These findings are consistent with the recent emphasis of military policy/leadership on improving sleep practices within military personnel[2,3]. Specifically, sleep was identified as one of three pillars of health along with nutrition and physical activity in the Army Medicine's Performance Triad[2]. Further, sleep banking, the practice of obtaining more sleep prior to planned/expected periods of sleep loss via sleep extension or napping has been highlighted as an operationally relevant strategy to optimize performance.

Military operations involve physically demanding tasks; thus, ensuring optimal physical performance of military personnel is a necessity. Still, whether the beneficial effects of habitual sleep on physical performance translate to military-specific tasks remains less clear. Additionally, it remains to be established which aspects of sleep, namely sleep architecture, spectral activity, and/or characteristics of habitual sleep, underlie the beneficial effects of sleep on physical performance and other military-specific tasks. Slow wave sleep (SWS) and slow wave activity (SWA; 0.5 – 4 Hz) play an important role in the restorative function of sleep has been associated with better baseline fitness[299–303] (but see[304–307]). Further, it has been shown that SWS and rapid-eye movement (REM) sleep can contribute to muscle recovery,[308,309] thus suggesting that SWS and REM sleep may impact daily changes (or lack thereof) in physical performance within operational settings that involve high physical demands. SWS, SWA and REM sleep may also protect marksmanship within operational settings through their beneficial effects on cognitive and sensorimotor improvements[104,109,140]. Based on these findings, it is reasonable to assume that these aspects of sleep architecture may also contribute to military-relevant aspects of physical performance and marksmanship. Marksmanship, in particular, relies on aspects of sensorimotor function including perceptual discrimination, visuomotor tracking and perception-action coupling[168].

Of further importance in military settings, is examining whether specific sleep features serve a protective role during exposure to sleep loss. Military personnel must maintain high levels of performance during exposure to sleep loss and caloric restriction[5]. Identifying factors that predict whether an individual will be able to maintain performance despite exposure to military operational stressors could inform intervention strategies aimed to enhance performance. For example, sleep extension prior to exposure to sleep loss or military operational stress mitigates sleep loss-related performance decrements[239]. Further, naps during periods of sleep loss help alleviate deficits in mood, alertness and cognitive function that would otherwise be observed[187]. Sleep architecture during naps can also positively impact subsequent performance. Specifically, perceptual discrimination performance was restored following naps that contained both SWS and REM sleep but not after naps that contained only SWS[140]. Further, more SWS during naps mitigated cognitive deficits observed during a night of sleep deprivation[310]. It is, however, unclear whether individual differences in sleep features may serve a protective role on military-specific aspects of performance. SWS, SWA and REM have been implicated in muscle recovery and, therefore, may contribute to the ability to restore and maintain physical function across periods of operational stress[308,309].

In this study, we aimed to examine relationships between habitual sleep (i.e., assessed with the PSQI, the Insomnia Severity Index, and the Epworth Sleepiness Scale), baseline sleep (i.e., night 1 sleep EEG measures) and sleep EEG parameters throughout exposure to simulated military operational stress (SMOS) with marksmanship and physical performance. We hypothesized that habitual sleep quality, baseline SWS, REM and SWA would predict better marksmanship and physical performance at baseline. Further, we hypothesized that baseline SWS, REM and SWA would predict marksmanship and physical performance throughout the SMOS exposure.

5.2 Methods

5.2.1 Participants

Sixty-nine active duty and reserve status military personnel completed the SMOS protocol across 5 consecutive days. Participants were recruited predominately through fliers, briefings, and word-of-mouth. Inclusion and exclusion criteria have been described in detail elsewhere[288]. In brief, participants had to be active duty or reserve status military personnel who were medically eligible to deploy and had successfully completed their branch-specific yearly physical fitness test. As such, participants had to be free from physical injury and mental health diagnosis. Additionally, participants were excluded if they took any medications that would impact their sleep, cognitive performance, or hormone levels.

5.2.2 *Protocol*

Participants arrived at the lab at approximately 18:00 to complete informed consent, baseline psychological questionnaires, and an adaptation night of sleep (i.e., night 0) with a full apnea-screen to assess sleep disordered breathing. Participants with an apnea-hypopnea index > 15 were excluded due to high risk of sleep apnea and safety considerations related to sleep depriving already sleep deprived individuals. Baseline questionnaires included assessments of habitual nighttime sleep disturbance (PSQI[258], ISI[261]) and daytime sleepiness (ESS[263]). Across the study participants received 8-hour sleep opportunities (23:00 – 07:00) on nights 0 (adaptation), 1 (baseline) and 4 (recovery) and 100% of estimated caloric need on days 0 (familiarization), 1 (baseline) and 4 (recovery). Sleep and caloric intake were restricted by 50% on days 2 and 3. Specifically, participants received two 2-hour sleep opportunities (01:00 – 03:00 and 05:00 – 07:00) and 50% of their estimated caloric need on these days. Across all study days, participants completed extensive cognitive[166] and physical testing[288] (Figure 6). Familiarization to study tasks and baseline testing of body composition and aerobic fitness occurred on day 0. Estimates of total daily energy expenditure obtained from body composition testing were used to determine caloric allotment throughout the study. To characterize aerobic fitness, participants completed a treadmill (Woodway; Waukesha, WI) Bruce protocol[311] to determine peak relative oxygen consumption ($\dot{V}O_{2peak}$; Parvo TrueOne® 2400; Salt Lake City, UT).

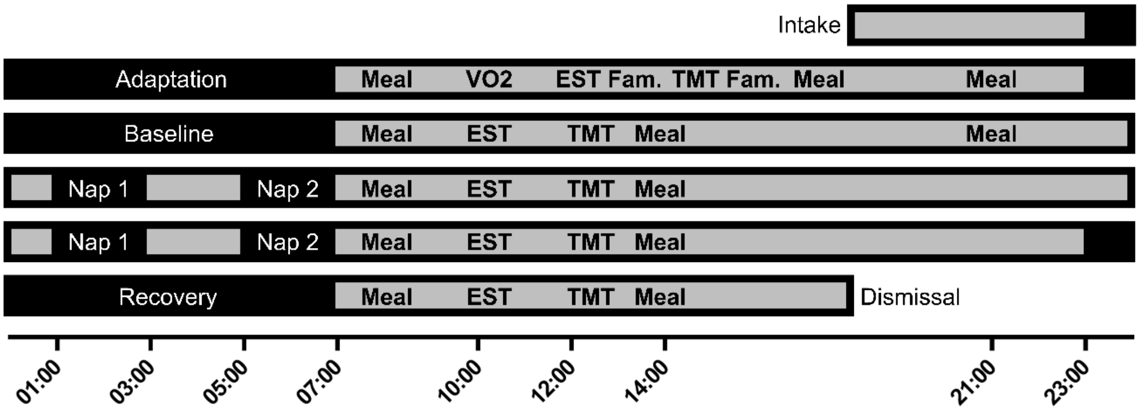


Figure 6. General study timeline including operational tasks

5.2.3 Marksmanship: Engagement Skills Trainer 3000 (EST)

Marksmanship testing involved custom scenarios within a computer-based marksmanship training system that simulates live fire scenarios (Engagement Skills Trainer-3000; Cubic Corporation, Orlando FL). Participants used M4 or M16 adapted for use on the system and used the same weapon each day. After familiarization on day 0, marksmanship testing occurred each day starting at approximately 10:00. Testing included four scenarios: zeroing (weapon calibration), qualification, varied distance and moving target. Marksmanship sessions in which participants did not successfully zero their weapons were not included in analyses. Analyses included marksmanship performance from the varied distance and moving target scenarios. The varied distance scenario, completed after qualification, presented 180 targets left and right of center at distances of 50, 100, 150, 200, 250 and 300-meters. Targets were displayed for 3-seconds with 2-3 seconds between each target. Following varied distance, the moving target scenario presented 80 targets at distances of 50, 100, 150 and 200-meters which moved horizontally across the screen at a speed of 3.5 miles per hour. Testing for the varied distance and moving target scenarios were completed with participants in a prone unsupported position. Primary outcomes of interest were accuracy which was averaged across both scenarios to examine overall marksmanship performance.

5.2.4 Daily Physical Performance Testing: Tactical Mobility Test

The Tactical Mobility Test (TMT) was designed to assess operationally relevant aspects of physical performance and included seven tasks: 1) unloaded vertical jumps, 2) loaded vertical jumps, 3) water can carry, 4) fire and movement drill, 4) casualty drag, 5) unloaded 300-meter shuttle run, 6) loaded 300-meter shuttle run and 7) a 4-mile ruck march. Data from the unloaded and loaded vertical jumps is presented elsewhere and was not considered in the present analyses. Further a detailed description of TMT task performance across SMOS is provided elsewhere[288]. Ratings of perceived exertion (RPE) were collected before and after each task using the Borg scale[312] (ratings of 6-20).

Participants began the TMT at approximately 12:00 each day and completed testing in a climate-controlled indoor sports facility while wearing their service-specific uniform and combat boots. A detailed description of the TMT battery is provided elsewhere[288]. See Table 4 for a description of each task. Briefly, the battery began with 5 unloaded and loaded vertical jumps followed immediately by the water can carry. Participants then completed the fire and movement drill followed immediately by the casualty drag. After a 3-minute break, participants completed the 300-meter unloaded and loaded shuttle runs with a 3-minute break between each condition before again completing 5 unloaded and loaded vertical jumps. Following a 10-minute break, participants completed the 4-mile ruck march with a 30-second break provided at the 2-mile mark.

A final set of 5 unloaded and loaded vertical jumps was completed upon completion of the ruck march.

Table 4. Description of individual TMT tasks

Task	Task Description	Load
Water Can Carry	Participants walked as far as possible along a path while holding 20-kg water cans filled with sand in each hand	12-kg
Fire and Movement Drill	Participants ran between a series of 16 cones placed 6.6 meters apart adopting kneeling or prone positions in a 2:1 pattern	12-kg
Casualty Drag	Participants dragged a 91-kg Rescue Randy dummy 20 meters	12-kg
300-meter Unloaded Shuttle Run	Participants completed 10 30-meter sprints continuously, touching an end line with their hand and turning upon completion of each 30-meter sprint.	N/A
300-meter Loaded Shuttle Run	Participants completed the 10 30-meter sprints while wearing a loaded vest	16-kg
Ruck March	Participants completed the first 2-miles of the ruck march at a pace of 6.0 km/hr and completed the final 2-miles at their best effort pace.	16-kg

*Participants were instructed to complete all tasks at best effort

Overall physical performance was quantified through calculation of a composite TMT score. Outcomes from each TMT task (i.e., distance traveled for the water can carry and completion time for all other tasks) were transformed to z-scores to standardize outcomes. Individual task z-scores were then added to create a composite TMT score. An exception was made for the water can carry score, which was subtracted from the other scores to ensure that the interpretation of z-scores was in a consistent direction. Lower composite scores were indicative of better TMT performance.

To quantify change in TMT performance, absolute changes from baseline were calculated before being transformed to z-scores for each day, which were summed to create a composite z-score of change. The inverse of the z-score for change in the water can carry was used so interpretation was again in a consistent direction. Lower composite scores were indicative of improvement in TMT performance or less deterioration in TMT performance while higher scores indicated deterioration in TMT performance.

5.2.5 Sleep Data Collection and Processing

Participants slept on cots in suites shared with their study cohort to simulate some aspects of the sleeping environment they would experience on deployment. Standard polysomnography (Compumedics Grael 4K PSG:EEG amplifier, Charlotte, NC) with a 10:20 montage (C3/4, F3/4, O1/2, M1/2, 3 EMG, 2 EOG, ground and reference) was used to monitor sleep each night. Certified sleep technicians scored sleep in 30-second epochs using established guideline[74] and measures of sleep architecture were subsequently determined. Outcomes of interest included: sleep efficiency (SE; percent of time in bed spent asleep), WASO and the time spent in N1, N2, SWS and REM sleep.

To extract spectral outcomes, raw EEG data were digitized at 256 Hz and filtered (high-pass: 0.3 Hz; low-pass 30 Hz; notch: 60 Hz). Data were then converted to optimize use of legacy processing pipelines. After being decimated to 128 Hz, EEG data were band-limited to 64 Hz and a Hamming window was applied to non-overlapping 4-second epochs. After a Fast Fourier Transform was performed, validated algorithms, confirmed via visual review, were used to remove muscle and ocular artifacts[270–272]. Power spectral analysis quantified spectral activity in bands from 0.5 – 32 Hz. Outcomes of interest included NREM absolute spectral activity in SWA (0.5 – 4 Hz), theta (4 – 8 Hz), alpha (8 – 12 Hz), sigma (12 – 16 Hz) and beta (16 – 32 Hz) frequency bands at the C3/4 and F3/4 electrode derivations. Spectral data from the 2 central electrodes and from the 2 frontal electrodes were averaged together.

5.2.6 Statistical Analysis

SPSS (Version 25; IBM, Armonk, NY, USA) and R (Version 4.0) were used for all analyses. Outliers were defined as +/- 3 standard deviations from the mean. Analyses were performed with and without outliers to explore the influence of outliers on study outcomes. Analyses without outliers are reported in the main text. Details regarding the influence of outliers on outcome measures are included in the supplemental materials.

To examine the impact of baseline factors (i.e., age, sex, $\dot{V}O_{2peak}$), habitual sleep (i.e., PSQI, ISI, ESS) sleep architecture (i.e., SE, N1, N2, SWS and REM) and NREM spectral activity (i.e., absolute frontal and central SWA, theta, alpha, sigma and beta activity) on physical performance and marksmanship, penalized least squares (Lasso) regressions were performed (glmnet package[313]). Lasso regression is a form of regularization regression that is able to eliminate noninformative predictors by reducing their coefficients to zero and is appropriate when examining a large number of predictors relative to sample size and when examining correlated predictors as is the case with the sleep outcome variables[314]. The penalty term, chosen as 1 standard error away from the penalty term that minimized mean cross-validated error, was determined via ten-fold cross validation and was used to identify the most parsimonious set of informative predictors[314,315]. Coefficients for informative predictors and the proportion of variance explained by the lasso models are reported in the results. Proportion of variance explained by each predictor was determined by performing multiple linear regressions and using the leave-one-out method to determine change in variance explained when each variable was left out from the model.

To examine whether differences in baseline sleep characteristics protected against deficits in operational performance across the SMOS protocol, we performed separate lasso regressions of baseline sleep on the change in operational performance outcomes from baseline to the peak stress day (Day 3) and to the recovery day (Day 4).

Based on results of the primary analyses, several post hoc exploratory analyses were performed. Based on findings from the lasso regression of baseline factors and sleep on baseline TMT performance, we decided to further explore whether lasso-identified predictors were related to specific aspects of physical performance. Separate multiple regressions of lasso-identified predictors on baseline performance of individual TMT tasks were performed to examine whether identified predictors impacted specific TMT tasks (*lme* package). In all statistical models, participants were included as a random effect. Further, to explore whether relationships between sleep and the subjective experience of the TMT existed in the current sample, lasso-regressions were repeated with post-RPE averaged across TMT tasks as the outcome variable. Lastly, we examined differences in sleep across SMOS in high and low TMT performers to further explore whether SMOS impacted the sleep of high and low performers to a similar extent. If low performers were more sensitive to SMOS, we would have expected their sleep to change more across SMOS. To define high and low performance groups, a median split of baseline TMT performance was performed. Repeated measures ANOVA were performed with sleep opportunity, performance group and their interaction as fixed effects and with participant as a random effect (See Appendix C.2).

5.3 Results

5.3.1 Final Sample

For physical performance outcomes, there was complete data for 54 participants, of which 9 were excluded for being outliers. Data for a sample which included outliers (+/- 3 standard deviations) are presented in Appendix C.1. 34 participants had complete marksmanship data, 24 of whom also had complete physical performance data.

Descriptive information for each subset of participants is presented in Table 5. Aerobic fitness ($\dot{V}O_{2peak}$) of the sample used for primary TMT analyses was compared to normative values. Based on ACSM guidelines, 9 participants had superior fitness, 15 excellent, 8 good, 9 fair, 3 poor and 1 very poor. $\dot{V}O_{2peak}$ did not differ significantly between included and excluded participants. Overall, the sample consisted of healthy sleepers and was representative of the sex, racial and ethnic composition of the military.

Table 5. Descriptive information

		TMT Sample (n = 45)	All TMT (n = 54)	EST Subset
Sex	Men	36	43	21
	Women	9	11	3
Racial Identity	White	31	36	18
	Black/African-American	11	13	5
	Multiracial	2	2	1
	Undisclosed	1	2	0
Ethnicity	Not Hispanic/Latino	41	48	23
	Hispanic/Latino	4	6	1
Age (years)		26.3 (5.3)	26.6 (5.7)	25.9 (5.1)
CD-RISC		83.3 (9.9)	83.2 (10.3)	85.1 (9.9)
Trauma History		2.9 (2.5)	3.3 (2.8)	3.3 (2.5)
DRRI		19.7 (7.3)	19.6 (6.7)	19.8 (6.5)
$\dot{V}O_{2peak}$ (mL*kg*min^{-1})		47.0 (6.5)	46.0 (7.3)	49.6 (6.0)
PSQI		4 (2)	4 (2)	4 (2)
ISI		4 (3)	5 (4)	4 (4)
ESS		5 (2)	6 (2)	5 (3)
TST (min)		444.7 (19.0)	445.5 (19.9)	443.1 (19.1)
SE (%)		92.5 (4.0)	92.7 (4.1)	92.4 (4.0)
WASO (min)		28.8 (16.8)	28.3 (17.1)	28.7 (15.5)
N1 (min)		32.6 (18.3)	31.5 (18.1)	33.3 (16.6)
N2 (min)		235.5 (31.0)	235.7 (33.5)	231.8 (30.6)
SWS (min)		60.3 (30.7)	62.3 (31.9)	57.7 (26.3)
REM (min)		116.2 (21.7)	115.9 (20.8)	120.4 (20.7)
Central SWA (μV^2)		2.42 (.22)	2.43 (.22)*	2.38 (.17)
Central Theta (μV^2)		1.37 (.24)	1.39 (.23)	1.33 (.18)
Central Alpha (μV^2)		1.02 (.27)	1.01 (.27)	.99 (.23)
Central Sigma (μV^2)		.83 (.21)	.83 (.21)	.82 (.18)
Central Beta (μV^2)		.51 (.18)	.53 (.18)	.52 (.16)
Frontal SWA (μV^2)		2.59 (.20)	2.61 (.20)	2.55 (.15)
Frontal Theta (μV^2)		1.41 (.23)	1.42 (.22)	1.37 (.17)
Frontal Alpha (μV^2)		1.08 (.28)	1.08 (.27)	1.07 (.24)
Frontal Sigma (μV^2)		.77 (.22)	.78 (.22)	.76 (.18)
Frontal Beta (μV^2)		.51 (.16)	.53 (.17)	.53 (.15)

*Significantly higher ($p < .05$) in excluded participants than included participants

5.3.2 Relationship between baseline sleep and marksmanship performance

For marksmanship performance, no informative predictors were identified (all predictor coefficients were reduced to zero). Baseline characteristics, sleep architecture and NREM spectral activity did not predict baseline marksmanship accuracy. Similarly, no informative predictors were identified when examining relationships between baseline characteristics and sleep with change in marksmanship accuracy from baseline to peak stress.

5.3.3 Relationship between baseline sleep and physical performance

For physical performance, $\dot{V}O_{2peak}$ (β = -1.849), ESS (β = 0.038) and frontal NREM SWA (β = 0.415) were identified as informative predictors of baseline performance. Higher $\dot{V}O_{2peak}$ (better aerobic fitness), lower Epworth Sleepiness Scale scores (lower daytime sleepiness) and lower frontal SWA collectively predicted better baseline physical performance. Collectively, this model predicted 66.1% of the variance in baseline physical performance. Of the explained variance, $\dot{V}O_{2peak}$ explained 66.4% (43.9% of total variance), ESS explained 10.1% (6.7% of total variance) and frontal SWA explained 23.4% (15.5% of total variance). Lasso-identified predictors and TMT composite scores are displayed in Figure 7.

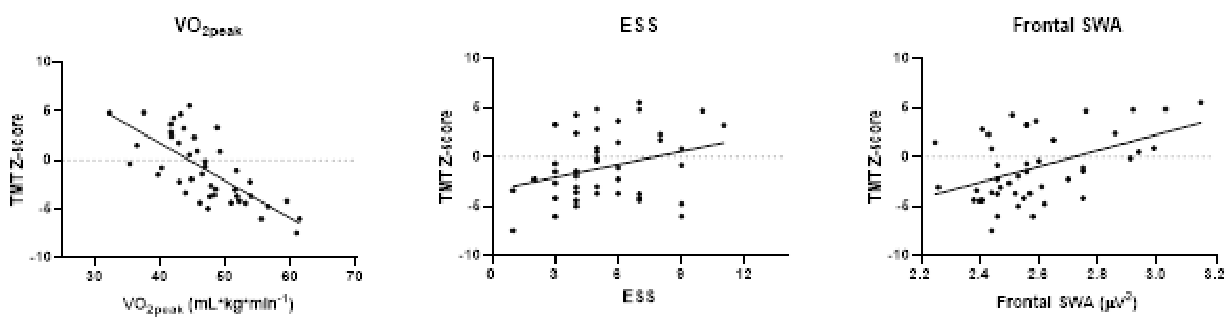


Figure 7. Relationships between lasso-identified predictors and TMT composite scores at baseline

5.3.4 Post-hoc Exploratory Analyses

To further explore whether lasso-identified predictors impacted specific aspects of physical performance, separate multiple regressions were performed for each TMT task with $\dot{V}O_{2peak}$, ESS and frontal SWA included as predictors (Table 6). $\dot{V}O_{2peak}$ was a significant predictor of all TMT tasks; higher $\dot{V}O_{2peak}$ predicted better performance across tasks. Higher ESS scores significantly predicted shorter water can carry distance and longer 300-m loaded shuttle time. Higher frontal SWA significantly predicted shorter water can carry distance and longer ruck march time. No other significant relationships between sleep outcomes and TMT task performance were found.

Additionally, to examine whether subjective experiences of TMT tasks were influenced by baseline characteristics and sleep, lasso-regressions were performed on average RPE from after each TMT task at baseline. No influential predictors of RPE were identified.

Lastly, no significant performance group*sleep bout interaction effect was found for SWA, but significant main effects of group and time were found. SWA was higher in low TMT performers throughout the SMOS protocol. Results for SWA are presented here (Figure 8) due to the relationship between SWA and TMT performance at baseline; additional sleep variables are presented in Appendix C for completeness.

Table 6. Linear mixed model of baseline fitness (V̇O_2peak), sleepiness (ESS) and NREM frontal SWA on the performance of individual TMT tasks

	$\dot{V}O_{2peak}$			ESS			Frontal SWA		
	β	Std. Error	*p*	β	Std. Error	*p*	β	Std. Error	*p*
WCC	**20.668**	**6.907**	**.005**	**-12.776**	**5.479**	**.025**	**-15.914**	**5.744**	**.008**
FM	**-6.495**	**2.513**	**.013**	1.815	1.993	.368	1.957	2.090	.355
CD	**-13.692**	**3.919**	**.001**	2.945	3.109	.349	4.672	3.259	.159
US	**-11.248**	**1.737**	**<.001**	2.574	1.378	.069	2.867	1.445	.054
LS	**-14.579**	**2.632**	**<.001**	**5.422**	**2.088**	**.013**	3.138	2.189	.159
Ruck	**-179.792**	**45.106**	**<.001**	17.751	35.778	.622	**111.339**	**37.511**	**.005**

Abbreviations; WCC = water can carry; FM = fire and movement drill; CD = casualty drag; US = unloaded 300-m shuttle run; LS = loaded 300-m shuttle run; ESS = Epworth Sleepiness Scale; SWA = slow wave activity

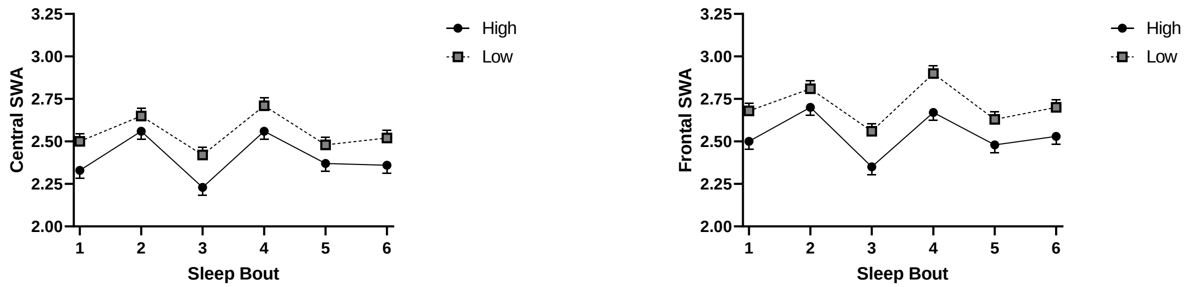


Figure 8: Differences in slow wave activity across simulated military operational stress in high and low performers

5.4 Discussion

In operational settings, military personnel must maintain high levels of marksmanship and physical performance. We examined the influence of baseline characteristics and different aspects of sleep on physical performance and marksmanship at baseline and throughout a SMOS protocol. Neither baseline characteristics nor baseline sleep predicted marksmanship performance contrary to our hypothesis. Conversely, higher aerobic fitness ($\dot{V}O_{2peak}$), lower habitual daytime sleepiness (ESS) and lower frontal NREM SWA predicted better baseline physical performance but did not relate to change in performance across SMOS. That better aerobic fitness was related to better performance across a physical performance battery that included endurance-based tasks was consistent with the intended task design. Of further interest was that two sleep variables, ESS and frontal SWA also contributed to baseline physical performance, but not to change in performance.

While we expected a decremental effect of daytime sleepiness, that higher frontal SWA predicted worse physical performance was opposite of our hypothesis. We had hypothesized that more SWA would reflect a greater restorative capacity of sleep, due in part to the physiological underpinnings of sleep[12,152,299]. Further, prior work has demonstrated positive associations between SWS and fitness[299]. Conversely, in the current study, higher SWA (and daytime sleepiness) may have reflected chronic, insufficient sleep and/or higher inherent/baseline sleep need, which then contributed to reduced physical performance capabilities. As SWA reflects homeostatic sleep need, higher SWA may have reflected a homeostatic response to chronic insufficient sleep or higher inherent sleep need[37].

While $\dot{V}O_{2peak}$, ESS and SWA were related to baseline physical performance, these variables did not predict changes in physical performance across SMOS. We had originally hypothesized that higher SE, lower WASO, more SWS and more SWA would prevent SMOS-related decrements in physical performance; however, based on the findings from baseline performance, a second possibility was presented. If more SWA reflects greater sleep need as suggested above, then participants with higher SWA may be more sensitive to sleep loss and have greater vulnerability to SMOS[153]. Therefore, participants with more baseline SWA would experience greater performance decrements during SMOS. However, neither hypothesis was supported. Instead, no baseline sleep variables were identified as meaningful predictors of change in physical performance. Importantly, TMT performance was highly stable across time (ICC = .940); participants who performed better at baseline performed better throughout the SMOS protocol. This high stability may have impacted our ability to identify meaningful relationships between baseline sleep and performance change. Still, we did observe consistent relationships between SWA and TMT performance across the study. An intriguing possibility that warrants further investigation is that the stability of spectral sleep parameters across time contributed to the ability of participants to maintain physical performance across time.

We also found that baseline sleep parameters were not identified as meaningful predictors of baseline marksmanship or change in marksmanship performance throughout SMOS. That baseline sleep did not predict baseline marksmanship or change in marksmanship was contrary to our hypothesis. Marksmanship involves different aspects of cognitive and sensorimotor function, such as vigilance, perception-action coupling, perceptual discrimination and visuomotor function, which have demonstrated sensitivity to sleep duration and individual differences in sleep architecture[36,140,168,316]. However, within the current study, no sleep-related predictors were selected through lasso regressions on baseline marksmanship performance or change in performance across SMOS. As such individual differences in habitual sleep quality/daytime sleepiness, baseline sleep architecture and baseline NREM spectral activity may not impact marksmanship abilities at baseline or performance throughout exposure to SMOS. Importantly, this sample consisted of individuals who were experienced in marksmanship. Therefore, in well-trained tasks habitual sleep disturbances and daytime sleepiness may not have decremental effects that outweigh prior training or differences in overall performance capabilities[317]. It is, however, unclear whether differences in specific sleep features would influence marksmanship performance/skill acquisition in novice participants.

This study has several limitations that must be considered when interpreting results. First, while RPE was assessed throughout the TMT, we did not collect measures of motivation or mood which may have provided additional insight into psychological factors that may have impacted performance. Given the self-paced nature of TMT tasks, both motivation and mood during testing can influence physical performance. Sleep loss-induced decrements in motivation and mood during such tasks has been identified as underlying factors contributing to sleep loss-related performance decrements on self-paced endurance tasks. Motivation and mood outcomes were not captured during physical testing within the current study, but we were able to explore the relationships between lasso-identified predictors and subjective responses to TMT performance (RPE). $\dot{V}O_{2peak}$, ESS and frontal SWA did not predict RPE across the TMT. Second, we did not collect measures of sleep history. Physical performance is sensitive to sleep duration. Therefore, quantifying differences in sleep leading up to the laboratory stay would have allowed us to examine whether chronic insufficient sleep impacted baseline performance and related to ESS or SWA at baseline. Lastly, based on the military sample and military-specific stressor, these results may not be generalizable to the broader population.

In conclusion, aerobic fitness, daytime sleepiness and frontal SWA predicted baseline physical performance but not marksmanship performance. Additionally, baseline sleep did not influence change in physical performance or marksmanship throughout exposure to SMOS. Individual differences in sleep architecture and spectral activity did not influence operationally-relevant outcomes in a sample of military personnel. Still, these findings were observed within the context of an acute stressor and experimentally-controlled sleep duration. Therefore, these findings must be confirmed within real-world settings which often involve chronic sleep loss and variable sleep duration.

6.0 Aim 3: Combined effects of time-of-day and simulated military operational stress on perception-action coupling performance

Abstract

Perception-action coupling, the ability to 'read and react' to the environment, is essential for military personnel to operate within complex and unpredictable environments. Exposure to military operational stressors (e.g., caloric restriction, sleep loss, physical exertion), including around-the-clock operations, may compromise perception-action coupling, thereby impacting performance and safety. We examined the combined effects of simulated military operational stress (SMOS) and time-of-day on perception-action coupling. Fifty-seven active duty and reservist military personnel (45 M; 26.4 ± 5.6 years) completed a 5-day SMOS protocol that included two consecutive days of caloric restriction, sleep restriction, and disruption. Participants completed a tablet-based perception-action coupling task (PACT) that involves perceiving whether virtual balls fit through virtual apertures. Familiarization occurred on day 0. Eight trials across day 1 (18:00, 22:00), 2 (04:00, 18:00, 22:00) and 3 (04:00, 18:00, 22:00) were analyzed. Mixed models were run to examine the interactive and main effects of day, and time-of-day on PACT response speed and accuracy outcomes. PACT response speed and accuracy outcomes improved at 18:00 and 22:00, whereas performance at 04:00 deteriorated across days. Perception-action coupling performance was resilient to SMOS, except overnight when the circadian drive for sleep is high, and the effects of sleep loss are more prominent.

6.1 Introduction

Military personnel need to sustain high levels of performance despite exposure to different stressors, collectively referred to as military operational stress, which include sleep loss, caloric restriction, and high physical and cognitive demands[5]. Operational stressors can have an adverse impact on individual and team performance, psychological and physical health, and mission success. In both laboratory- and field-based studies, exposure to military operational stress can compromise cognitive and physical aspects of performance which underlie operational performance[18,50]. For example, vigilance, the ability to react quickly to stimuli, and working memory were compromised during an 84-hour simulated military operational stress (SMOS) scenario in which 13 male soldiers underwent severe sleep deprivation (i.e., slept for approximately 6-hours total) and restricted caloric intake to 1650 kcal/day[49]. Further time-of-day may have additional effects on operational performance, which is of particular relevance for military personnel who often operate during unconventional and rapidly changing shifts[5,38]. Cognitive and physical performance demonstrate circadian rhythmicity throughout the day, with performance being best in the morning shortly after waking and worst overnight during the early morning hours[195,318]. During a night of total sleep deprivation, vigilance, as assessed via the Psychomotor Vigilance Task (PVT)[194,196], deteriorates in association with increasing homeostatic drive for sleep and low circadian drive for wake but can be partially recovered in the morning as the circadian drive for wake increases[196]. Poor sleep and performing when the circadian drive for wakefulness is low contributes to falling asleep during watch, aviation accidents and friendly fire incidents[10,31,319]. As such, assessing the impact of military operational stress, including time-of-day, on cognitive and perceptual functions, which may underlie operational performance, is essential to understanding the demands placed on military personnel and for developing mitigation strategies and interventions.

Although the detrimental impact of military operational stress on cognitive and physical performance in military personnel is widely described[18,50], there is a need to examine the impact of military operational stress on other essential aspects of function, including the ability to adapt to ever-changing scenarios. Military personnel operate within dynamic environments which require that they continuously 'read and react' to their surroundings to efficiently adapt to changing circumstances[10]. This ability to 'read and react' involves perceiving and attuning to task-relevant, spatiotemporal characteristics of the environment, and coupling these perceptions with the appropriate and efficient execution of action - also known as *perception-action coupling*[51]. Examining the effects of military operational stress on perception-action coupling performance would provide greater insight on the effects of military operational stress on the performance capabilities of military personnel within operational settings.

Perception-action coupling, which involves perceiving and actualizing affordances, underlies the ability of individuals to successfully and efficiently maneuver through the environment[52,203]. *Affordance* refers to the opportunity for action available to an individual based on their interaction with the surrounding environment[204]. As such, affordances depend on both the characteristics and capabilities of the individual and on spatiotemporal features of the environment. To successfully navigate and operate within an environment an individual must be attuned to properties of the environment that alter or limit affordances; in other words, they must perceive both the available affordances and the changes in affordances[51]. In particular, individuals must be attuned to *action boundaries*, the points at which specific affordances change[52]. Further, individuals must actualize affordances, (i.e., execute actions) in accordance with their perceptions of affordances, and they must do so in an efficient manner[204,320].

One simplistic example that can be used to contextualize affordance-based behaviors is that of walking through a narrow passageway. When an individual tries to navigate a passageway, afforded behavior is determined by the relationship between the width of the passageway and the shoulder width or size of the individual. If an individual tries to walk straight through a passageway (i.e. with their shoulders parallel to the opening), the action boundary for a particular individual is the width at which they are no longer able to walk straight through the passage and must, instead, turn their body slightly to fit through the passage. Of note, this action boundary is specific to the individual and to the specific affordance of walking through the passage with their shoulders parallel to the opening. The inability to accurately perceive action boundaries, and therefore affordances, could lead an individual to attempt actions that are not possible, or to unnecessarily modify or not attempt actions that are possible, thereby increasing behavioral risk. For military personnel conducting training exercises or operations requiring navigation through unfamiliar territory, attempting actions that are not afforded, and not attempting actions that are afforded, could both have substantial implications for personnel safety and operational performance.

To date, no studies have empirically examined the effects of military operational stress on perception-action coupling capabilities using affordance-based tasks. Prior studies have demonstrated sensitivity of affordance perception and actualization to the state of the individual. Affordance-based behaviors are altered under states of physical fatigue[207,208], anxiety[207], prior concussion[210], and perhaps, most relevant to military operational stress, altered sleep[56,213,242]. Although the negative impact of sleep loss on cognitive[19] and physical[17,18] aspects of performance have been widely described, only two studies have directly examined the effects of sleep loss on affordance-based aspects of performance[55,56]. Affordance actualization efficiency[55] and affordance perception accuracy[55,56] deteriorated following one night of complete sleep deprivation. It remains unknown whether sleep restriction protocols with more ecological validity, result in similar perception-action coupling deficits as total sleep deprivation protocols. Examining the effects of sleep restriction on affordance perception accuracy and affordance actualization efficiency could provide essential insight into operationally-relevant aspects of behavior that may be compromised in operational settings and could inform development of fatigue risk prediction tools. Additionally, the effects of time-of-day circadian factors and potential interactive effects of time-of-day and sleep loss on perception-action coupling performance are uninvestigated.

To address this knowledge gap, we examined the effects of a 5-day, 5-night simulated military operational stress (SMOS) protocol on perception-action coupling during an affordance-based task. In doing so we also examined the effects of time-of-day on perception-action coupling performance throughout SMOS exposure. We hypothesized that perception-action coupling performance would deteriorate throughout SMOS and that perception-action coupling performance would be worse overnight (04:00) than during typical waking hours (18:00 and 22:00). Finally, we examined perception-action coupling performance on different trial types in a perception-action task to determine whether systematic changes in sensitivity to behavioral risk occurred during exposure to SMOS. Examining the impact of SMOS on how individuals respond to different affordances may provide insight on whether individuals are likely to adopt more risky or conservative movement behaviors during SMOS. Findings from prior studies of total sleep deprivation are mixed; in one study participants made more conservative affordance perception judgements[56] while no effects of total sleep deprivation on behavioral risk were observed in the second study[55].

6.2 Methods

6.2.1 Participants

Participants were active duty and reservist military personnel who were considered medically ready to deploy. Potential participants were recruited through word of mouth, briefs, and fliers. Interested participants completed a telephone screening to determine eligibility. Eligibility criteria included: 1) 18-40 years old; 2) active duty or recently separated (< 2 years) military personnel; 3) eligible for deployment; 4) successful completion of branch-specific annual physical fitness test; 5) ability to complete marksmanship qualification with a M4/M16. Exclusion criteria included: 1) injury profile or current musculoskeletal injury that would limit the ability to run, jump or march with a load; 2) medications that influence sleep, hormone concentrations or cognitive function including, hypnotics, benzodiazepines, antidepressants, anxiolytics, antipsychotics, decongestants and sedating antihistamines, beta blockers, corticosteroids, non-birth control related hormonal treatment; 3) current or recent history of concussion or traumatic brain injury; 4) currently working overnight shifts; 5) currently breastfeeding or pregnant; 5) high-risk of sleep apnea (STOPBANG > 4[254] or apnea-hypopnea index > 15 assessed using standard polysomnography during the first study night); 6) alcohol use disorder (AUDIT > 16)[255]; 7) severe, untreated, or recent treatment for schizophrenia, bipolar disorder or other psychotic disorder; 8) hospitalization for severe depression, suicidal thoughts or attempts in the past three months; and 9) drug abuse, including heroin and cocaine, in the past three months.

At intake, written informed consent was obtained. Participants could subsequently be withdrawn from the study if they failed a urine drug screen or breathalyzer completed after consent.

All study procedures were approved by the University of Pittsburgh IRB (STUDY19090271) and Department of Defense Human Research Protection Office.

6.2.2 Protocol

The SMOS protocol took place across five consecutive days and nights and was completed in cohorts of up to 4 participants at a time. Participants arrived to the laboratory at 18:00, the night prior to testing. At this time, participants completed baseline questionnaires: the Pittsburgh Sleep Quality Index[258], Insomnia Severity Index[262] and Epworth Sleepiness Scale[263] to quantify habitual sleep complaints. Participants had an 8-hour sleep opportunity (23:00 – 07:00) on nights 0 (adaptation), 1 (baseline) and 4. Participants received 100% of their estimated caloric need on these days. Caloric need was determined from estimated daily energy expenditure predicted via air-displacement plethysmography (Bod Pod® Body Composition System; Life Measurement Instruments, Concord, CA) during the morning of day 0. On nights 2 and 3, participants had two 2-hour sleep opportunities (01:00 – 03:00 and 05:00 – 07:00) and received 50% of their estimated caloric need. Throughout each study day, participants completed cognitive, physical and marksmanship testing. The physical test battery, designed to physically fatigue participants, has been described elsewhere and included military-specific tests such as a fire-and-movement drill and a loaded 4-mile ruck march[288].

The Perception-Action Coupling Task (PACT), described below, was completed 10 times throughout the SMOS protocol. Participants completed PACT at approximately 18:00 on days 0-4 (D0-4), at 22:00 on D2-4 and at 04:00 on D2 and D3 (Figure 9). PACT administrations at 18:00 were part of test battery that assessed sensorimotor function, military-specific decision making, and cognitive function. PACT administrations at 22:00 and 04:00 were part of cognitive test batteries. Further, the administrations at 04:00 were completed 1-hour after waking up to minimize potential effects of sleep inertia (post-waking grogginess or reduced alertness) due to the 01:00 – 03:00 sleep opportunities. The PACT administration on D0 at 18:00 served as a familiarization trial and was not included in analyses[268]. The trial completed on D4 was also not included in the analyses since PACT was only completed at one time point (18:00), prohibiting a time-of-day factor.

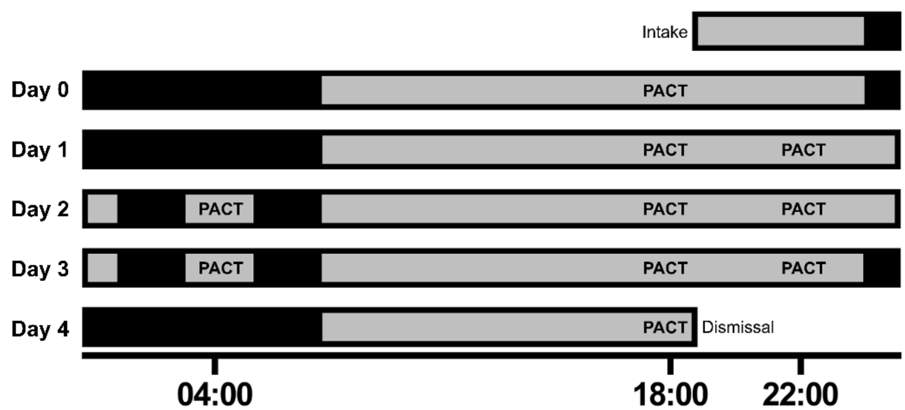
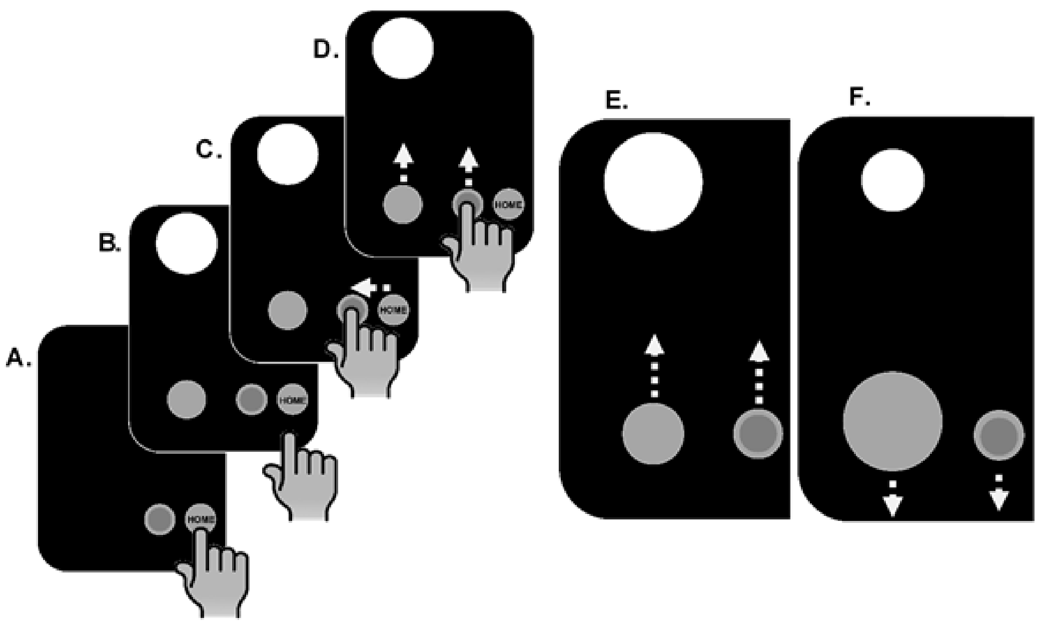


Figure 9. Perception-action coupling (PACT) task testing schedule

6.2.3 Perception-Action Coupling Task (PACT)

The PACT is a tablet-based assessment lasting approximately 15-minutes that evaluates affordance perception, the ability of individuals to perceive changes in action possibilities. During the task, a series of yellow balls and white apertures of varying sizes are presented on the tablet screen, and participants need to make perceptual judgements as quickly and accurately as possible regarding whether the ball could fit through the aperture. Participants completed a response by moving their index finger from a home button (standardized starting position) to a joystick which they moved up to move the ball towards the aperture, or down, to move the ball away from the aperture depending on their judgement of the relative fit between the ball and the aperture (Figure 10). The relative size of the ball and aperture varied between eight ball-aperture ratios: 0.2, 0.4, 0.6, 0.8, 1.2, 1.4, 1.6 and 1.8. Ratios less than 1 reflected that the affordance of the ball fitting through the aperture was available (the ball could fit through the aperture). For afforded trials, a correct response required moving the joystick up to move the ball towards the aperture. Conversely, ratios more than 1 reflected that the affordance of the ball fitting through the aperture was not available (the ball could not fit through the aperture; these trials were referred to as unafforded). For unafforded trials, a correct response required moving the joystick down to move the ball away from the aperture.



Participants start with their finger on the HOME button (**a**). Reaction time (RXT) is the time from the presentation of the ball (grey circle) and aperture (white circle) to when participants lift their finger off the HOME button (**b**). Movement time (MT) is the time to move from the HOME button to the joystick (**c**). Initiation time (IT) is the time to complete the response using the joystick (**d**). Participants move the joystick up, to move the ball towards the aperture, during afforded trials (**e**) and move the joystick down, to move the ball away from the aperture, during unafforded trials (**f**)

Figure 10. Perception-action coupling task (PACT) interface throughout completion of a trial

Primary outcomes of affordance actualization included reaction time (RXT; the time to lift the finger off the home button), movement time (MT; the time to move from the home button to the joystick), initiation time (IT; the time to complete the response using the joystick), and response time (RT; overall time to complete the response). Primary outcomes of affordance perception accuracy (ACC) included the total number of correct responses, incorrect responses (responses completed with an inaccurate affordance judgement), and lapses (responses that were not completed).

6.2.4 Statistical Analysis

All statistics were performed in R (Version 4.0.3). Shapiro-Wilk tests were used to assess normality. Due to violations of assumptions of normality of the standardized residuals, RT measures were reciprocally transformed, and ACC measures were log-transformed. To examine the effects of SMOS exposure across time on perception-action coupling performance, separate linear mixed effects models (*lmer* function from the *lmerTest* package) were performed for each PACT outcome variable using the restricted maximum likelihood approach[275]. Time-of-day (04:00, 18:00, 22:00) and study day (D1-3) and the interaction between time and day were included as categorical fixed effects. Participants were included as random effects; random slopes for the crossed effects of time and day were also included. When models failed to converge, random slopes were removed, and random intercept models were performed[276]. Unstructured random effects covariance structures were used. All models controlled for age. To address the primary aims of the study which were to examine the combined effects of SMOS and time-of-day on PACT outcomes, pairwise comparisons with Tukey adjustments for multiple comparisons were performed to examine differences between test timepoints when interaction effects were significant (*emmeans* package)[277,278]. When adding the interaction effect was not significant, the interaction term was removed and main effects from the additive model were examined. Pairwise comparisons were performed between test timepoints using Tukey adjustments for multiple comparisons The Kenward-Rogers method was used to determine the denominator degrees of freedom. To examine changes in behavioral risk within PACT performance during SMOS exposure, affordance condition (afforded, unafforded) was added as a fixed effect to the above-described models. All interaction effects were also added. When the interaction effects including affordance condition were not significant, affordance condition was removed from the interaction effect and the main effect of affordance condition was examined. This study and analyses were not preregistered.

6.3 Results

Out of 69 enrolled participants, 12 participants were missing task data due to technical issues. While linear mixed models are robust to missing data, we excluded participants with missing data due to participants missing data from multiple timepoints. Thus, data from 57 participants (45 men, 12 women; 26.4 ± 5.6 years) were included in analyses. Participants were predominantly white, in the Army, and reported minimal sleep complaints (Table 7). Compared to non-restriction days, participants consumed 37.5 ± 9.6% less calories and slept 49.0 ± 2.7% less time on the two restriction days.

Table 7. Descriptive information of study participants

Racial Identity	Count (%)
White	38 (66.67%)
Black or African American	15 (26.31%)
Multiracial	2 (3.50%)
Asian	1 (1.75%)
Undisclosed	1 (1.75%)
Military Branch	
Army	48
Marines	6
Air Force	3
Sleep History	Mean (SD)
PSQI	4.0 (2.5)
ISI	4.3 (3.4)
ESS	5.3 (2.2)

PSQI, Pittsburgh Sleep Quality Index; ISI, Insomnia Severity Index; ESS, Epworth Sleepiness Scale

6.3.1 Effect of SMOS on affordance actualization

All affordance actualization measures underwent a reciprocal transformation, therefore higher values reflect faster responses (shorter times) and lower values reflect slower responses (longer times). A significant day x time interaction effect was found for RT (Table 8).

Table 8. Interactive and main effects of time-of-day and day on aspects of PACT performance during exposure to simulated military operational stress

		F	df_1	df_2	*P*
1/RT	Time*Day	9.656	3	168	< .001
1/RXT	Time*Day	0.507	3	280	.678
	Time	12.974	2	58.902	< .001
	Day	4.283	2	280	.010
1/MT	Time*Day	6.192	3	280	< .001
1/IT	Time*Day	0.953	3	392	.410
	Time	18.731	2	392	< .001
	Day	1.061	2	392	.347
Correct	Time*Day	7.218	3	392	< .001
Lapses	Time*Day	7.218	3	392	< .001
Incorrect	Time*Day	1.901	3	278.741	.130
	Time	4.954	2	59.157	.010
	Day	2.212	2	279.050	.111

Main effects of time and day were not examined when a significant interaction effect was found; RT, response time; RXT, reaction time; MT, movement time; IT, initiation time

Pairwise comparisons confirmed that RT at 22:00 got faster across study days while RT at 04:00 got slower (Figure 11; Appendix D). RT at 04:00 on D2 was slower than RT at 18:00 on D3 (β = -0.071, SE = 0.017, $t_{70.7}$ = -4.342, p = .001) and at 22:00 on all days (D1: β = -0.0642, SE = 0.016, $t_{82.3}$ = -3.918, p = .005; D2: β = -0.102, SE = 0.015, $t_{123.2}$ = -6.886, p < .001; D3: β = -0.137, SE = 0.015, $t_{123.2}$ = -9.188, p < .001). Further, RT at 04:00 on D3 was slower than RT at 18:00 on D1 and D3 (β = -0.0594, SE = 0.017, $t_{80.4}$ = -3.519, p = .02; β = -0.093, SE = 0.015, $t_{118.5}$ = -6.079, p < .001, respectively) and slower than at 22:00 on all days (D1: β = -0.085, SE = 0.017, $t_{81.7}$ = -5.162, p < .001; D2: β = -0.124, SE = 0.015, $t_{74.2}$ = -8.227, p < .001; D3: β = -0.137, SE = 0.015, $t_{123.2}$ = -9.188, p < .001). Conversely, RT at 22:00 on D2 was faster than RT at 18:00 on D1 and D2 (β = 0.064, SE = 0.015, $t_{74.4}$ = 4.293, p = .002; β = 0.084, SE = 0.013, $t_{181.3}$ = 6.240, p < .001, respectively). Similarly, RT at 22:00 on D3 was faster than RT at 18:00 on all days (D1: β = 0.077, SE = 0.015, $t_{72.8}$ = 4.973, $p < .001$; D2: β = 0.097, SE = 0.014, $t_{95.3}$ = 6.893, $p < .001$; D3: β = 0.044, SE = 0.013, $t_{181.3}$ = 3.276, $p = .03$, respectively). Lastly, RT at both 18:00 and 22:00 got faster across the study from D1 to D3 (18:00: β = 0.053, SE = 0.013, $t_{196.0}$ = 4.100, $p = .002$; 22:00: β = 0.0513, SE = 0.014, $t_{130.2}$ = 3.562, $p = .01$). No other significant differences were found between timepoints.

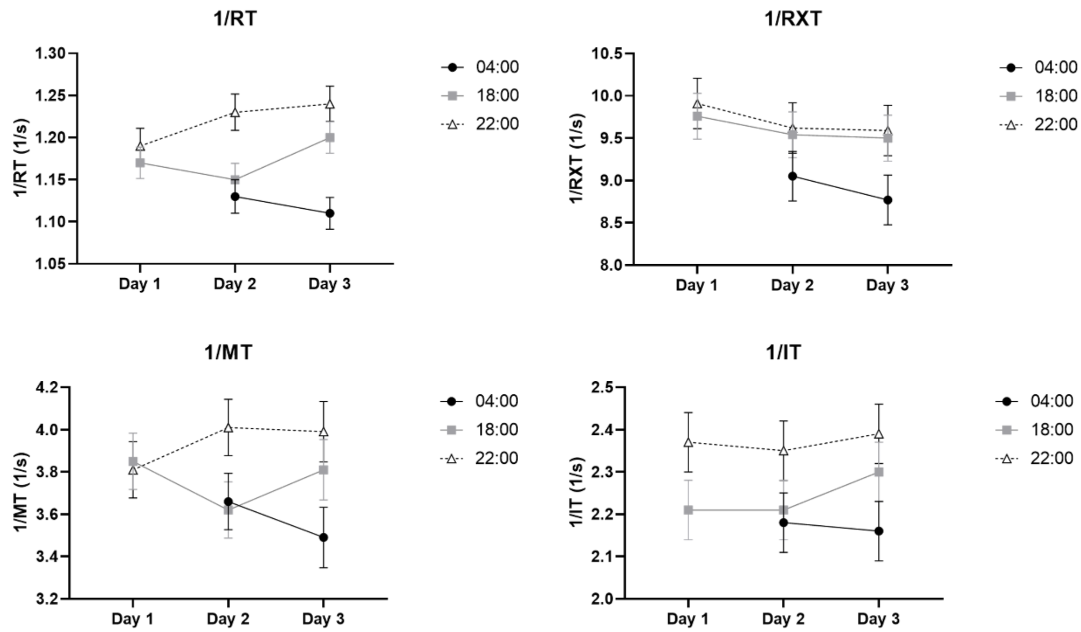


Figure 11. Changes in affordance actualization measures across exposure to simulated military operational stress at three times of day

For RXT, significant main effects of time and day were found but no interaction effect was found (Table 8). RXT was slower during sleep disruption and got slower across SMOS (Figure 11). Compared to 04:00, RXT was faster at 18:00 (β = 0.599, SE = 0.143, $t_{62.7}$ = 4.199, $p < .001$) and at 22:00 (β = 0.705, SE = 0.140, $t_{63.0}$ = 5.052, $p < .001$). Compared to D1, RXT was slower on D3 (β = -0.327, SE = 0.111, t_{283} = -2.934, $p = .01$).

For MT, a significant day x time interaction effect was found (Table 8). Pairwise comparisons confirmed that MT at 22:00 got faster across study days while MT at 04:00 got slower (Figure 11; Appendix D). Accordingly, MT at 04:00 on D2 was slower than MT at 22:00 on D2 and D3 (β = -0.355, SE = 0.085, $t_{280} = -4.160$, $p = .001$; β = -0.333, SE = 0.093, $t_{219} = -3.581$, $p = .012$, respectively). Further MT at 04:00 on D3 was slower than MT at 18:00 on D1 and D3 (β = -0.364, SE = 0.105, $t_{137} = -3.454$, $p = .02$; β = -0.326, SE = 0.085, $t_{280} = -3.819$, $p = .005$, respectively) and slower than MT at 22:00 on D2 and D3 (β = -0.524, SE = 0.093, $t_{219} = -5.633$, $p < .001$; β = -0.502, SE = 0.085, $t_{280} = -5.878$, $p < .001$, respectively). MT at 18:00 on D2 was also slower than MT at 22:00 on D2 (β = -0.387, SE = 0.085, $t_{280} = -4.527$, $p < .001$) and D3 (β = -0.364, SE = 0.093, $t_{219} = -3.918$, $p < .001$, respectively). No other significant differences were found between timepoints.

For IT, the main effect of day and interaction effect were not significant but a significant main effect of time was found (Table 8). IT at 22:00 was faster than at 18:00 (β = 0.131, SE = 0.031, $t_{395} = 4.287$, $p < .001$; Figure 11) or 04:00 (β = 0.207, SE = 0.036, $t_{395} = 5.781$, $p < .001$; Figure 11). IT at 18:00 did not significantly differ from 04:00.

6.3.2 Effect of SMOS on affordance perception accuracy

For log-transformed correct responses, a significant day x time interaction effect was found (Table 8). Pairwise comparisons confirmed that correct responses decreased at 04:00 across the study (Figure 12; Appendix D). Participants completed more correct responses at 22:00 on D3 than at 18:00 on D2 (β = 0.032, SE = 0.010, $t_{277} = 3.245$, $p = .035$). Compared to 04:00 on D3, participants completed more correct responses at 18:00 (β = 0.052, SE = 0.010, $t_{197} = 4.985$, $p < .001$) and 22:00 on D1 (β = 0.058, SE = 0.011, $t_{182} = 5.374$, $p < .001$), at 04:00 (β = 0.039, SE =

0.010, $t_{280} = 4.018$, $p = .002$) and 22:00 on D2 ($\beta = 0.045$, SE = 0.012, $t_{182} = 4.195$, $p = .001$) and at 18:00 ($\beta = 0.054$, SE = 0.010, $t_{197} = 5.150$, $p < .001$) and 22:00 on D3 ($\beta = 0.059$, SE = 0.011, $t_{182} = 5.534$, $p < .001$). No other significant differences were observed between timepoints.

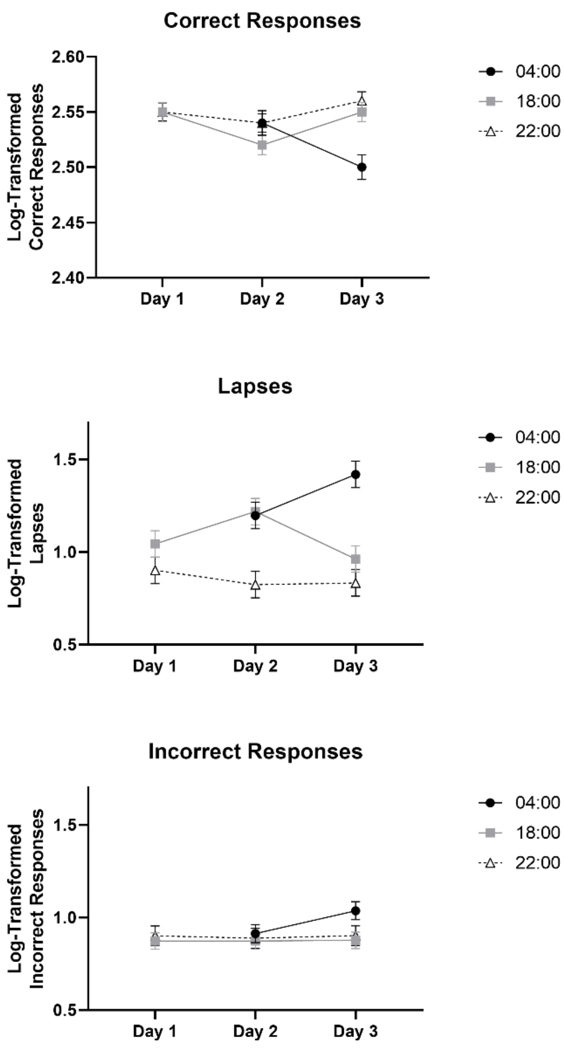


Figure 12. Changes in affordance perception accuracy measures across exposure to simulated military operational stress at three times of day

For log-transformed lapses, a significant day x time interaction effect was found (Table 8). Pairwise comparisons confirmed that lapses at 04:00 increased across study days and were lower at 22:00 (Figure 12; Appendix D). Lapses were higher at 04:00 on D2 than at 22:00 on all days (D1: β = 0.296, SE = 0.076, t_{392} = 3.910, p = .003; D2: β = 0.373, SE = 0.076, t_{392} = 4.920, p < .001; D3: β = -0.364, SE = 0.076, t_{392} = 4.807, p < .001). Similarly, lapses were higher at 04:00 on D3 than at 18:00 on D1 and D3 (β = 0.377, SE = 0.0758, t_{392} = 4.966, p < .001; β = 0.457, SE = 0.076, t_{392} = 6.031, p < .001, respectively) and higher than at 22:00 on all days (D1: β = 0.519, SE = 0.076, t_{392} = 6.839, p < .001; D2: β = 0.595, SE = 0.076, t_{392} = 7.849, p < .001; D3: β = 0.587, SE = 0.076, t_{392} = 7.736, p < .001). Lastly, lapses at 18:00 on D2 were higher than at 22:00 on all days (D1: β = 0.318, SE = 0.076, t_{392} = 4.190, p = .001; D2: β = 0.394, SE = 0.076, t_{392} = 5.200, p < .001; D3: β = -0.386, SE = 0.076, t_{392} = -5.087, p < .001, respectively). No other significant differences were found between timepoints.

For log-transformed incorrect responses, the effect of day and interaction effect were not significant, but there was a significant effect of time (Table 8). Compared to 04:00, less incorrect responses occurred at 18:00 (β = -0.102, SE = 0.032, $t_{63.3}$ = -3.153, p = .007; Figure 4) and at 22:00 (β = -0.079, SE = 0.033, $t_{63.6}$ = -2.429, p = .05; Figure 12).

6.3.3 Changes in behavioral risk during exposure to SMOS

No significant affordance condition x time-of-day or affordance condition x day effects were found for any PACT outcome measure (Table 9). Models were re-run after removing affordance condition from the interaction term to examine the main effect of affordance condition across the stress exposure. RT (β = -0.079, SE = 0.004, t_{623} = -19.794, p < .001), RXT (β = -0.818, SE =

0.0579, t_{623} = -14.144, p < .001), MT (β = -0.238, SE = 0.027, t_{623} = --8.810, p < .001) and IT (β = -0.127, SE = 0.018, t_{847} = -6.904, p < .001) were slower during afforded than unafforded trials. Further, participants completed more correct responses on unafforded trials than afforded trials (β = 0.019, SE = 0.004, t_{735} = 4.140, p < .001). Both lapses and incorrect responses contributed to the difference in correct responses between trial types. There were significantly more lapses (β = 0.058, SE = 0.019, t_{693} = 3.014, p = .002) and more incorrect responses (β = 0.219, SE = 0.018, t_{729} = 11.997, p < .001) during afforded trials than during unafforded trials.

Table 9. Differences in performance during afforded and unafforded PACT trials across exposure to simulated military operational stress for different trial types

		F	df_1	df_2	p
1/RT	Afford*Time*Day	0.4929	3	616	.687
	Afford*Time	1.3388	2	616	.263
	Afford*Day	0.4196	2	616	.657
1/RXT	Afford*Time*Day	2.1486	3	616	.093
	Afford*Time	1.5045	2	616	.223
	Afford*Day	0.7496	2	616	.473
1/MT	Afford*Time*Day	0.6212	3	616	.601
	Afford*Time	0.0471	2	616	.954
	Afford*Day	0.4930	2	616	.611
1/IT	Afford*Time*Day	0.0359	3	616	.991
	Afford*Time	0.2331	2	616	.792
	Afford*Day	0.1074	2	616	.898
Correct	Afford*Time*Day	1.0581	3	728	.366
	Afford*Time	0.2410	2	728	.786
	Afford*Day	0.4865	2	728	.615
Lapses	Afford*Time*Day	0.1737	3	616	.914
	Afford*Time	0.1442	2	616	.866
	Afford*Day	0.4481	2	616	.639
Incorrect	Afford*Time*Day	1.0391	3	721	.375
	Afford*Time	1.4780	2	721.57	.229
	Afford*Day	0.2072	2	721.18	.813

RT, response time; RXT, reaction time; MT, movement time; IT, initiation time

6.4 Discussion

In the current study we examined the impact of SMOS on perception-action coupling across three times-of-day in military personnel. Changes in perception-action coupling performance were related to both the duration of exposure to SMOS and time-of-day. Perception-action coupling performance was worse at 04:00 than at 18:00 and 22:00. Further, perception-action coupling capabilities at 04:00 deteriorated across two consecutive nights of sleep restriction and disruption. Conversely, perception-action coupling capabilities were resilient to SMOS at 18:00 and 22:00 and improved across study days. Both affordance actualization efficiency (e.g., RT) and affordance perception accuracy (e.g., number of correct responses) followed similar patterns of change. Lastly, SMOS exposure and time-of-day did not systematically alter the behavioral risk strategies adopted by participants; that is, participants were not riskier or more conservative in their responses.

In support of our hypothesis, measures of RT and ACC changed across different times of day. Slower RXT, MT and IT contributed to slower overall RT at 04:00 compared to 18:00 and 22:00. On D2, MT and RT at 04:00 and 18:00 was slower than at 22:00 but on D3 MT and RT at 04:00 deteriorated while performance at 18:00 improved. The significant interaction between study day and time-of-day observed for RT and MT reflects the cumulative effects of SMOS and the combined effects of sleep loss and circadian-related processes on affordance actualization efficiency. Performance during the circadian night, when the circadian drive for sleep is high, was more susceptible to the deleterious cumulative effects of SMOS, consistent with the sleep loss literature[194,196]. The combined effects of being awake during the circadian night, and the accumulated homeostatic sleep need from consecutive nights of sleep restriction and disruption compromised perception-action coupling performance. As military personnel often operate under similar conditions, military leadership must be cognizant of how these conditions may influence operational efficiency. Further, when overnight operations are required, fatigue prevention countermeasures may be needed to mitigate deleterious effects of time-of-day, particularly when sleep loss is also involved.

Decrements in RT reflect an overall deterioration of affordance actualization efficiency, but the separation of RT into different components allowed us to further examine specific aspects of perception-action coupling. RXT, MT and IT reflect the actualization of the action response, characterizing the reaction to the initial presentation of visual stimuli, coupling of a perceptual judgement with a motor response and execution of a motor response, respectively, although some overlap exists. Decrements in MT and IT demonstrate the importance of examining motor function in the context of perceptual judgements. Isolated aspects of motor function (i.e. maximal strength or aerobic endurance) can be maintained despite exposure to pronounced sleep loss and SMOS [18,179], but altered perception-action coupling may still contribute to compromised movement behaviors and increased movement errors.

Unlike MT and RT, RXT slowed across days. RXT on D3 was significantly slower than on D1. Within each time-of-day, minimal changes in RXT were observed across days. Rather, the significant slowing of RXT across days was due to the addition of the 04:00 timepoint on D2 and D3; RXT at 04:00 was significantly slower than at 18:00 and 22:00. Still, that RXT did not get faster at 18:00 and 22:00, while MT and IT did, highlights that different aspects of perception-action coupling may respond to SMOS exposure differently. Additionally, these findings demonstrate the ability of individuals to adapt their movement behaviors to maintain and improve movement efficiency despite a delayed initial reaction to task-relevant visual information. Despite slower RXT, participants maintained RT at 04:00 on D2. These findings highlight the importance of assessing changes in performance by using tasks with behavioral endpoints rather than simple reaction time tasks; reaction time may be compromised but individuals can still perform at a high level, maintaining overall RT, by adapting the movement behaviors used to complete a task.

Similar combined effects of time-of-day and SMOS exposure were observed for ACC measures. Correct responses were lowest and lapses and incorrect responses were highest at 04:00 on D3. The deterioration in affordance perception accuracy at 04:00 on D3 was related both to increased attentional lapses, potentially due to microsleeps, and to increased incorrect perceptual judgements. Microsleeps are brief periods of sleep, often occurring locally rather than across the entire brain cortex, that cause brief unresponsive periods and lead to lapses[23,200]. More incorrect responses at 04:00 demonstrates the detrimental effect of performing at this time-of-day on the ability of participants to make appropriate perceptual judgements about affordance possibilities. Making inaccurate affordance judgements could lead individuals to attempt actions that are not possible or to not attempt actions that are, compromising performance and safety. This finding further highlights the importance of examining perception-action coupling capabilities; not only did participants have more lapses but they also made more inaccurate perceptual judgements and therefore were more likely to execute inappropriate movement behaviors. That these decrements in accuracy occurred with similar decrements in RT also highlights that a speed-accuracy trade-off was insufficient to maintain perception-action coupling performance.

Although these findings suggest that performance capabilities may be compromised during around-the-clock or sustained operations, the magnitude of PACT performance deficits observed, for both RT and ACC measures, is less than previously reported after total sleep deprivation[55]. Following total sleep deprivation, RXT slowed by 16.8%, MT by 21.4%, and IT by 11.8%, while accuracy decreased by 3.9%. In the current study, RXT and IT were 7.4% and 8.9% slower at

04:00 than 22:00, respectively. MT was 10.2% slower and correct responses were 2.0% lower at 04:00 on D3 than at 18:00 on D1. SMOS exposure and time-of-day compromised PACT performance, but to a lesser extent than one night of total sleep deprivation.

Contrary to our hypothesis, participants maintained and improved perception-action coupling performance at 18:00 and 22:00 across increasing exposure to SMOS as reflected by faster RT and increased correct responses across study days. High resilience to SMOS was most evident at 22:00 for MT and RT. Faster MT and RT, and more correct responses at 18:00 and 22:00 across days may reflect improved abilities to attune to task-relevant spatial characteristics or to increased efficiency of movement behaviors used to complete responses[320]. Repeated PACT administrations across study days allowed participants greater exposure to task-relevant spatial characteristics and allowed them greater exploration of efficient movement strategies to complete PACT responses. Optimizing movement strategies would have allowed participants to increase response and movement speed without compromising response accuracy. A prior reliability study[268] established that one familiarization session is needed to ensure within-individual stability of PACT performance. Differing testing schedules between studies may have contributed to the unexpected improvement in PACT performance in the current study. Specifically, here participants completed PACT administrations across multiple consecutive days and across different times-of-day which may have influenced PACT performance. Future neuroimaging and event-related potential studies would be beneficial to examine changes in brain activity underlying changes in PACT performance and provide a better understanding of the mechanisms contributing to performance improvement or deterioration during SMOS. However, the fact that participants were able to improve perception-action coupling performance despite exposure to SMOS further suggests resilience of perception-action coupling to acute SMOS exposure conditions.

Responses were slower and less accurate on afforded trials than unafforded trials across the study protocol. Differences in performance between afforded and unafforded trials remained consistent across time-of-day and SMOS exposure. Slower performance on PACT during afforded trials has been previously described[55]. When action is not possible, participants respond quickly and accurately. Conversely when action is possible, participants respond slower and less accurately. This may reflect greater hesitation when action is possible to ensure appropriate execution of possible actions[207]; although the combination of slower and less accurate responses suggests that effects were independent of a speed-accuracy trade-off[321]. The slowing of responses did not enable participants to maintain levels of accuracy. Further, the lack of study day or time-of-day effects demonstrates that deterioration in PACT performance during the study protocol reflected a general decline in perception-action coupling performance rather than specific behavioral changes. Participants did not systematically respond more or less conservatively during SMOS.

Several limitations must be considered when interpreting study findings. First, PACT performance was assessed only at three times of day; therefore, we were unable to assess changes in performance across the entire day or to examine circadian rhythmicity in PACT performance in greater detail. Although the current study provides preliminary evidence showing circadian influences on PACT performance, future studies with more frequent PACT administrations throughout the day are needed to fully examine circadian influences on perception-action coupling performance. Further, more work is needed to examine circadian influences on different aspects of perception-action coupling in relation to real-world aspects of performance. Second, the study sample consisted of military personnel who self-selected to participate in a study about resilience. It is unclear whether these findings can be generalized beyond such a population. Third, participants completed the study protocol in cohorts and it is unclear to what extent this team setting, and differences in team dynamics across different cohorts may have impacted the findings reported here.

In conclusion, perception-action coupling performance in the afternoon and evening is resilient to SMOS exposure involving 48-hours of sleep restriction and disruption, caloric restriction, and daily physical exertion. Perception-action coupling performance is sensitive to time-of-day and the accumulation of sleep loss exacerbated time-of-day-related performance deficits contributing to greater performance deficits on the second consecutive night of sleep restriction and disruption. These findings demonstrate the importance of assessing the impact of SMOS on tasks that examine behavioral outcomes beyond the initial reaction to stimuli. Fatigue prediction tools must therefore incorporate tasks with behavioral endpoints in order to accurately quantify fatigue risk. Relevant to military leadership, these findings also demonstrate that military personnel may maintain high levels of performance in the evening despite exposure to operational stressors. Conversely, performance overnight may be more sensitive to stress exposure; therefore, countermeasures must be developed to mitigate increased fatigue risk during around-the-clock operations.

7.0 Aim 4: Distinct aspects of neurobehavioral resilience captured by assessments of vigor, fatigue, vigilance and perception-action coupling

Abstract

Pronounced individual differences in responses to sleep loss and operational stress exist whereby some individuals can maintain performance despite such stressors while other individuals experience substantial decrements in alertness and performance. Further, this neurobehavioral resilience to operational stress is highly task-dependent. We examined whether a subjective measure of alertness and behavioral measures of vigilance and perception-action coupling reflected distinct aspects of neurobehavioral resilience. Further, we examined whether resilient and vulnerable individuals differed in baseline sleep or sleep throughout exposure to simulated military operational stress. Forty-nine active duty and reserve status military personnel completed a 5-day simulated military operational stress protocol that included two nights of sleep restriction and disruption. Participants completed subjective reports of mood (alertness) and behavioral assessments of vigilance and perception-action coupling at baseline and at 04:00 across the 2 nights of sleep restriction and disruption. Resilient participants were those who maintained high levels of alertness/performance across both nights of sleep disruption as defined by each neurobehavioral assessment. Different neurobehavioral assessments did not agree in their classification of resilient individuals further highlighting the task-specific nature of neurobehavioral resilience. Interestingly, resilient participants, defined by a subjective report of alertness, had lower slow wave activity during non-rapid eye movement sleep than vulnerable participants. Slow wave activity, a marker of homeostatic sleep need, may reflect sensitivity to sleep loss and operational stress.

7.1 Introduction

While exposure to military operational stressors such as sleep loss, caloric restriction and physical exertion compromises neurobehavioral performance, the severity of performance deficits is not the same in all individuals[49]; individuals display different levels of neurobehavioral resilience to military operational stress. Neurobehavioral resilience to sleep loss, in particular, has been observed to be stable across repeated exposures to sleep loss and to different sleep manipulation protocols[57,59,228,230]. Within the sleep loss literature, neurobehavioral resilience has been defined using raw alertness/performance during sleep loss[58,229,322] or change in alertness/performance from baseline[317,323–326]. Combining both approaches, neurobehavioral resilience can be defined as the ability to maintain high levels of alertness and performance despite exposure to adverse or challenging conditions such as military operational stress and sleep loss. This definition of resilience necessitates that 1) individuals demonstrate a high level of alertness, and 2) that individuals demonstrate minimal deterioration in alertness from baseline.

However, when identifying and classifying resilient and vulnerable individuals it is important to consider the task-specific nature of resilience[57,58]. Whether an individual is classified as resilient varies across different domains of neurobehavioral function. Individuals who demonstrate neurobehavioral resilience on subjective measures of alertness such as the Profile of Mood States (POMS) vigor subscale do not necessarily demonstrate neurobehavioral resilience on behavioral assessments such as the Psychomotor Vigilance Task (PVT)[57,228,327] (but see[328]). Therefore, subjective and behavioral measures of alertness likely reflect distinct aspects of neurobehavioral function and resilience[327,329]. It remains unknown how traditional subjective and behavioral measures of neurobehavioral function relate to measures of perception-action coupling, which is also a critical aspect of neurobehavioral function. The PVT, which has been widely used to examine neurobehavioral resilience to sleep loss, provides a measure of reaction time and sustained attention that is sensitive to sleep loss[153,190]. During the PVT individuals must react quickly to the presentation of a visual or auditory stimulus. Still, to maintain optimal neurobehavioral function, individuals must not only react *quickly* but must also respond *appropriately*, an ability that may be particularly important within unpredictable and ever-changing environments such as those experienced by military personnel in the field. Responding appropriately relies on effective perception-action coupling, or the ability to couple perceptions of task-relevant information within a dynamic environment with an efficient and appropriate motor response or action. Perception-action coupling tasks, which similar to the PVT have demonstrated sensitivity to sleep loss[55,56], can thereby provide measures of both response speed and accuracy. Importantly, making a perceptual judgement while executing a motor response alters the timing of the motor response. Therefore, the underlying motor behaviors contributing to simple reaction time and perception-action coupling response times likely reflect distinct aspects of behavior/function. Examining the extent to which, perception-action coupling behaviors reflect distinct aspects of neurobehavioral resilience captured using more traditional subjective and behavioral measures would provide greater insight into the task-specific nature of neurobehavioral resilience and inform the development of fatigue assessment batteries to identify increased fatigue risk. Improved identification of fatigue risk, and fatigue-related behavioral deficits, would allow more effective use of fatigue mitigation strategies (e.g., caffeine[174,234–236,330,331], strategic naps[31,214,245,247,332–334]).

Of further interest is the examination of baseline factors, such as sleep, that may contribute to neurobehavioral resilience defined using different neurobehavioral assessments. Habitual and baseline sleep may mitigate sleep loss-related decrements in performance[237–239,335]. For example, experimental sleep extension protocols attenuate vigilance decrements throughout a night of sleep deprivation compared to decrements observed following a night of normal sleep suggesting a role of baseline sleep in resilience to sleep loss[237,335]. However, when comparing sleep between resilient and vulnerable individuals defined using different neurobehavioral tasks, the importance of sleep to neurobehavioral resilience is less clearly defined. Several studies have reported no difference in habitual sleep quality or duration between resilient and vulnerable individuals[57,228,322]. Still, it remains unclear whether baseline differences in specific aspects of sleep such as sleep continuity (sleep efficiency, SE; wake after sleep onset, WASO), sleep architecture (slow wave sleep, SWS; rapid-eye movement sleep; REM sleep) or spectral activity (slow wave activity; SWA) contribute to neurobehavioral resilience. These aspects of sleep relate to different aspects of neurobehavioral and cognitive performance under normal sleep conditions[35,87,336,337]. In particular, SWS and SWA may contribute to the restorative function of sleep and therefore, may be protective during subsequent exposure to sleep loss. Further, a recent study demonstrated that more SWS during a early morning nap during a night of sleep deprivation mitigated sleep loss-related neurobehavioral deficits[310]. Therefore, sleep during exposure to operational stress, in addition to baseline sleep, may contribute to neurobehavioral resilience.

Therefore, we aimed to examine whether subjective and behavioral measures of alertness reflected distinct aspects of neurobehavioral resilience during exposure to a simulated military operational stress (SMOS) protocol. We hypothesized that subjective and behavioral measures of alertness would reflect distinct aspects of neurobehavioral resilience. We further explored the impact of baseline characteristics, baseline sleep and sleep during the SMOS protocol on neurobehavioral resilience across subjective and behavioral measures. Therefore, we aimed to determine whether subjective measures of alertness, and behavioral measures of vigilance and perception-action coupling reflected distinct aspects of neurobehavioral resilience during exposure to a simulated military operational stress (SMOS) protocol. We hypothesized that subjective and behavioral measures would reflect distinct aspects of neurobehavioral resilience. We further determined differences in habitual (Pittsburgh Sleep Quality Index, PSQI; Insomnia Severity Index, ISI; Epworth Sleepiness Scale, ESS) and baseline sleep (SWS, REM, SWA) between resilient and vulnerable individuals defined using different neurobehavioral assessments. We hypothesized that individuals with high neurobehavioral resilience measures would demonstrate better habitual sleep quality (PSQI), lower daytime sleepiness (ESS), higher sleep continuity, higher SWS and SWA at baseline. Lastly, we explored differences in SWS, SWA and REM sleep throughout the SMOS protocol between resilient and vulnerable participants.

7.2 Methods

7.2.1 Participants

Active duty and reserve-status military personnel were recruited to complete the 5-day SMOS protocol. Participants included in the study were medically-eligible for deployment, had passed their most recent annual physical fitness test, endorsed comfort using a M4/M16. Participants were excluded if they had a recent musculoskeletal injury that would limit their ability to complete physical testing, if they had a recent concussion, if they took medication that impacted their sleep, hormone levels or cognitive performance, if they were deemed at high risk for sleep disordered breathing, and if they took drugs of abuse (See [166] for additional details)

7.2.2 Protocol

As part of a larger 5-day study examining predictors of cognitive resilience during SMOS, participants completed assessments of subjective alertness (POMS), and behavioral measures of vigilance (PVT) and perception-action coupling (PACT) at three common timepoints: at baseline (22:00) and across two consecutive nights of sleep disruption and restriction (03:45; Figure 13). POMS was completed prior to the behavioral measures. PVT and PACT were completed in a counterbalanced order. Details of the study protocol have been outlined elsewhere. Briefly, participants had 8-hour (23:00 – 07:00) sleep opportunities on Night 0 (adaptation/familiarization), Night 1 (baseline) and Night 4 (recovery). On Nights 2 and 3, sleep was restricted and disrupted: participants had two 2-hour sleep opportunities (01:00 – 03:00 and 05:00 – 07:00). Participants received 100% of their estimated caloric need on Day 0 (familiarization), Day 1 (baseline) and Day 4 and received 50% of estimated caloric need on Days 2 and 3. Across all study days participants completed extensive cognitive and physical testing.

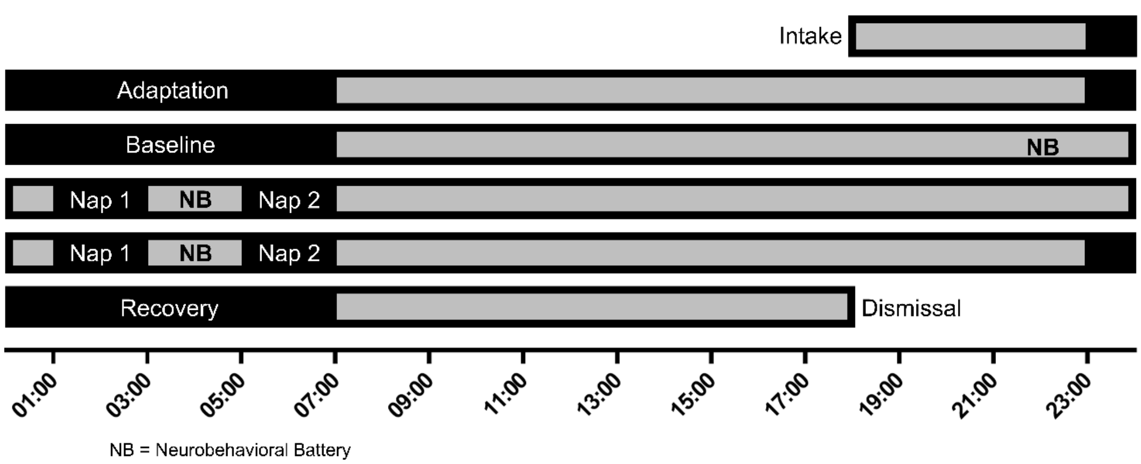


Figure 13. Timeline of neurobehavioral assessments

7.2.3 Profile of Mood States Questionnaire

The POMS is a 65-item questionnaire that asks participants to rate how well different aspects of mood describe their current state on a scale from 0 (not at all) to 4 (extremely)[267]. Subsets of items are then used to generate subscale scores and an overall score reflecting total mood disturbance. To examine alertness, primary POMS outcomes included the vigor and fatigue subscales. The vigor subscale includes items related to feeling energetic, alert and lively. Scores range from 0 to 32 with higher scores indicating more vigor (higher levels of alertness). The fatigue subscale includes items related to feeling weary, exhausted and worn out. Scores range from 0 to 28 with higher sores indicating more fatigue (lower levels of alertness).

7.2.4 Psychomotor Vigilance Task

A computer-based version of the 10-minute PVT (PC-PVT 2.0)[269] was completed 4 times across the protocol: Day 0 (22:00, familiarization) and 1 (22:00, baseline); and Day 2 and 3 (03:45). Participants were seated upright at the computer and completed responses using their dominant hand. At randomly spaced intervals (interstimulus interval = 1 – 10 seconds), red numbers appeared on the screen counting up from 0. Participants clicked the mouse key on the laptop as quickly as possible after seeing the numbers appear. Primary outcomes of interest included reaction time of the slowest 10% of trials (SLOW) and of the fastest 10% of trials (FAST). SLOW was selected to provide a measure of lapse severity and FAST was selected to provide a measure of optimal performance[192]. Both measures are sensitive to sleep loss[190].

7.2.5 Perception-Action Coupling Task

PACT is a tablet-based assessment of perception-action coupling efficiency and accuracy that lasts approximately 15 minutes (384 trials) and is sensitive to one night of total sleep deprivation[55]. During PACT a series of virtual balls and apertures of varying sizes are presented on the tablet. Participants made perceptual judgements as to the relative fit between the ball and aperture. Participants began with the index finger of their dominant hand placed on a standardized starting position on the tablet screen (home button). Upon the appearance of the ball and aperture pairing, participants lifted their finger off the home button and move it to the virtual joystick used to complete a response. If the ball was judged to be smaller than the aperture, participants swiped the virtual joystick towards the top of the tablet, which moved the ball towards the aperture. If the ball was judged to be larger than the aperture, participants swiped the joystick down towards the bottom of the tablet, which moved the ball away from the aperture. After completing a response, participants moved their index finger back to the home button and awaited the next trial. Participants were instructed to respond as quickly and accurately as possible. Primary outcomes of interest for PACT included the average time to complete a response (RT), lapses (no response completed) and incorrect responses. A familiarization trial on PACT was completed on Day 0[268]. Complete results of PACT from the 5-day protocol are detailed elsewhere (Aim 3).

7.2.6 Sleep Outcomes

At intake, participants completed baseline psychological questionnaires that included assessments of habitual sleep disturbances and daytime sleepiness: the Pittsburgh Sleep Quality

Index (PSQI), the Insomnia Severity Index (ISI) and the Epworth Sleepiness Scale (ESS). The PSQI assesses different aspects of sleep quality from the prior month. The ISI quantifies insomnia-related sleep disturbances. The ESS assesses typical daytime sleepiness. Across all questionnaires, higher scores reflect more sleep disturbances/more daytime sleepiness.

During the SMOS protocol, sleep was monitored each night using polysomnography (Compumedics Grael 4K PSG:EEG amplifier, Charlotte, NC) involving a standard 10-20 AASM montage that included: F3/4, C3/4, O1/2, M1/2, 2 EOG, 3 submentalis EMG, ground and reference at Fpz. Sleep staging was performed by certified sleep technicians according to AASM guidelines[74]. Power spectral analysis was used to extract spectral outcomes. Briefly, raw EEG data were digitized (256 Hz), filtered (0.3 – 30 Hz; 60 Hz), decimated and band-limited to 64 Hz after which a Fast Fourier Transform was performed and artifacts were removed using validated algorithms[271,272]. Primary outcomes of interest included measures of sleep continuity (sleep efficiency, SE; wake after sleep onset, WASO), sleep architecture (SWS, REM), and sleep depth (slow wave activity; SWA). Sleep measures from baseline and from the sleep opportunities immediately prior to sleep disruption neurobehavioral assessment were used.

7.2.7 Defining Resilience

To define participants as resilient or vulnerable to SMOS on each outcome measure of interest, a 2-step decision-making process was used (Figure 14). Tertile splits were conducted at 2 levels. First tertile splits were performed on the average mood or performance across both sleep disruption periods for each study outcome. Participants in the tertile corresponding to low performers/reduced alertness were classified as vulnerable at this stage. For the subset of participants in the two tertiles corresponding to moderate and high performance/alertness, a second tertile split was performed on the average change from baseline across both sleep disruption periods for each study outcome. Participants in the tertile corresponding to greater reduction in alertness from baseline (classified as unstable performers in Fig. 14) were classified as vulnerable. Participants in the two tertiles corresponding to minimal reductions (or an increase) in performance/alertness were classified as resilient. Through this two-step approach, participants classified as resilient had to demonstrate not only high overall performance and alertness during periods of sleep disruption but also had to maintain performance and alertness relative to baseline. In this way, the two-step approach allowed us to provide a more comprehensive definition of neurobehavioral resilience and vulnerability across each study outcome.

	Measure	Resilient	Vulnerable
POMS	Vigor	20	29
	Fatigue	25	24
PVT	SLOW	25	24
	FAST	25	24
PACT	1/RT	22	27
	Lapses	28	21
	Incorrect	27	22

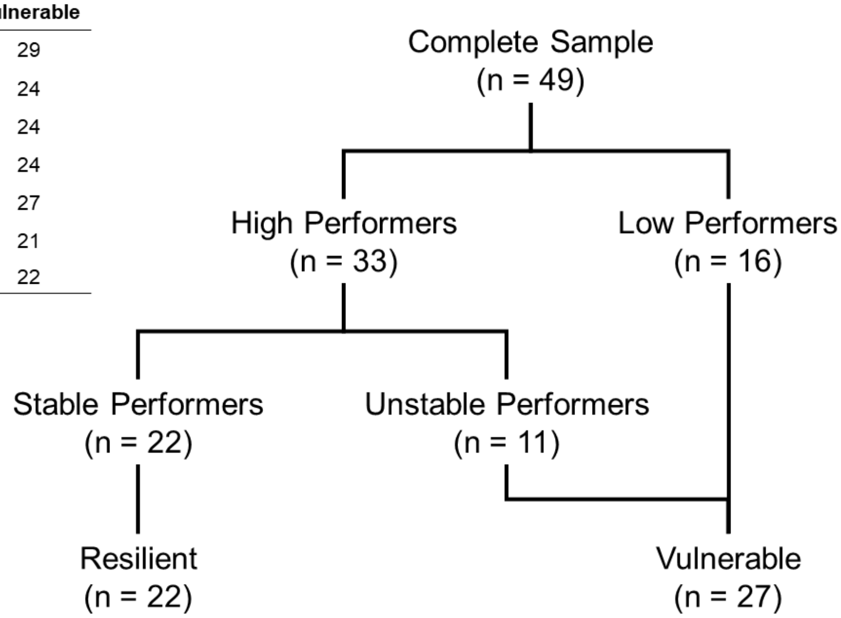


Figure 14: Flowchart of resilience definition process. Sample sizes for 1/RT displayed in flowchart, final sample sizes for each measure included in table

7.2.8 Statistical Analysis

All statistical analyses were performed in SPSS (Version 25, IBM, Armonk, NY) and R (Version 4.0). To assess normality, histograms were visually examined and Shapiro-Wilk tests were performed. Due to high skewness, reciprocal transformations of PACT RT and PVT SLOW were performed. Further, NREM spectral data was log-transformed.

To examine successful group allocation, differences in average sleep disruption performance and average change from baseline were examined using independent samples t-tests. T-tests were also used to examine differences in baseline performance between groups. To examine whether POMS, PVT and PACT outcomes assessed similar aspects of neurobehavioral resilience, Cohen's kappa coefficient and percent agreement between the different resilience groups were calculated. If a kappa coefficient > 0.6, reflecting substantial agreement between groups, was found between different measures then measures were considered to capture overlapping aspects of neurobehavioral resilience. If kappa coefficients were < 0.6 for different measures then these measures were considered to capture different aspects of neurobehavioral resilience. Kappa values were interpreted as follows: no agreement (< 0), slight (.01 - .20), fair (.21 - .40), moderate (.41 - .60), substantial (.61 - .80) and almost perfect (.81 – 1.00) agreement[338].

To examine the influence of baseline factors and sleep on different aspects of neurobehavioral resilience, t-tests and ANOVA were performed. T-tests were used to examine differences in habitual sleep questionnaires (PSQI, ISI, ESS) and baseline sleep EEG measures. To explore the impact of sleep during SMOS on neurobehavioral resilience, 2x2 (Resilience Group X Study Day) ANOVA were performed examining differences in sleep EEG measures from nap 1s (prior to the sleep disruption testing periods) between the resilient and vulnerable groups for each measure.

7.3 Results

7.3.1 Sample Characteristics

The final sample used for analysis included 49 participants (11 Women) for whom we had complete neurobehavioral and sleep data. Participants were 26.6 ± 5.8 years old and were predominantly from the Army. Participants were generally healthy sleepers (PSQI: 3.8 ± 2.5; ISI = 4.3 ± 3.6) with minimal complaints of daytime sleepiness (ESS: 5.5 ± 2.4). The racial identity of the sample was: white (n = 34, 69.4%), Black or African American (n = 11, 22.4%), Asian (n = 1, 2.0%), Multiracial (n = 1, 2.0%), and Undisclosed (n = 2, 4.1%). Further, 4 participants (8.2% of the sample) identified as Hispanic or Latino.

7.3.2 Resilience Group Allocation

Confirming successful group allocation, resilient and vulnerable groups for each measure differed in average alertness/performance during sleep disruption periods and in average change from baseline (Table 10). To further understand whether there we inherent differences in alertness and performance capabilities of different groups, we examined differences in baseline neurobehavioral function between resilient and vulnerable groups for each measure. Significant differences in baseline outcomes were found for fatigue and PVT FAST (Table 10). Resilient groups displayed lower baseline fatigue and lower PVT FAST (faster optimal PVT performance). No other significant baseline differences were found.

Table 10. Differences in baseline and average sleep disruption performance and in average change from baseline between resilient and vulnerable participants defined by each neurobehavioral outcome.

		Baseline		Average Disruption		Average Change	
		t	*p*	*t*	*p*	*t*	*p*
POMS	Vigor	0.484	.630	**-2.108**	**.041**	**-3.644**	**<.001**
	Fatigue	**2.354**	**.024**	**6.846**	**<.001**	**4.211**	**<.001**
PVT	SLOW	-0.771	.445	**-7.804**	**<.001**	**-5.545**	**<.001**
	FAST	**2.885**	**.006**	**7.381**	**<.001**	**5.077**	**<.001**
PACT	1/RT	-0.407	.686	**-4.509**	**<.001**	**-5.109**	**<.001**
	Lapse	1.679	.105	**6.562**	**<.001**	**5.389**	**<.001**
	Incorrect	1.981	.058	**6.125**	**<.001**	**3.829**	**.001**

Abbreviations: POMS = Profile of Mood States; PVT = Psychomotor Vigilance Task; PACT = Perception-action coupling task; SLOW = 1/slowest 10% of PVT reaction times; FAST = fastest 10% of PVT reaction times

7.3.3 Overlap in Neurobehavioral Resilience and Vulnerability across Neurobehavioral Measures

Examination of Cohen's kappa coefficients revealed limited agreement between classification of resilient and vulnerable groups across different neurobehavioral outcomes (Table 11). Moderate agreement (.4 - .6) was observed for PACT lapses with PACT 1/RT, PACT incorrect responses and PVT SLOW. Moderate agreement was also observed between PVT SLOW and PVT FAST. Fair agreement (.2 - .4) was observed for POMS vigor with PACT 1/RT and PVT outcomes. Fair agreement was also observed for PVT FAST with PACT lapses and incorrect responses and for PVT SLOW with POMS fatigue and PACT 1/RT. No/slight agreement was observed for fatigue with all PACT and PVT outcomes (except SLOW) and for vigor with PACT incorrect responses and lapses. PACT 1/RT also had no/slight agreement with incorrect responses and PVT FAST. In summary, the highest levels of agreement were observed between behavioral tasks but this agreement varied depending across outcome measures. Further, low levels of agreement were observed between subjective and behavioral outcomes especially with fatigue.

Table 11. Kappa coefficient for agreement and percent agreement between neurobehavioral resilience groups classified using outcomes from different neurobehavioral domains

		POMS		PACT			PVT	
		Vigor	Fatigue	1/RT	Incorrect	Lapse	Slow	Fast
POMS	Vigor		.146 (S)	.334 (F)	-.002 (N)	.125 (S)	.309 (F)	.146 (F)
	Fatigue	57.1%		.063 (S)	.100 (S)	.140 (S)	.265 (F)	.020 (S)
PACT	1/RT	67.3%	53.1%		.232 (F)	.517 (M)	.389 (F)	.145(S)
	Incorrect	49.0%	55.1%	61.2%		.462 (M)	.427 (M)	.264 (F)
	Lapse	55.1%	57.1%	75.5%	73.5%		.468 (M)	.304 (F)
PVT	Slow	65.3%	63.2%	69.4%	71.4%	73.5%		.510(M)
	Fast	57.1%	51.0%	57.1%	63.3%	65.3%	75.5%	

POMS = Profile of Mood States; PACT = Perception-action coupling task; PVT = Psychomotor vigilance task; RT = response time; SLOW = 1/slowest 10% of PVT reaction time; FAST = fastest 10% of PVT reaction time;
S = no/slight agreement; F = fair agreement; M = moderate agreement

7.3.4 Differences in Habitual and Baseline Sleep between Resilient and Vulnerable Participants

No significant differences in habitual sleep or sleepiness on the PSQI, ISI or ESS were found between resilient and vulnerable groups for any neurobehavioral measure (Table 12). Differences in baseline sleep EEG measures were found for the POMS but not for the PVT or PACT (Table 13). For Vigor, the resilient group had significantly less baseline SWS and SWA than the vulnerable group (Table 13; Figure 15). For Fatigue, the resilient group had significantly more baseline REM than the vulnerable group (Table 13; Figure 15).

Table 12. Differences in habitual sleep and sleepiness between resilient and vulnerable groups defined using different neurobehavioral measures

	PSQI		ISI		ESS	
	t	*p*	*t*	*P*	*t*	*p*
Vigor	0.905	.370	-0.208	.836	-0.406	.687
Fatigue	1.278	.208	1.186	.242	1.150	.256
SLOW	0.243	.809	-0.278	.782	0.487	.628
FAST	1.192	.239	0.691	.493	-0.315	.755
1/RT	1.001	.322	0.916	.364	0.698	.488
Incorrect	-1.578	.121	0.261	.795	1.699	.096

PSQI = Pittsburgh Sleep Quality Index; ISI = Insomnia Severity Index; ESS = Epworth Sleepiness Scale; SLOW = 1/slowest 10% reaction time; FAST = fastest 10% reaction time; RT = response time

Table 13. Differences in select baseline sleep parameters between resilient and vulnerable participants defined by each neurobehavioral

		SE (%)		WASO (min)		SWS (%)		REM (%)		SWA	
		t	*p*	*t*	*p*	*t*	*p*	*t*	*p*	*t*	*p*
POMS	Vigor	0.243	.809	-0.883	.382	**2.146**	**.037**	-1.134	.264	**2.059**	**.046**
	Fatigue	-0.533	.597	-0.211	.833	1.400	.168	**-2.448**	**.018**	-0.227	.821
PVT	SLOW	0.809	.423	-0.383	.704	1.861	.069	-1.081	.319	1.101	.277
	FAST	1.397	.170	-1.302	.199	0.111	.912	-0.552	.584	-0.108	.914
PACT	1/RT	-0.222	.825	0.444	.659	-0.215	.855	0.676	.503	-0.558	.580
	Lapse	-0.640	.526	0.626	.536	-0.684	.497	0.658	.514	-1.580	.122
	Incorrect	-0.844	.404	1.428	.162	0.691	.493	0.255	.800	0.243	.809

Abbreviations: SE = sleep efficiency; WASO = wake after sleep onset; SWS = slow wave sleep; REM = rapid-eye movement sleep; SWA = slow wave activity; POMS = Profile of Mood States; PVT = Psychomotor Vigilance Task; PACT = Perception-Action Coupling Task; SLOW = reciprocal transformation of the slowest 10% of PVT reaction times; FAST = fastest 10% of PVT reaction times; RT = PACT response time

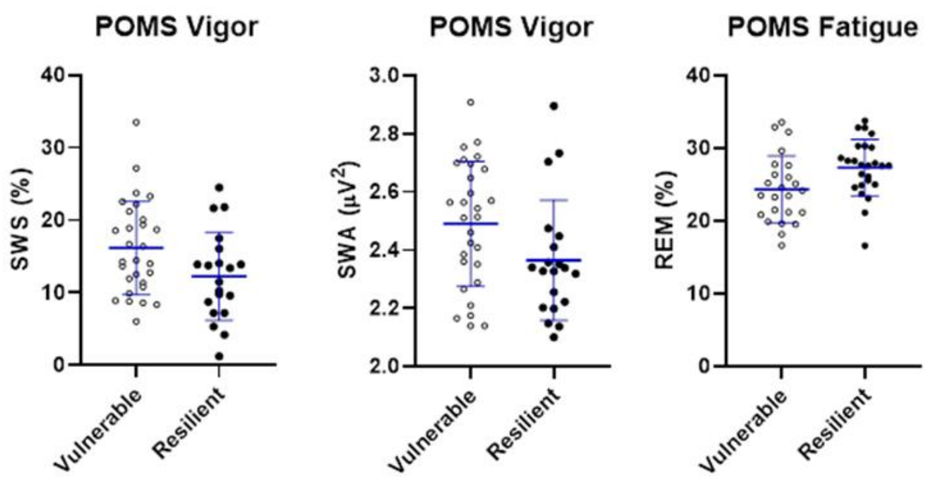


Figure 15.Differences in baseline sleep between resilient and vulnerable participants defined by POMS Vigor and Fatigue

7.3.5 Differences in Sleep throughout SMOS between Resilient and Vulnerable Participants

Significant group*day interaction effects were found for PVT SLOW (F = 4.15, p = .047, n2p = .081), PVT FAST (F = 6.08, p = .017, n2p = .115), and PACT 1/RT (F = 6.81, p = .012, n2p = .127) on WASO. For PVT, resilient groups had more WASO on Day 2 but did not differ in WASO on Day 3 than the vulnerable groups (Table 14; Figure 16). For PACT, groups did not differ between days but WASO in the resilient group decreased across days while WASO in the vulnerable group increased. No other significant group*day effects were found. As expected, due to consecutive nights of sleep restriction, significant effects of day were found for SE, SWS, and REM which all increased from Day 2 to Day 3 (Table 14). A significant effect of group was found only for the POMS vigor resilience groups on SWA (F =5.139, p = .028, n2p = .099); the resilient group had less SWA than the vulnerable group across both days (Table 14; Figure 17).

Table 14. Changes in sleep architecture and NREM spectral activity across consecutive days of sleep disruption, results from 2*2 ANOVA (group*day)

		Group*Day			Group			Day		
		F	*p*	*n2p*	*F*	*p*	*n2p*	*F*	*p*	*n2p*
Vigor	SE (%)	1.47	.231	.030	0.20	.658	.004	**7.96**	**.007**	**.145**
	WASO (min)	1.05	.310	.022	<0.001	.979	<.001	0.20	.655	.004
	SWS (%)	<0.01	.966	<.001	3.41	.071	.068	**9.03**	**.004**	**.161**
	REM (%)	0.29	.594	.006	1.22	.275	.025	3.32	.079	.064
	SWA	<.001	.995	<.001	**5.14**	**.028**	**.099**	**5.24**	**.027**	**.100**
Fatigue	SE (%)	0.44	.512	.009	0.91	.345	.019	**7.79**	**.008**	**.142**
	WASO (min)	0.65	.423	.014	0.20	.657	.004	0.20	.656	.004
	SWS (%)	0.01	.921	<.001	2.89	.095	.058	**9.03**	**.004**	**.161**
	REM (%)	0.07	.789	.004	0.13	.720	.021	3.22	.079	.064
	SWA	<.001	.992	<.001	.03	.876	.001	**5.24**	**.027**	**.100**
PVT SLOW	SE (%)	2.09	.155	.043	1.24	.271	.026	**8.06**	**.007**	**.146**
	WASO (min)	**4.15**	**.047**	**.081**						
	SWS (%)	1.60	.212	.033	2.76	.103	.055	**9.34**	**.004**	**.166**
	REM (%)	2.91	.094	.058	0.67	.417	.014	3.41	.071	.068
	SWA	0.17	.686	.004	1.29	.261	.027	**5.26**	**.026**	**.101**
PVT FAST	SE (%)	3.75	.059	.074	3.26	.077	.065	**8.33**	**.006**	**.151**
	WASO (min)	**6.08**	**.017**	**.115**						
	SWS (%)	3.16	.082	.063	0.01	.904	<.001	**9.64**	**.003**	**.170**
	REM (%)	3.09	.085	.062	0.17	.677	.004	3.42	.071	.068
	SWA	0.10	.757	.002	0.02	.893	<.001	**5.25**	**.026**	**.101**
PACT 1/RT	SE (%)	1.28	.263	.027	1.00	.321	.021	**7.93**	**.007**	**.144**
	WASO (min)	**6.81**	**.012**	**.127**						
	SWS (%)	0.79	.378	.017	1.95	.169	.040	**9.19**	**.004**	**.163**
	REM (%)	0.21	.652	.004	0.99	.323	.021	3.23	.079	.064
	SWA	0.01	.921	<.001	.20	.656	.004	**5.25**	**.027**	**.100**
PACT Lapses	SE (%)	0.40	.531	.008	0.60	.443	.013	**7.78**	**.007**	**.142**
	WASO (min)	3.53	.066	.070	0.03	.852	.001	0.21	.647	.005
	SWS (%)	0.03	.857	.001	0.89	.350	.019	**9.04**	**.004**	**.161**
	REM (%)	1.42	.239	.029	0.87	.357	.018	3.31	.075	.066
	SWA	0.02	.898	<.001	1.71	.197	.035	**5.246**	**.027**	**.100**
PACT Incorrect Responses	SE (%)	0.21	.648	.004	0.18	.677	.004	**7.75**	**.008**	**.142**
	WASO (min)	0.78	.382	.016	0.19	.662	.004	0.20	.656	.004
	SWS (%)	1.54	.221	.032	0.08	.780	.002	**9.33**	**.004**	**.166**
	REM (%)	1.41	.240	.029	0.96	.332	.020	3.31	.075	.066
	SWA	1.10	.300	.023	<0.01	.963	<.001	**5.37**	**.025**	**.102**

SE = Sleep efficiency; WASO = wake after sleep onset; SWS = slow wave sleep; REM = rapid eye movement sleep; SWA = slow wave activity, 0.5 – 4 Hz

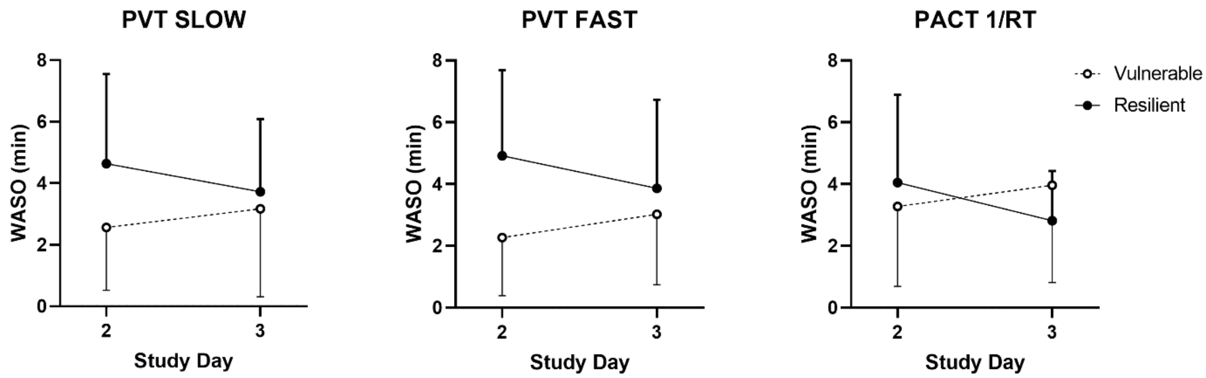


Figure 16: Difference in wake after sleep onset (WASO) across two nights of sleep disruption between resilient and vulnerable groups defined using PVT and PACT outcomes. SD displayed

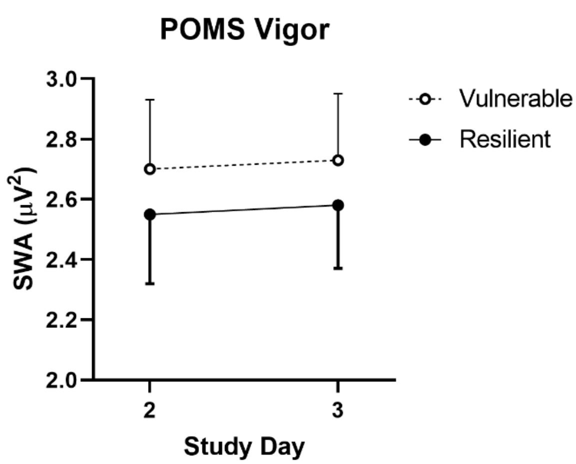


Figure 17: Differences in slow wave activity (SWA) between resilient and vulnerable groups defined using POMS Vigor. SD displayed

7.4 Discussion

We examined whether different neurobehavioral assessments (POMS, PVT, PACT) consistently defined participants as resilient or vulnerable to SMOS based on both absolute values during sleep disruption and average change from baseline. Limited agreement in resilience classification between different neurobehavioral assessments demonstrated that POMS, PVT and PACT assess distinct aspects of neurobehavioral resilience. As such, neurobehavioral resilience is highly task-specific. That subjective and behavioral measures of alertness such as POMS and PVT reflect distinct aspects of alertness and neurobehavioral function has been widely suggested across normal sleep conditions and during periods of sleep loss[57,327,329,339]. The current study extends these findings by finding that POMS and PVT reflected distinct aspects of neurobehavioral function/resilience from PACT. Further, the lack of agreement in resilience classification across the PVT and PACT highlights that measures of vigilance and perception-action coupling reflect distinct aspects of neurobehavioral resilience despite both requiring timely reactions/responses. Differentiating PVT and PACT is the context in which participants are required to react: during PVT participants respond the same way to each stimulus presentation but during PACT participants must respond differently depending on the action possibilities provided by that visual information. This additional perceptual challenge likely contributed to the lack of agreement between the PVT and PACT. Importantly, this lack of agreement suggests that participants who maintain the ability to react quickly (PVT) during exposure to SMOS do not necessarily maintain the ability to respond appropriately (PACT).

An additional finding that further highlighted the task-specific nature of neurobehavioral resilience was the limited agreement across measures from the same neurobehavioral assessments. That vigor and fatigue resilience groups only demonstrated fair agreement was consistent from recent work from Casale and colleagues[231]. It has been suggested that vigor and fatigue reflect distinct constructs of subjective alertness; vigor may be more related to sleepiness while fatigue reflects physical weariness[186,231]. Further, while agreement within behavioral tasks was higher than agreement between tasks, this agreement remained below .6, our *a prori* threshold for defining overlapping resilience groups. Therefore, when identifying resilient and vulnerable individuals in operational settings, it is important to consider what measures of neurobehavioral function are most important and relevant within that particular context and for that particular population.

Additional important findings from this study involve a potential role of sleep in different aspects of neurobehavioral resilience. Baseline sleep differed between resilient and vulnerable participants for the subjective, but not the behavioral, measures. Participants who maintained higher levels of vigor across the SMOS exposure had lower SWS and SWA at baseline. Further, these resilient participants for vigor had lower SWA across SMOS. We had hypothesized more SWS and SWA would contribute to higher levels of resilience due to the role of these sleep parameters in the restoration and enhancement of alertness and neurobehavioral function[36,336]. Conversely, our results demonstrate that higher SWS and SWA may reflect an increased vulnerability to sleep loss, at least as characterized by vigor. SWS and SWA reflect homeostatic sleep need; participants with more SWS and SWA may have had greater inherent sleep need and therefore, were more affected by the loss of sleep during the SMOS protocol[153,340]. This finding is consistent with work finding more SWA was related to greater vulnerability to sleep loss defined using an assessment of working memory[340] (but see[310]).

Differences in baseline sleep were also related to fatigue. Resilient participants, defined by POMS fatigue, had more REM sleep at baseline than vulnerable participants. REM sleep plays a role in emotional memory consolidation, sensorimotor integration during development and may contribute to perceptual processing/recovery[104,136,137,140]. More so than the other neurobehavioral measures, fatigue may reflect general weariness related to the high cognitive and physical loads throughout the study. A role of baseline REM sleep in the ability to adapt and better handle these stressors is an intriguing possibility but the mechanistic underpinnings contributing to the relationship between fatigue and REM sleep observed here warrant further investigation.

Interestingly, WASO throughout exposure to SMOS, during the sleep opportunities immediately prior to neurobehavioral assessment, differed in participants classified as resilient and vulnerable across different behavioral measures: PVT SLOW, FAST and PACT 1/RT. Across all three measures, WASO on Day 2 in resilient groups was higher than in vulnerable groups but no differences were found on Day 3. This change across days was caused by decreases in WASO in the resilient groups between days. WASO provides a measure of sleep fragmentation and may relate to differences in arousal. A reduced sensitivity to SMOS in resilient participants may have presented as higher WASO, as participants with reduced sleep need were less able to maintain consolidated sleep, especially on the first night of sleep restriction. Still, the clinical meaningfulness of group differences in WASO remains unclear. Between resilient and vulnerable groups across the different measures WASO only differed by ~2 minutes. While differences in WASO were statistically significant, it is unclear to what extent these differences reflected true differences in sleep need.

There are several limitations that must be addressed. First, the study was conducted in military personnel and may not be generalizable to civilian populations. Second, while PVT and PACT order was counterbalanced, POMS was completed first in every neurobehavioral test battery. Whether task order impacted our ability to identify meaningful relationships between sleep during SMOS and resilience across behavioral measures is unknown but must be considered. Lastly, sleep history prior to beginning the study may have differed between participants. While sleep history may not impact all aspects of neurobehavioral resilience the inter-individual differences in sleep history may have impacted sleep and performance throughout SMOS.

In conclusion, neurobehavioral resilience is highly task-specific and varies across measures of alertness, fatigue, vigilance and perception-action coupling. Not only do subjective and behavioral measures of neurobehavioral function reflect distinct aspects of resilience but different behavioral measures of reaction time also reflect distinct aspects of resilience. Vigilance (PVT) and perception-action coupling (PACT) are distinct elements of function that contribute differently to neurobehavioral resilience. Understanding how vigilance and perception-action coupling relate to aspects of operational performance is imperative to developing fatigue risk prediction batteries. Further, higher inherent sleep need may contribute to lower vigor across exposure to operational stress but behavioral measures of neurobehavioral function may be less sensitive to baseline sleep.

8.0 Summary and Future Directions

We aimed to examine the impact of SMOS on sleep and perception-action coupling performance. Additionally, we examined relationships between sleep and different aspects of performance, both at baseline and throughout exposure to SMOS. In doing so, several key findings emerged: 1) sleep demonstrated trait-like behavior across SMOS exposure but this trait-like behavior varied based on trauma exposure and psychological resilience (Aim 1); 2) the ability to maintain performance despite SMOS exposure may be dependent on time-of-day (Aim 3); 3) differences in sleep may impact operational performance and neurobehavioral resilience, specifically, SWA may be a marker of vulnerability to SMOS (Aim 2 and 4); and 4) neurobehavioral resilience presents in a highly task-specific manner (Aim 4), which has practical considerations, especially when making operationally-meaningful predictions regarding fatigue risk.

Robust individual differences in responses to SMOS were found for sleep spectral parameters across nights (Aim 1). This finding confirms and extends prior work demonstrating the trait-like nature of sleep. However, a novel extension of prior work was that this trait-like nature of sleep was less robust in participants with lower psychological resilience and higher trauma exposure. Whether inter-individual differences in sleep and in changes in sleep across SMOS had functional implications was an intriguing possibility. Consequently, we next examined the operational relevance of inter-individual differences in sleep (Aim 2). Higher daytime sleepiness and higher frontal SWA, in addition to lower $\dot{V}O_{2peak}$, predicted worse baseline physical performance. Importantly, these sleep parameters did not predict change in physical performance across days or marksmanship accuracy, at baseline or across days. However, a factor compromising our ability to identify relationships between baseline sleep and changes in operational performance may have been the high stability of operationally-relevant performance outcomes across days (ICC > .6). Trait-like differences in physical performance during operational stress have been suggested and may have contributed to the high stability of performance observed in the current study. Further, the findings from the current study, and additional work from this same study[288], demonstrate that participants were generally able to maintain physical performance despite exposure to SMOS. An intriguing possibility is that the high stability of spectral sleep parameters across days may have contributed to the high stability in performance across days as well. Consistent relationships between baseline SWA and physical performance were observed across days; high performers consistently had lower SWA than low performers.

Of note, while minimal changes in operational performance were observed across SMOS, performance was assessed during typical waking hours. Time-of-day related variations in physical and sensorimotor performance have been observed previously[318,341,342]. Further, exposure to sleep loss may exacerbate time-of-day related variation in performance[194]. Consistent with this prior work, we demonstrated time-of-day related changes in performance across SMOS. During typical waking hours (18:00 and 22:00) participants were able to maintain or improve perception-action coupling performance across days (Aim 3). Conversely, at 04:00, when participants typically would have been sleeping, perception-action coupling performance deteriorated across days. This finding not only demonstrates that perception-action coupling behaviors may be impaired during overnight operations but also demonstrates the cumulative effects of sleep loss and time-of-day on performance. Within operational settings where individuals may be exposed to multiple nights of restricted sleep, these cumulative effects of sleep loss may contribute to pronounced impairments in operational tasks that rely on perception-action coupling, which could have implications for overall operational efficiency and safety.

Pronounced individual differences in SMOS (and sleep loss) related performance decrements have been widely observed. Therefore, while deficits in perception-action coupling performance were observed at 04:00 across the whole sample, we sought to further examine individual differences in neurobehavioral resilience defined using different perception-action coupling outcomes (Aim 4). Further, we examined the relationship between neurobehavioral resilience defined using perception-action coupling outcomes with neurobehavioral resilience defined using subjective assessments of alertness and behavioral assessments of vigilance. A lack of agreement in participants defined as resilient using the different neurobehavioral assessments highlighted that neurobehavioral assessments of subjective alertness, vigilance and perception-action coupling reflect different aspects of neurobehavioral resilience. This task-specific nature of neurobehavioral resilience has implications for fatigue prediction and identification. Namely, the neurobehavioral underpinnings of operational tasks most relevant for a particular individual must be considered when deciding which assessments to use for fatigue monitoring.

A final important finding from this work was that SWA may be a biological marker of increased vulnerability to SMOS (Aim 2 and Aim 4). Higher baseline SWA was related to both worse baseline TMT performance and lower neurobehavioral resilience defined using POMS Vigor. Higher SWA during the sleep opportunities prior to sleep disruption periods also predicted lower neurobehavioral resilience defined using POMS Vigor. Collectively, these findings demonstrate that participants with higher SWA had worse overall physical performance, had lower vigor and greater decreases in vigor than participants with lower SWA. Individuals with greater sleep need, indexed by higher SWA, may be more vulnerable to operational stress and sleep loss in particular. Whether fatigue countermeasures such as strategic naps, physical activity or caffeine can mitigate the higher vulnerability of these individuals is an important area of future research. Further, additional work is needed to better understand the observed relationship between REM sleep and neurobehavioral resilience defined using POMS Fatigue. The fatigue subscale of POMS may reflect physical aspects of weariness more so than the vigor subscale which captures more behavioral and psychological aspects of alertness. As recent work has suggested a role of REM sleep in muscle recovery, the relationship between REM sleep and the ability to withstand high physical loads is intriguing.

Overall, while SWA appeared to indicate increased vulnerability to SMOS across physical performance and subjective alertness, habitual sleep quality did not protect against SMOS-related performance decrements. Military personnel were largely able to maintain physical performance and perception-action coupling performance during typical waking hours despite SMOS exposure. To what extent these aspects of performance could be maintained across more chronic exposures to operational stress must be addressed in future research. Additionally, whether sleep plays a more prominent role in different aspects of neurobehavioral resilience across more chronic stress exposures must also be further examined. Finally, future research examining the interplay and relationships between different aspects of neurobehavioral resilience and operationally-relevant aspects of performance is required to better understand aspects of neurobehavioral function that contribute to operational performance. Further, this future research would inform the development and implementation of fatigue risk batteries to predict and identify operationally-relevant changes in fatigue risk within operational settings.

Appendix A Abbreviations

ACC	Accuracy on the perception-action coupling task
CD-RISC	Connor Davidson Resilience Inventory Scale
EEG	Electroencephalography
EMG	Electromyography
EOG	Electrooculography
ESS	Epworth Sleepiness Scale
EST	Engagement Skills Trainer-3000; marksmanship
FAST	Fastest 10% of reaction time on the psychomotor vigilance task
HTHR	High trauma, high resilience group
HTLR	High trauma, low resilience group
ICC	Intraclass correlation coefficient
ISI	Insomnia severity index
IT	Initiation time; time to move the joystick during the perception-action coupling task
LTHR	Low trauma, high resilience group
LTLR	Low trauma, low resilience group
MT	Movement time on the perception-action coupling task
N1	Stage 1 sleep
N2	Stage 2 sleep
NREM	Non-rapid eye movement sleep
PACT	Perception-action Coupling Task
POMS	Profile of Mood States
PSQI	Pittsburgh Sleep Quality index
PSTD	Post-traumatic stress disorder
PVT	Psychomotor Vigilance Task
REM	Rapid-eye movement sleep
RPE	Ratings of perceived exertion
RT	Response time; overall time to complete a response during the perception-action coupling task
RXT	Reaction time; time to lift finger off the home button during the perception-action coupling task
SE	Sleep efficiency
SLOW	Reciprocal transformation of slowest 10% of reaction times on the psychomotor vigilance task
SMOS	Simulated military operational stress
SWA	Slow wave activity; 0.5 – 5 Hz
SWS	Slow wave sleep; stage 3 sleep
THQ	Trauma History Questionnaire
TMT	Tactical mobility test; physical performance
TST	Total sleep time
VO2	Peak oxygen intake during an incremental maximal treadmill test
WASO	Wake after sleep onset

Appendix B Supplementary Material for Aim 1

Table 15. Intraclass correlation coefficients of sleep architecture and NREM spectral activity across the SMOS protocol

		8-hour	Nap 1	Nap 2	2-hour	All
SE (%)		.392 (.176 - .573)	.314 (.092 - .509)	.548 (.258 - .727)	.371 (.246 - .505)	.378 (.275 - .496)
N1 (%)		.628 (.268 - .801)	.584 (.366 - .733)	.401 (.098 - .618)	.327 (.186 - .475)	.433 (.309 - .561)
N2 (%)		.649 (.487 - .768)	.587 (.369 - .736)	.444 (.233 - .615)	.381 (.258 - .514)	.302 (.175 - .441)
SWS (%)		.867 (.723 - .930)	.422 (.210 - .597)	.503 (.287 - .667)	.173 (.017 - .359)	.209 (.062 - .381)
REM (%)		.253 (.014 - .463)	.191 (-.065 - .403)	.235 (.036 - .448)	.032 (-.009 - .092)	.047 (.005 - .108)
Total	C3	.931 (.891 - .957)	.592 (.410 - .729)	.784 (.636 - .870)	.473 (.265 - .642)	.551 (.379 - .692)
	F3	.933 (.859 - .965)	.590 (.409 - .727)	.763 (.603 - .857)	.435 (.221 - .614)	.526 (.351 - .672)
Delta	C3	.928 (.885 - .955)	.701 (.555 - .806)	.691 (.503 - .810)	.514 (.215 - .712)	.616 (.388 - .766)
(Abs.)	F3	.940 (.887 - .966)	.640 (.467 - .765)	.659 (.456 - .789)	.463 (.207 - .657)	.565 (.370 - .714)
Theta	C3	.948 (.803 - .979)	.698 (.538 - .807)	.908 (.771 - .956)	.741 (.553 - .849)	.790 (.646 - .875)
(Abs.)	F3	.912 (.651 - .965)	.692 (.535 - .802)	.878 (.724 - .938)	.704 (.480 - .830)	.755 (.600 - .852)
Alpha	C3	.972 (.952 - .983)	.935 (.854 - .967)	.932 (.879 - .961)	.882 (.765 - .936)	.901 (.830 - .942)
(Abs.)	F3	.960 (.902 - .980)	.931 (.877 - .960)	.942 (.862 - .971)	.860 (.702 - .927)	.883 (.792 - .933).
Sigma	C3	.959 (.934 - .975)	.827 (.732 - .890)	.892 (.831 - .932)	.828 (.763 - .882)	.866 (.818 - .907)
(Abs.)	F3	.953 (.916 - .973)	.931 (.888 - .958)	.903 (.846 - .940)	.896 (.852 - .931)	.913 (.878 - .941)
Beta	C3	.847 (.764 - .903)	.800 (.693 - .872)	.749 (.623 - .838)	.725 (.633 - .805)	.750 (.673 - .821)
(Abs.)	F3	.806 (.700 - .878)	.821 (.721 - .888)	.762 (.633 - .849)	.725 (.631 - .807)	.737 (.655 - .813)
Delta	C3	.926 (.880 - .954)	.821 (.723 - .886)	.457 (.246 - .626)	.448 (.222 - .630)	.574 (.398 - .712)
(Rel.)	F3	.942 (.898 - .966)	.530 (.334 - .683)	.610 (.431 - .742)	.480 (.321 - .624)	.563 (.439 - .680)
Theta	C3	.929 (.858 - .961)	.902 (.795 - .948)	.584 (.404 - .722)	.593 (.292 - .769)	.690 (.496 - .812)
(Rel.)	F3	.936 (.840 - .969)	.895 (.814 - .939)	.748 (.618 - .838)	.664 (.401 - .810)	.746 (.589 - .845)
Alpha	C3	.950 (.921 - .969)	.832 (.740 - .893)	.664 (.505 - .779)	.662 (.465 - .791)	.745 (.616 - .835)
(Rel.)	F3	.962 (.939 - .977)	.904 (.847 - .940)	.758 (.634 - .844)	.753 (.611 - .846)	.812 (.725 - .877)
Sigma	C3	.910 (.859 - .944)	.831 (.734 - .894)	.507 (.302 - .666)	.446 (.161 - .656)	.544 (.317 - .709)
(Rel.)	F3	.940 (.904 - .963)	.762 (.638 - .847)	.577 (.387 - .719)	.465 (.200 - .662)	.572 (.373 - .721)
Beta	C3	.874 (.801 - .921)	.795 (.686 - .869)	.572 (.360 - .722)	.525 (.291 - .696)	.608 (.439 - .737)
(Rel.)	F3	.871 (.785 - .922)	.747 (.618 - .837)	.548 (.319 - .709)	.469 (.247 - .645)	.553 (.390 - .690)

Almost perfect stability = Yellow shading; Substantial stability = Green shading; Moderate stability = Blue shading; Fair stability = Grey shading; Slight stability = unshaded; SE = sleep efficiency; N1 = stage 1 sleep; N2 = stage 2 sleep; SWS = slow wave sleep; REM = rapid eye movement sleep; Abs. = absolute spectral activity; Rel = relative spectral activity

Appendix B.1 Sleep architecture across simulated military operational stress based on different levels of trauma exposure and resilience

Repeated measures ANOVA were performed to examine differences in sleep architecture parameters across the SMOS protocol in 4 groups: low trauma, high resilience; low trauma, low resilience; high trauma, high resilience; and high trauma, low resilience. As expected, all sleep architecture parameters varied across time due to differences in timing and sleep opportunity (Table S2). However, no significant group x time interaction effects or main effects of group were found for any sleep architecture parameter (p > .05).

Table 16. Sleep architecture parameters across time in participants with different levels of trauma exposure and resilience

	Interaction			Time			Group		
	F	p	n_p^2	F	p	n_p^2	F	p	n_p^2
SE (%)	1.045	.408	.053	7.221	<.001	.114	1.425	.245	.071
N1 (%)	0.498	.903	.026	18.724	< .001	.251	0.225	.878	.012
N2 (%)	0.817	.610	.042	33.371	< .001	.373	0.574	.634	.030
SWS (%)	0.994	.447	.051	171.054	< .001	.753	0.574	.635	.030
REM (%)	0.322	.978	.017	137.806	< .001	.711	0.882	.456	.045

SE = sleep efficiency; N1 = stage 1 sleep; N2 = stage 2 sleep; SWS = slow wave sleep; REM = rapid eye movement sleep

Appendix B.2 Examination of differences in sleep stability related to PSQI scores

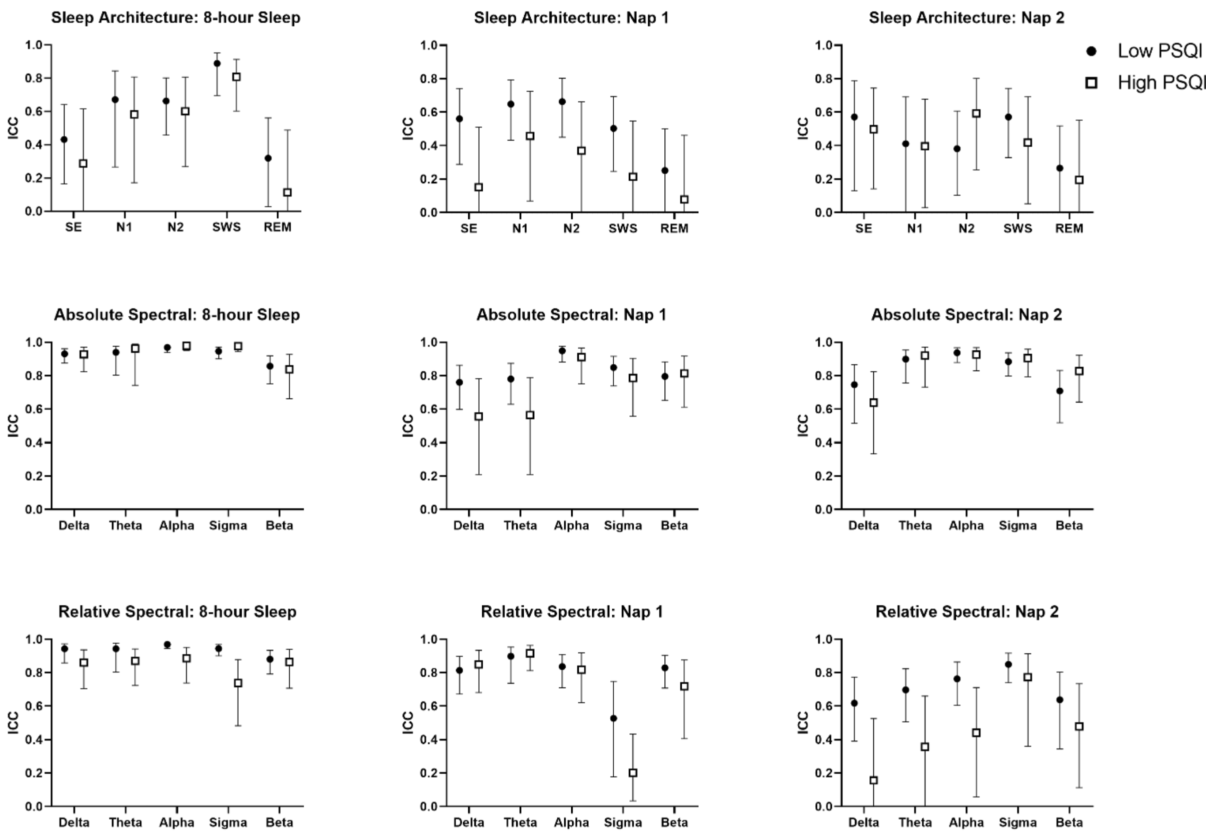


Figure 18. Intra-class correlation coefficients (ICC) of sleep architecture, absolute and relative NREM spectral activity across 8-hour sleep opportunities, nap 1 and nap 2 in good (PSQI < 5) and poor (PSQI ≥ 5) sleepers

The stability of relative sigma activity across 8-hour sleep opportunities was significantly lower in poor sleepers than good sleepers. No other significant differences were observed.

Appendix B.3 Stability and Robustness of Absolute and Relative Spectral Activity at F3 across exposure to simulated military operational stress

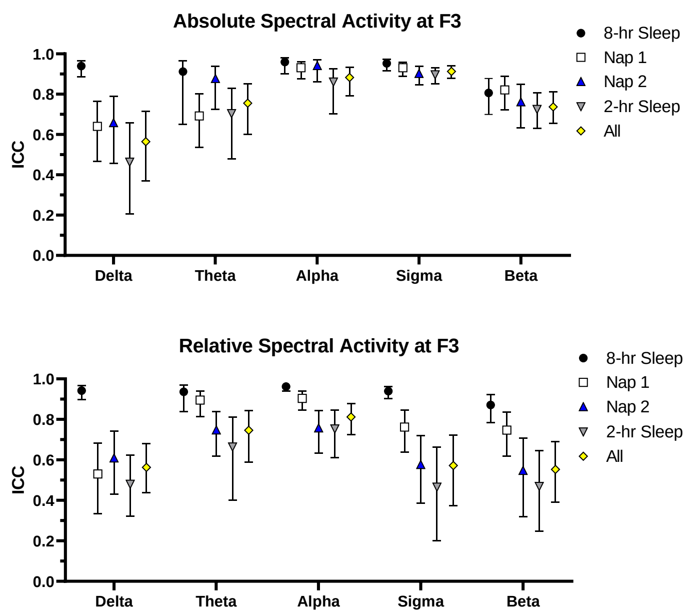


Figure 19. Intra-class correlation coefficients (ICC) of absolute NREM spectral and relative NREM spectral activity at F3 across different sleep ortunities during a simulated military operational stress protocol

95% confidence intervals displayed. ICC values are consistent with those reported at C3 with the exception of relative delta activity during nap 1 which demonstrated near perfect stability at C3, but only moderate stability at F3. This difference may be related to the frontal predominance of delta activity changes across sleep manipulations.

Appendix B.4 Examination of robustness of sleep stability across groups with different levels of resilience and trauma exposure

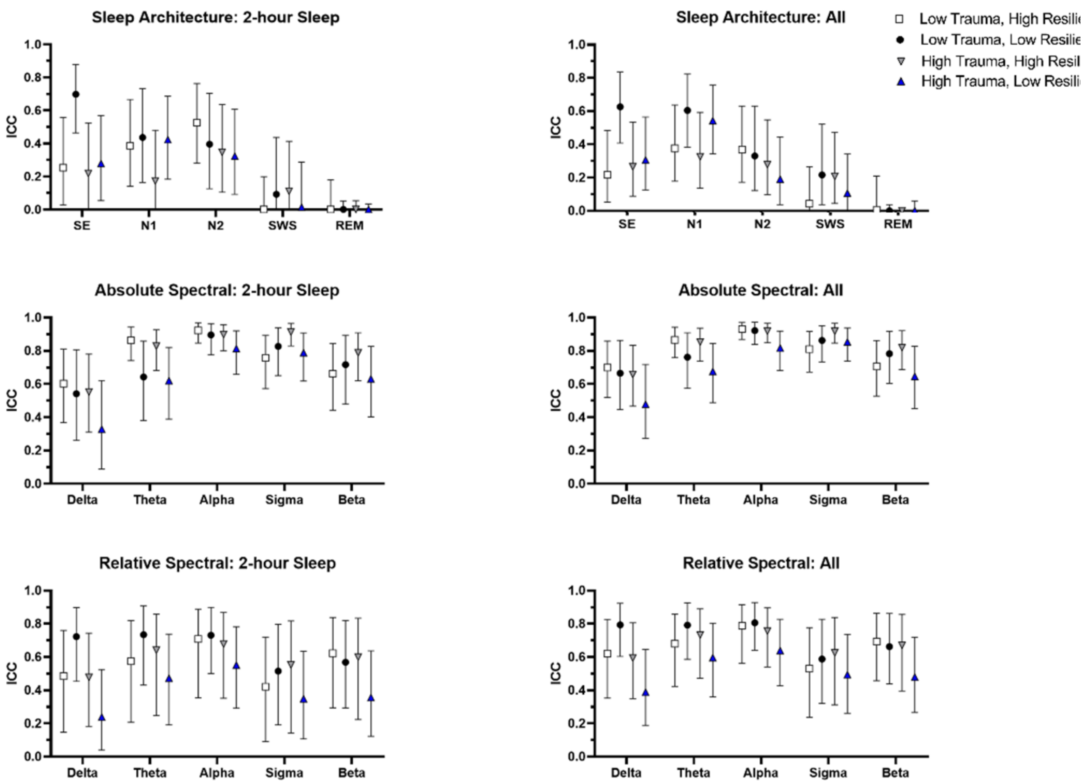


Figure 20. Intra-class correlation coefficients (ICC) of sleep architecture, absolute and relative NREM spectral activity across 2-hour sleep opportunities and all sleep opportunities across groups with different levels of trauma exposure and resilience

No significant differences were observed between groups for any sleep parameters.

Appendix B.5 Examination of differences in sleep stability related to age

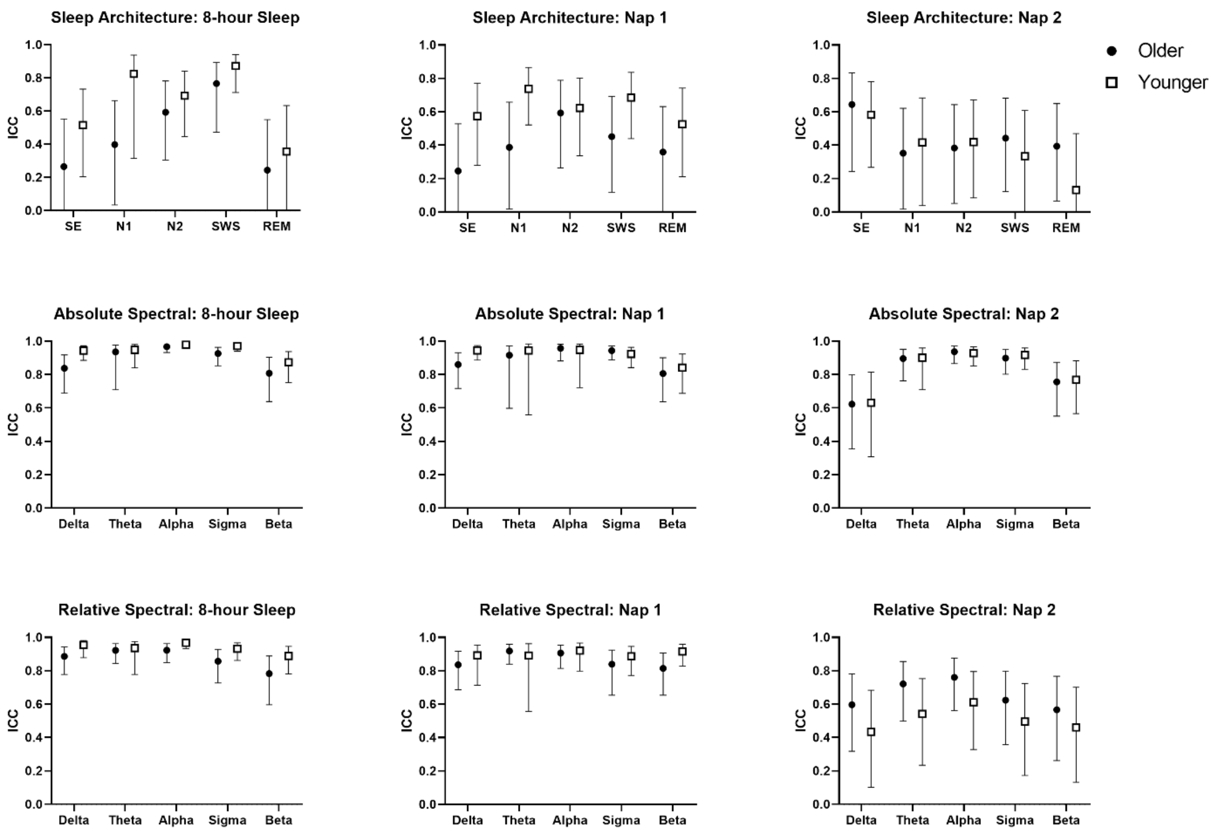


Figure 21. Intra-class correlation coefficients (ICC) of sleep architecture, absolute and relative NREM spectral activity across 8-hour sleep opportunities, nap 1 and nap 2 across older (age ≥ 25.3 years) and younger (age < 25.3 years) participants

No significant differences in sleep stability were observed between groups.

Appendix C Aim 2 Supplemental Information

Appendix C.1 Initial Examination of Univariate Relationships between Baseline Factors/Sleep and Baseline Performance

Prior to performing lasso regressions, an initial inspection of univariate relationships between baseline characteristics, habitual sleep and baseline sleep EEG measures with baseline operational performance were examined. Individual predictors were regressed on operational performance outcomes using random intercept models (lme package). To provide an initial examination of the impact of outliers on statistical relationships between sleep and physical performance, we examined the aforementioned univariate relationships in samples with (n = 54) and without (n = 45) outliers included (Table S1).

Lasso regressions were also performed using samples with and without outliers included. When outliers were included in the sample, the lasso regression identified sex, VO2, ESS, central sigma, and frontal theta and beta activity as informative predictors. Similar to the model when outliers were removed, most of the variance explained by the model could be attributed to VO2; better aerobic fitness (higher VO2) predicted better overall TMT performance. Further higher daytime sleepiness on the ESS predicted worse TMT performance regardless of whether outliers were included or not. However, the rest of the identified predictors differed between models. When outliers were included, higher central sigma, frontal theta and frontal beta activity predicted worse TMT performance. Further, men were predicted to have better performance. These relationships were not identified when outliers were removed.

Appendix C.2 Differences in sleep between high and low physical performers across the SMOS protocol

To examine relationships between physical performance and sleep across the SMOS protocol, repeated measures ANOVA were performed to examine differences in sleep across the 6 sleep opportunities throughout the study between high and low performers. High and low performers on the TMT were identified using a median split of baseline performance. Baseline TMT performance was used to define groups due to the high stability (ICC = .940) of TMT performance across days. No significant group*sleep opportunity interaction effects were observed. A significant effect of group was found for SWS, REM, and frontal SWA (Table 16). High performers on the TMT had lower SWS than low performers (Figure 18). Further, high performers had more REM sleep than low performers across the SMOS protocol.

Table 17. Differences in sleep architecture and NREM spectral activity across the SMOS protocol between high and low performers on the TMT

		Group*Bout			Group			Bout		
		F	*p*	*n2p*	*F*	*p*	*n2p*	*F*	*p*	*n2p*
Sleep Architecture	SE (%)	2.076	.069	.046	0.875	.355	.020	**5.956**	**<.001**	**.122**
	N1 (%)	1.291	.269	.029	0.268	.607	.006	**11.570**	**<.001**	**.212**
	N2 (%)	1.528	.182	.034	0.625	.434	.014	**23.118**	**<.001**	**.350**
	SWS (%)	0.237	.946	.005	**5.599**	**.023**	**.115**	**116.525**	**<.001**	**.730**
	REM (%)	1.469	.201	.033	**6.161**	**.017**	**.125**	**97.699**	**<.001**	**.694**
Central	SWA	1.307	.262	.030	**6.472**	**.015**	**.131**	**48.698**	**<.001**	**.532**
	Theta	2.124	.064	.047	3.467	.069	.075	**31.030**	**<.001**	**.420**
	Alpha	**2.875**	**.015**	**.063**						
	Sigma	1.135	.343	.026	0.154	.696	.004	1.753	.124	.039
	Beta	0.745	.590	.017	3.355	.074	.072	1.253	.285	.028
Frontal	SWA	0.978	.432	.023	**10.864**	**.002**	**.201**	**43.423**	**<.001**	**.507**
	Theta	1.187	.316	.027	**4.269**	**.045**	**.090**	**29.439**	**<.001**	**.411**
	Alpha	1.113	.355	.026	0.893	.350	.020	**29.811**	**<.001**	**.414**
	Sigma	0.758	.581	.018	0.047	.829	.001	2.157	.060	.049
	Beta	1.279	.274	.029	2.016	.163	.045	1.159	.330	.027

TST = total sleep time; SE = sleep efficiency; N1 = stage 1 sleep; N2 = stage 2 sleep; SWS = slow wave sleep; REM = rapid eye movement

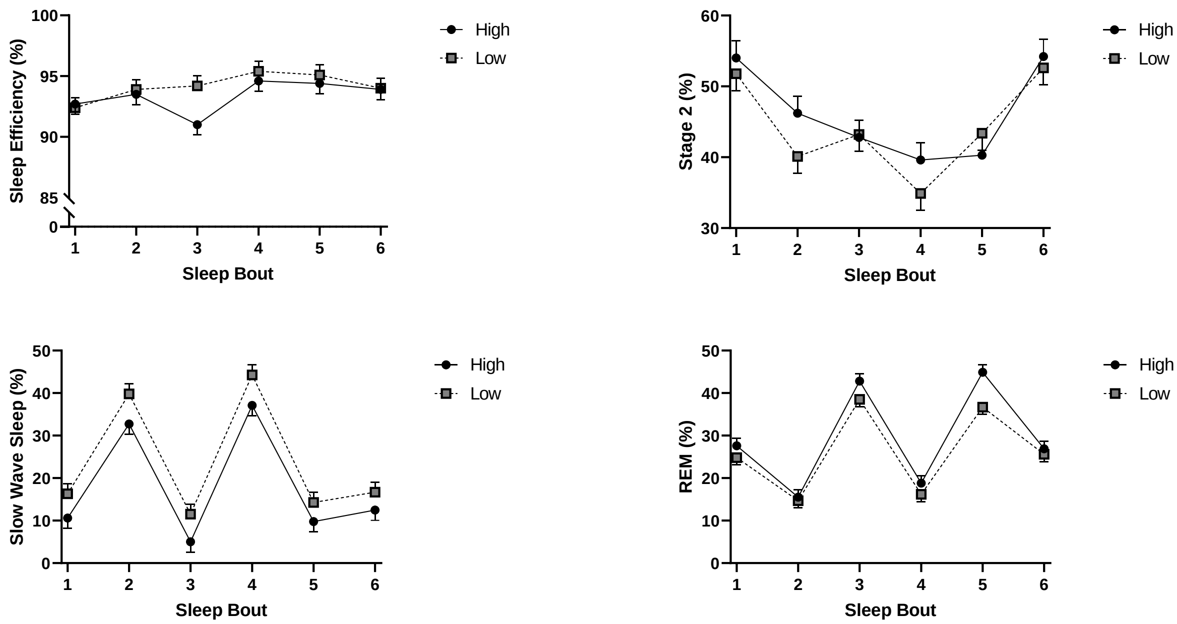


Figure 22. Sleep architecture parameters across exposure to simulated military operational stress in high and low TMT performers

Appendix D Aim 3

Pairwise comparisons for PACT outcomes where significant Day*Time interaction effects were found are presented below.

Table 18. Pairwise comparisons of differences in response time across different PACT administrations

Day	Time	Day	Time	β	SE	t	df	p
1	1800	1	22:00	-0.026	0.013	-1.935	181.3	.590
		2	04:00	0.038	0.017	2.271	80.7	.372
			18:00	0.020	0.014	1.435	143.1	.882
			22:00	-0.064	0.015	-4.293	74.4	.002
		3	04:00	0.059	0.017	3.519	80.4	.019
			18:00	-0.033	0.014	-2.311	130.2	.343
			22:00	-0.077	0.015	-4.973	72.8	<.001
	22:00	2	04:00	0.064	0.016	3.918	82.3	0.005
			18:00	0.046	0.015	3.090	75.0	0.066
			22:00	-0.038	0.014	-2.799	143.1	0.125
		3	04:00	0.085	0.017	5.162	81.7	<.001
			18:00	-0.007	0.015	-0.467	72.8	.999
			22:00	-0.051	0.014	-3.564	130.2	.015
2	04:00	2	18:00	0.019	0.015	1.217	118.5	.951
			22:00	0.102	0.015	6.886	123.2	< .001
		3	04:00	0.021	0.013	1.643	196.0	.780
			18:00	-0.071	0.017	-4.342	70.7	.001
			22:00	-0.115	0.016	-7.207	71.7	<.001
	18:00	2	22:00	-0.084	0.013	-6.240	181.3	<.001
		3	04:00	0.040	0.015	2.599	73.5	.205
			18:00	-0.053	0.013	-4.100	196.0	.002
			22:00	-0.097	0.014	-6.893	95.3	<.001
	22:00	3	04:00	0.124	0.015	8.227	74.2	<.001
			18:00	0.031	0.014	2.171	93.7	.433
			22:00	-0.013	0.013	-1.011	196.0	.985
3	04:00	3	18:00	0.093	0.015	6.079	118.5	<.001
			22:00	0.137	0.015	9.188	123.2	<.001
	18:00	3	22:00	-0.044	0.013	-3.276	181.3	.034

Table 19. Pairwise comparisons of differences in movement time across PACT administrations

Day	Time	Day	Time	β	SE	t	df	p
1	1800	1	22:00	0.045	0.085	0.526	280	.999
		2	04:00	0.195	0.093	2.084	180	.487
			18:00	0.226	0.093	2.419	180	.280
			22:00	-0.160	0.093	-1.713	180	.738
		3	04:00	0.364	0.105	3.454	137	.020
			18:00	0.038	0.105	0.358	137	>.999
			22:00	-0.138	0.105	-1.312	137	.926
	22:00	2	04:00	0.150	0.093	1.604	180	.801
			18:00	0.181	0.093	1.940	180	.587
			22:00	-0.205	0.093	-2.193	180	.415
		3	04:00	0.319	0.105	3.028	137	.070
			18:00	-0.007	0.105	-0.069	137	>.999
			22:00	-0.183	0.105	-1.738	137	.722
2	04:00	2	18:00	-0.031	0.085	-0.367	280	>.999
			22:00	0.355	0.085	4.160	280	.001
		3	04:00	0.169	0.093	1.814	219	.673
			18:00	-0.157	0.093	-1.691	219	.751
			22:00	-0.333	0.093	3.581	219	.012
	18:00	2	22:00	-0.387	0.085	-4.527	280	<.001
		3	04:00	0.137	0.093	1.477	219	.865
			18:00	-0.189	0.093	-2.028	219	.526
			22:00	-0.364	0.093	-3.918	219	.004
	22:00	3	04:00	0.524	0.093	5.633	219	<.001
			18:00	0.198	0.093	2.128	219	.457
			22:00	0.022	0.093	0.238	219	>.999
3	04:00	3	18:00	0.326	0.085	3.819	280	.005
			22:00	0.502	0.085	5.878	280	<.001
	18:00	3	22:00	-0.176	0.085	-2.059	280	.504

Table 20. Pairwise comparisons of differences in correct responses across different PACT administrations

Day	Time	Day	Time	β	SE	t	df	p
1	1800	1	22:00	-0.006	0.010	-0.576	277	.999
		2	04:00	0.012	0.010	1.194	197	.957
			18:00	0.025	0.010	2.505	280	.234
			22:00	0.007	0.010	0.705	277	.999
		3	04:00	0.052	0.010	4.985	197	<.001
			18:00	-0.002	0.010	-0.175	280	>.999
			22:00	-0.007	0.010	-0.750	277	.998
1	22:00	2	04:00	0.018	0.011	1.690	182	.752
			18:00	0.030	0.010	3.071	277	.059
			22:00	0.013	0.010	1.286	280	.935
		3	04:00	0.058	0.011	5.374	182	<.001
			18:00	0.004	0.010	0.401	277	>.999
			22:00	-0.002	0.010	-0.175	280	>.999
2	04:00	2	18:00	-0.012	0.010	-1.170	197	.962
			22:00	0.005	0.011	0.511	182	.999
		3	04:00	0.039	0.010	4.018	280	.002
			18:00	-0.014	0.010	-1.359	197	.912
			22:00	-0.045	0.011	-1.851	182	.648
2	18:00	2	22:00	-0.018	0.010	-1.790	277	.689
		3	04:00	0.027	0.010	2.621	197	.185
			18:00	-0.026	0.010	-2.680	280	.160
			22:00	-0.032	0.010	-3.245	277	.035
2	22:00	3	04:00	0.045	0.011	4.195	182	.002
			18:00	-0.009	0.010	-0.879	277	.912
			22:00	-0.014	0.010	-1.461	280	.648
3	04:00	3	18:00	0.054	0.010	5.150	197	<.001
			22:00	0.059	0.011	5.534	182	<.001
3	18:00	3	22:00	-0.006	0.010	-0.576	277	.999

Table 21. Pairwise comparisons of differences in lapses across PACT administrations

Day	Time	Day	Time	β	SE	t	df	p
1	1800	1	22:00	0.142	0.076	1.873	392	.633
		2	04:00	-0.154	0.076	-2.037	392	.518
			18:00	-0.176	0.076	-2.317	392	.334
			22:00	0.218	0.076	2.882	392	.096
		3	04:00	-0.377	0.076	-4.966	392	<.001
			18:00	0.081	0.076	1.065	392	.979
			22:00	0.210	0.076	2.770	392	.128
	22:00	2	04:00	-0.296	0.076	-3.910	392	.003
			18:00	-0.318	0.076	-4.190	392	.001
			22:00	0.077	0.076	1.010	392	.985
		3	04:00	-0.519	0.076	-6.839	392	<.001
			18:00	-0.061	0.076	-0.808	392	.997
			22:00	0.068	0.076	0.897	392	.993
2	04:00	2	18:00	0.021	0.076	0.280	392	>.999
			22:00	-0.373	0.076	-4.920	392	<.001
		3	04:00	-0.222	0.076	-2.929	392	.085
			18:00	0.235	0.076	3.102	392	.053
			22:00	0.364	0.076	4.807	392	<.001
	18:00	2	22:00	0.394	0.076	5.200	392	<.001
		3	04:00	-0.201	0.076	-2.649	392	.170
			18:00	0.256	0.076	3.382	392	.022
			22:00	0.386	0.076	5.087	392	<.001
	22:00	3	04:00	-0.595	0.076	-7.849	392	<.001
			18:00	-0.138	0.076	-1.818	392	.670
			22:00	-0.009	0.076	-0.113	392	>.999
3	04:00	3	18:00	-0.457	0.076	-6.031	392	<.001
			22:00	-0.587	0.076	-7.736	392	<.001
	18:00	3	22:00	0.129	0.076	1.705	392	.743

References

1. Representatives C o. ASH o. House Report. Published online 2014.

2. Army Medicine Department. Army Medicine's Performance Triad. Published online 2014.

3. Government Accountability Office. Navy Readiness: Additional Efforts Are Needed to Manage Fatigue, Reduce Crewing Shortfalls, and Implement Training. Published online 2021.

4. Hafner M, Stepanek M, Taylor J, Troxel WM, Van Stolk C. *Why Sleep Matters - the Economic Cost of Insufficient Sleep: A Cross Country Comparative Analysis*.; 2016. https://www.rand.org/pubs/research_reports/RR1791.html.

5. Good CH, Brager AJ, Capaldi VF, Mysliwiec V. Sleep in the United States Military. *Neuropsychopharmacology*. 2020;45(1):176-191. doi:10.1038/s41386-019-0431-7

6. Seelig AD, Jacobson IG, Smith B, et al. Sleep Patterns Before, During, and After Deployment to Iraq and Afghanistan. *Sleep*. 2010;33(12):1615-1622.

7. Seelig AD, Jacobson IG, Donoho CJ, Trone DW, Crum-Cianflone NF, Balkin TJ. Sleep and Health Resilience Metrics in a Large Military Cohort. *Sleep*. 2016;39(5):1111-1120. doi:10.5665/sleep.5766

8. Study on Effects of Sleep Deprivation on Readiness of Members of the Armed Forces.

9. Miller NL, Shattuck LG, Matsangas P. Sleep and fatigue issues in continuous operations: a survey of U.S. Army officers. *Behav Sleep Med*. 2011;9(1):53-65. doi:10.1080/15402002.2011.533994

10. Belenky G, Penetar DM, Thorne D, et al. The Effects of Sleep Deprivation on Performance During Continuous Combat Operations. In: BM M, ed. *Food Components to Enhance Performance: An Evaluation of Potential Performance-Enhancing Food Components for Operational Rations*. Vol 7. National Academies Press; 1994.

11. Grandner MA, Fernandez FX. The translational neuroscience of sleep: A contextual framework. *Science*. 2021;374(6567):568-573. doi:10.1126/science.abj8188

12. Chennaoui M, Arnal PJ, Sauvet F, Léger D. Sleep and exercise: a reciprocal issue? *Sleep Med Rev*. 2015;20:59-72. doi:10.1016/j.smrv.2014.06.008

13. Buysse DJ. Sleep health: can we define it? Does it matter? *Sleep*. 2014;37(1):9-17. doi:10.5665/sleep.3298

14. Grier T, Dinkeloo E, Reynolds M, Jones BH. Sleep duration and musculoskeletal injury incidence in physically active men and women: A study of U.S. Army Special Operation Forces soldiers. *Sleep Health*. 2020;6(3):344-349. doi:10.1016/j.sleh.2020.01.004

15. Milewski MD, Skaggs DL, Bishop GA, et al. Chronic lack of sleep is associated with increased sports injuries in adolescent athletes. *J Pediatr Orthop*. 2014;34(2):129-133. doi:10.1097/BPO.0000000000000151

16. Ogilvie RP, Patel SR. The Epidemiology of Sleep and Diabetes. *Curr Diab Rep*. 2018;18(10):82. doi:10.1007/s11892-018-1055-8

17. Fullagar HH, Skorski S, Duffield R, Hammes D, Coutts AJ, Meyer T. Sleep and athletic performance: the effects of sleep loss on exercise performance, and physiological and cognitive responses to exercise. *Sports Med*. 2015;45(2):161-186. doi:10.1007/s40279-014-0260-0

18. Grandou C, Wallace L, Fullagar HHK, Duffield R, Burley S. The Effects of Sleep Loss on Military Physical Performance. *Sports Med*. 2019;49(8):1159-1172. doi:10.1007/s40279-019-01123-8

19. Lim J, Dinges DF. A meta-analysis of the impact of short-term sleep deprivation on cognitive variables. *Psychol Bull*. 2010;136(3):375-389. doi:10.1037/a0018883

20. Pilcher JJ, Huffcutt AI. Effects of sleep deprivation on performance: a meta-analysis. *Sleep*. 1996;19(4):318-326. doi:10.1093/sleep/19.4.318

21. Tomaso CC, Johnson AB, Nelson TD. The effect of sleep deprivation and restriction on mood, emotion, and emotion regulation: three meta-analyses in one. *Sleep*. 2021;44(6):zsaa289. doi:10.1093/sleep/zsaa289

22. Harrison Y, Horne JA. The impact of sleep deprivation on decision making: a review. *J Exp Psychol Appl*. 2000;6(3):236-249.

23. Durmer JS, Dinges DF. Neurocognitive consequences of sleep deprivation. *Semin Neurol*. 2005;25(1):117-129. doi:10.1055/s-2005-867080

24. Goel N, Rao H, Durmer JS, Dinges DF. Neurocognitive consequences of sleep deprivation. *Semin Neurol*. 2009;29(4):320-339. doi:10.1055/s-0029-1237117

25. Yang DF, Shen YL, Wu C, et al. Sleep deprivation reduces the recovery of muscle injury induced by high-intensity exercise in a mouse model. *Life Sci*. 2019;235:116835. doi:10.1016/j.lfs.2019.116835

26. Skein M, Duffield R, Edge J, Short MJ, Mündel T. Intermittent-sprint performance and muscle glycogen after 30 h of sleep deprivation. *Med Sci Sports Exerc*. 2011;43(7):1301-1311. doi:10.1249/MSS.0b013e31820abc5a

27. Nédélec M, Halson S, Abaidia AE, Ahmaidi S, Dupont G. Stress, Sleep and Recovery in Elite Soccer: A Critical Review of the Literature. *Sports Med Auckl NZ*. 2015;45(10):1387-1400. doi:10.1007/s40279-015-0358-z

28. McHill AW, Wright KP Jr. Role of sleep and circadian disruption on energy expenditure and in metabolic predisposition to human obesity and metabolic disease. *Obes Rev*. 2017;18 Suppl 1:15-24. doi:10.1111/obr.12503

29. Depner CM, Stothard ER, Wright KP. Metabolic consequences of sleep and circadian disorders. *Curr Diab Rep*. 2014;14(7):507. doi:10.1007/s11892-014-0507-z

30. Markwald RR, Melanson EL, Smith MR, et al. Impact of insufficient sleep on total daily energy expenditure, food intake, and weight gain. *Proc Natl Acad Sci U S A*. 2013;110(14):5695-5700. doi:10.1073/pnas.1216951110

31. Hartzler BM. Fatigue on the flight deck: the consequences of sleep loss and the benefits of napping. *Accid Anal Prev*. 2014;62:309-318. doi:10.1016/j.aap.2013.10.010

32. Elliman TD, Schwalb ME, Adler AB. Sleep deprivation and hazardous unintended sleep in US army drill sergeants. *Sleep Health*. 2020;6(3):350-357. doi:10.1016/j.sleh.2020.04.007

33. Mantua J, Bessey AF, Sowden WJ. Poor Subjective Sleep Quality Is Associated with Poor Occupational Outcomes in Elite Soldiers. *Clocks Sleep*. 2020;2(2):182-193. doi:10.3390/clockssleep2020015

34. Westerberg CE, Florczak SM, Weintraub S, et al. Memory improvement via slow-oscillatory stimulation during sleep in older adults. *Neurobiol Aging*. 2015;36(9):2577-2586. doi:10.1016/j.neurobiolaging.2015.05.014

35. Ferrarelli F, Kaskie R, Laxminarayan S, Ramakrishnan S, Reifman J, Germain A. An increase in sleep slow waves predicts better working memory performance in healthy individuals. *Neuroimage*. 2019;191:1-9. doi:10.1016/j.neuroimage.2019.02.020

36. Huber R, Ghilardi MF, Massimini M, Tononi G. Local sleep and learning. *Nature*. 2004;430(6995):78-81. doi:10.1038/nature02663

37. Borbely AA, Daan S, Wirz-Justice A, Deboer T. The two-process model of sleep regulation: a reappraisal. *J Sleep Res*. 2016;25(2):131-143. doi:10.1111/jsr.12371

38. Dijk DJ, von Schantz M. Timing and consolidation of human sleep, wakefulness, and performance by a symphony of oscillators. *J Biol Rhythms*. 2005;20(4):279-290. doi:10.1177/0748730405278292

39. Fuller PM, Gooley JJ, Saper CB. Neurobiology of the sleep-wake cycle: sleep architecture, circadian regulation, and regulatory feedback. *J Biol Rhythms*. 2006;21(6):482-493. doi:10.1177/0748730406294627

40. Israel B, Buysse DJ, Krafty RT, Begley A, Miewald J, Hall M. Short-term stability of sleep and heart rate variability in good sleepers and patients with insomnia: for some measures, one night is enough. *Sleep*. 2012;35(9):1285-1291. doi:10.5665/sleep.2088

41. De Gennaro L, Ferrara M, Vecchio F, Curcio G, Bertini M. An electroencephalographic fingerprint of human sleep. *Neuroimage*. 2005;26(1):114-122. doi:10.1016/j.neuroimage.2005.01.020

42. Rusterholz T, Tarokh L, Van Dongen HP, Achermann P. Interindividual differences in the dynamics of the homeostatic process are trait-like and distinct for sleep versus wakefulness. *J Sleep Res*. 2017;26(2):171-178. doi:10.1111/jsr.12483

43. Brindle RC, Cribbet MR, Samuelsson LB, et al. The Relationship Between Childhood Trauma and Poor Sleep Health in Adulthood. *Psychosom Med*. 2018;80(2):200-207. doi:10.1097/PSY.0000000000000542

44. Cai Y, Wang J, Hou L. Resilience Improves the Sleep Quality in Disabled Elders: The Role of Perceived Stress. *Front Psychol*. 2021;12:585816. doi:10.3389/fpsyg.2021.585816

45. Lieberman HR, Bathalon GP, Falco CM, Morgan CA, Niro PJ, Tharion WJ. The fog of war: decrements in cognitive performance and mood associated with combat-like stress. *Aviat Space Environ Med*. 2005;76(7 Suppl):C7-14.

46. Tharion WJ, Shukitt-Hale B, Lieberman HR. Caffeine effects on marksmanship during high-stress military training with 72 hour sleep deprivation. *Aviat Space Environ Med*. 2003;74(4):309-314.

47. Lieberman HR, Bathalon GP, Falco CM, Kramer FM, Morgan CA, Niro P. Severe decrements in cognition function and mood induced by sleep loss, heat, dehydration, and undernutrition during simulated combat. *Biol Psychiatry*. 2005;57(4):422-429. doi:10.1016/j.biopsych.2004.11.014

48. Nindl BC, Leone CD, Tharion WJ, et al. Physical performance responses during 72 h of military operational stress. *Med Sci Sports Exerc*. 2002;34(11):1814-1822. doi:10.1097/00005768-200211000-00019

49. Lieberman HR, Niro P, Tharion WJ, Nindl BC, Castellani JW, Montain SJ. Cognition during sustained operations: comparison of a laboratory simulation to field studies. *Aviat Space Env Med*. 2006;77(9):929-935.

50. Vrijkotte S, Roelands B, Meeusen R, Pattyn N. Sustained Military Operations and Cognitive Performance. *Aerosp Med Hum Perform*. 2016;87(8):718-727. doi:10.3357/amhp.4468.2016

51. Fajen BR, Riley MA, Turvey MT. Information, affordances, and the control of action in sport. *Int J Sport Psychol*. 2008;40:79-107.

52. Smith J, Pepping GJ. Effects of Affordance Perception on the Initiation and Actualization of Action. *Ecol Psychol*. 2010;22(2):119-149. doi:10.1080/10407411003720080

53. Plumert JM, Kearney JK. Linking Decisions and Actions in Dynamic Environments: How Child and Adult Cyclists Cross Roads With Traffic. *Ecol Psychol*. 2014;26(1-2):125-133. doi:10.1080/10407413.2014.874933

54. Johnson CD, Eagle SR, Nindl BC, et al. The effects of fatiguing exercise and load carriage on the perception and initiation of movement. *Eur J Sport Sci*. Published online February 13, 2020:1-9. doi:10.1080/17461391.2020.1725137

55. Connaboy C, LaGoy AD, Johnson CD, et al. Sleep deprivation impairs affordance perception behavior during an action boundary accuracy assessment. *Acta Astronaut*. 2020;166:270-276.

56. Daviaux Y, Mignardot JB, Cornu C, Deschamps T. Effects of total sleep deprivation on the perception of action capabilities. *Exp Brain Res*. 2014;232(7):2243-2253. doi:10.1007/s00221-014-3915-z

57. Van Dongen HP, Baynard MD, Maislin G, Dinges DF. Systematic interindividual differences in neurobehavioral impairment from sleep loss: evidence of trait-like differential vulnerability. *Sleep*. 2004;27(3):423-433.

58. Van Dongen HP, Caldwell JA Jr, Caldwell JL. Investigating systematic individual differences in sleep-deprived performance on a high-fidelity flight simulator. *Behav Res Methods*. 2006;38(2):333-343. doi:10.3758/bf03192785

59. Sprecher KE, Ritchie HK, Burke TM, et al. Trait-like vulnerability of higher-order cognition and ability to maintain wakefulness during combined sleep restriction and circadian misalignment. *Sleep*. 2019;42(8):zsz113. doi:10.1093/sleep/zsz113

60. Van Dongen HP, Vitellaro KM, Dinges DF. Individual differences in adult human sleep and wakefulness: Leitmotif for a research agenda. *Sleep*. 2005;28(4):479-496. doi:10.1093/sleep/28.4.479

61. Harris E, Taylor MK, Drummond SPA, Larson GE, Potterat EG. Assessment of Sleep Disruption and Sleep Quality in Naval Special Warfare Operators. *Mil Med*. 2015;180(7):803-808. doi:10.7205/MILMED-D-14-00436

62. Shattuck NL, Matsangas P, Moore J, Wegemann L. Prevalence of Musculoskeletal Symptoms, Excessive Daytime Sleepiness, and Fatigue in the Crewmembers of a U.S. Navy Ship. *Mil Med*. 2016;181(7):655-662. doi:10.7205/MILMED-D-15-00279

63. Matsangas P, Shattuck NL. Sleep quality, occupational factors, and psychomotor vigilance performance in the U.S. Navy sailors. *Sleep*. 2020;43(12). doi:10.1093/sleep/zsaa118

64. Mantua J, Bessey A, Sowden WJ, et al. A Review of Environmental Barriers to Obtaining Adequate Sleep in the Military Operational Context. *Mil Med*. 2019;184(7-8):e259-e266. doi:10.1093/milmed/usz029

65. Nieuwenhuys A, Dora J, Knufinke-Meyfroyt M, Beckers D, Rietjens G, Helmhout P. “20,000 leagues under the sea”: Sleep, cognitive performance, and self-reported recovery status during a 67-day military submarine mission. *Appl Ergon*. 2021;91:103295. doi:10.1016/j.apergo.2020.103295

66. Harrison E, Glickman GL, Beckerley S, Taylor MK. Self-Reported Sleep During U.S. Navy Operations and the Impact of Deployment-Related Factors. *Mil Med*. 2017;182(S1):189-194. doi:10.7205/MILMED-D-16-00078

67. Matsangas P, Shattuck NL. Habitability in Berthing Compartments and Well-Being of Sailors Working on U.S. Navy Surface Ships. *Hum Factors*. 2021;63(3):462-473. doi:10.1177/0018720820906050

68. Mantua J, Pirner MC, Doyle ST, et al. Sleep and occupational well-being in active duty special operations soldiers: A replication and expansion. *Sleep Health*. Published online March 5, 2021:S2352-7218(21)00011-5. doi:10.1016/j.sleh.2021.02.003

69. Wang Z, Chen B, Li W, Xie F, Loke AY, Shu Q. Sleep quality and its impacts on quality of life among military personnel in remote frontier areas and extreme cold environments. *Health Qual Life Outcomes*. 2020;18(1):227. doi:10.1186/s12955-020-01460-7

70. Mantua J, Bessey AF, Mickelson CA, et al. Sleep and high-risk behavior in military service members: a mega-analysis of four diverse U.S. Army units. *Sleep*. 2021;44(4). doi:10.1093/sleep/zsaa221

71. O’Leary TJ, Wardle SL, Greeves JP. Energy Deficiency in Soldiers: The Risk of the Athlete Triad and Relative Energy Deficiency in Sport Syndromes in the Military. *Front Nutr*. 2020;7:142. doi:10.3389/fnut.2020.00142

72. Tharion WJ, Lieberman HR, Montain SJ, et al. Energy requirements of military personnel. *Appetite*. 2005;44(1):47-65. doi:10.1016/j.appet.2003.11.010

73. Shukitt-Hale B, Askew EW, Lieberman HR. Effects of 30 Days of Undernutrition on Reaction Time, Moods, and Symptoms. :7.

74. Berry RB, Albertario CL, Harding SM, et al. *The AASM Manual for the Scoring of Sleep and Associated Events: Rules, Terminology and Technical Specifications*. American Academy of Sleep Medicine; 2018.

75. Pivik RT, Broughton RJ, Coppola R, Davidson RJ, Fox N, Nuwer MR. Guidelines for the recording and quantitative analysis of electroencephalographic activity in research contexts. *Psychophysiology*. 1993;30(6):547-558. doi:10.1111/j.1469-8986.1993.tb02081.x

76. Ohayon MM, Carskadon MA, Guilleminault C, Vitiello MV. Meta-Analysis of Quantitative Sleep Parameters From Childhood to Old Age in Healthy Individuals: Developing Normative Sleep Values Across the Human Lifespan. *Sleep*. 2004;27(7):1255-1273. doi:10.1093/sleep/27.7.1255

77. Colrain IM. The K-complex: a 7-decade history. *Sleep*. 2005;28(2):255-273. doi:10.1093/sleep/28.2.255

78. Riedner BA, Hulse BK, Murphy MJ, Ferrarelli F, Tononi G. Temporal dynamics of cortical sources underlying spontaneous and peripherally evoked slow waves. *Prog Brain Res*. 2011;193:201-218. doi:10.1016/B978-0-444-53839-0.00013-2

79. Steriade M. The corticothalamic system in sleep. *Front Biosci*. 2003;8:d878-99.

80. Cox R, Schapiro AC, Manoach DS, Stickgold R. Individual Differences in Frequency and Topography of Slow and Fast Sleep Spindles. *Front Hum Neurosci*. 2017;11:433. doi:10.3389/fnhum.2017.00433

81. Fogel SM, Smith CT. Learning-dependent changes in sleep spindles and Stage 2 sleep. *J Sleep Res*. 2006;15(3):250-255. doi:10.1111/j.1365-2869.2006.00522.x

82. Fogel SM, Smith CT. The function of the sleep spindle: a physiological index of intelligence and a mechanism for sleep-dependent memory consolidation. *Neurosci Biobehav Rev*. 2011;35(5):1154-1165. doi:10.1016/j.neubiorev.2010.12.003

83. Schabus M, Gruber G, Parapatics S, et al. Sleep spindles and their significance for declarative memory consolidation. *Sleep*. 2004;27(8):1479-1485. doi:10.1093/sleep/27.7.1479

84. Schabus M, Hodlmoser K, Gruber G, et al. Sleep spindle-related activity in the human EEG and its relation to general cognitive and learning abilities. *Eur J Neurosci*. 2006;23(7):1738-1746. doi:10.1111/j.1460-9568.2006.04694.x

85. Smith C, MacNeill C. Impaired motor memory for a pursuit rotor task following Stage 2 sleep loss in college students. *J Sleep Res*. 1994;3(4):206-213. doi:10.1111/j.1365-2869.1994.tb00133.x

86. Nishida M, Walker MP. Daytime naps, motor memory consolidation and regionally specific sleep spindles. *PLoS One*. 2007;2(4):e341. doi:10.1371/journal.pone.0000341

87. Ketz N, Jones AP, Bryant NB, Clark VP, Pilly PK. Closed-Loop Slow-Wave tACS Improves Sleep-Dependent Long-Term Memory Generalization by Modulating Endogenous Oscillations. *J Neurosci*. 2018;38(33):7314-7326. doi:10.1523/JNEUROSCI.0273-18.2018

88. Lustenberger C, Boyle MR, Alagapan S, Mellin JM, Vaughn BV, Frohlich F. Feedback-Controlled Transcranial Alternating Current Stimulation Reveals a Functional Role of Sleep Spindles in Motor Memory Consolidation. *Curr Biol*. 2016;26(16):2127-2136. doi:10.1016/j.cub.2016.06.044

89. Jobert M, Poiseau E, Jahnig P, Schulz H, Kubicki S. Topographical analysis of sleep spindle activity. *Neuropsychobiology*. 1992;26(4):210-217. doi:10.1159/000118923

90. Bang JW, Khalilzadeh O, Hamalainen M, Watanabe T, Sasaki Y. Location specific sleep spindle activity in the early visual areas and perceptual learning. *Vis Res*. 2014;99:162-171. doi:10.1016/j.visres.2013.12.014

91. Mednick SC, McDevitt EA, Walsh JK, et al. The critical role of sleep spindles in hippocampal-dependent memory: a pharmacology study. *J Neurosci*. 2013;33(10):4494-4504. doi:10.1523/JNEUROSCI.3127-12.2013

92. Barakat M, Doyon J, Debas K, et al. Fast and slow spindle involvement in the consolidation of a new motor sequence. *Behav Brain Res*. 2011;217(1):117-121. doi:10.1016/j.bbr.2010.10.019

93. Barakat M, Carrier J, Debas K, et al. Sleep spindles predict neural and behavioral changes in motor sequence consolidation. *Hum Brain Mapp*. 2013;34(11):2918-2928. doi:10.1002/hbm.22116

94. Tamaki M, Matsuoka T, Nittono H, Hori T. Fast sleep spindle (13-15 hz) activity correlates with sleep-dependent improvement in visuomotor performance. *Sleep*. 2008;31(2):204-211.

95. Tamaki M, Matsuoka T, Nittono H, Hori T. Activation of fast sleep spindles at the premotor cortex and parietal areas contributes to motor learning: a study using sLORETA. *Clin Neurophysiol*. 2009;120(5):878-886. doi:10.1016/j.clinph.2009.03.006

96. Iber C, American Academy of Sleep M. *The AASM Manual for the Scoring of Sleep and Associated Events : Rules, Terminology and Technical Specifications*. American Academy of Sleep Medicine; 2007.

97. Massimini M, Huber R, Ferrarelli F, Hill S, Tononi G. The sleep slow oscillation as a traveling wave. *J Neurosci*. 2004;24(31):6862-6870. doi:10.1523/JNEUROSCI.1318-04.2004

98. Esser SK, Hill SL, Tononi G. Sleep homeostasis and cortical synchronization: I. Modeling the effects of synaptic strength on sleep slow waves. *Sleep*. 2007;30(12):1617-1630. doi:10.1093/sleep/30.12.1617

99. Vyazovskiy VV, Riedner BA, Cirelli C, Tononi G. Sleep homeostasis and cortical synchronization: II. A local field potential study of sleep slow waves in the rat. *Sleep*. 2007;30(12):1631-1642. doi:10.1093/sleep/30.12.1631

100. Riedner BA, Vyazovskiy VV, Huber R, et al. Sleep homeostasis and cortical synchronization: III. A high-density EEG study of sleep slow waves in humans. *Sleep*. 2007;30(12):1643-1657. doi:10.1093/sleep/30.12.1643

101. Tononi G, Cirelli C. Sleep and synaptic homeostasis: a hypothesis. *Brain Res Bull*. 2003;62(2):143-150. doi:10.1016/j.brainresbull.2003.09.004

102. Feld GB, Diekelmann S. Sleep smart—optimizing sleep for declarative learning and memory. 2015;6(622). doi:10.3389/fpsyg.2015.00622

103. Ribeiro S. Sleep and plasticity. *Pflugers Arch*. 2012;463(1):111-120. doi:10.1007/s00424-011-1031-5

104. Poe GR, Walsh CM, Bjorness TE. Cognitive Neuroscience of Sleep. *Prog Brain Res*. 2010;185:1-19. doi:10.1016/B978-0-444-53702-7.00001-4

105. Esser SK, Huber R, Massimini M, Peterson MJ, Ferrarelli F, Tononi G. A direct demonstration of cortical LTP in humans: a combined TMS/EEG study. *Brain Res Bull*. 2006;69(1):86-94. doi:10.1016/j.brainresbull.2005.11.003

106. Olcese U, Esser SK, Tononi G. Sleep and synaptic renormalization: a computational study. *J Neurophysiol*. 2010;104(6):3476-3493. doi:10.1152/jn.00593.2010

107. Huber R, Esser SK, Ferrarelli F, Massimini M, Peterson MJ, Tononi G. TMS-induced cortical potentiation during wakefulness locally increases slow wave activity during sleep. *PLoS One*. 2007;2(3):e276. doi:10.1371/journal.pone.0000276

108. Pugin F, Metz AJ, Wolf M, Achermann P, Jenni OG, Huber R. Local increase of sleep slow wave activity after three weeks of working memory training in children and adolescents. *Sleep*. 2015;38(4):607-614. doi:10.5665/sleep.4580

109. Astill RG, Piantoni G, Raymann RJ, et al. Sleep spindle and slow wave frequency reflect motor skill performance in primary school-age children. *Front Hum Neurosci*. 2014;8:910. doi:10.3389/fnhum.2014.00910

110. Landsness EC, Crupi D, Hulse BK, et al. Sleep-dependent improvement in visuomotor learning: a causal role for slow waves. *Sleep*. 2009;32(10):1273-1284.

111. Landsness EC, Ferrarelli F, Sarasso S, et al. Electrophysiological traces of visuomotor learning and their renormalization after sleep. *Clin Neurophysiol*. 2011;122(12):2418-2425. doi:10.1016/j.clinph.2011.05.001

112. Huber R, Ghilardi MF, Massimini M, et al. Arm immobilization causes cortical plastic changes and locally decreases sleep slow wave activity. *Nat Neurosci*. 2006;9(9):1169-1176. doi:10.1038/nn1758

113. Grimaldi D, Papalambros NA, Zee PC, Malkani RG. Neurostimulation techniques to enhance sleep and improve cognition in aging. *Neurobiol Dis*. 2020;141:104865. doi:10.1016/j.nbd.2020.104865

114. Wilckens KA, Ferrarelli F, Walker MP, Buysse DJ. Slow-Wave Activity Enhancement to Improve Cognition. *Trends Neurosci*. 2018;41(7):470-482. doi:10.1016/j.tins.2018.03.003

115. Malkani RG, Zee PC. Brain Stimulation for Improving Sleep and Memory. *Sleep Med Clin*. 2020;15(1):101-115. doi:10.1016/j.jsmc.2019.11.002

116. Diep C, Ftouni S, Manousakis JE, Nicholas CL, Drummond SPA, Anderson C. Acoustic slow wave sleep enhancement via a novel, automated device improves executive function in middle-aged men. *Sleep*. 2020;43(1). doi:10.1093/sleep/zsz197

117. Bellesi M, Riedner BA, Garcia-Molina GN, Cirelli C, Tononi G. Enhancement of sleep slow waves: underlying mechanisms and practical consequences. *Front Syst Neurosci*. 2014;8:208. doi:10.3389/fnsys.2014.00208

118. Leminen MM, Virkkala J, Saure E, et al. Enhanced Memory Consolidation Via Automatic Sound Stimulation During Non-REM Sleep. *Sleep*. 2017;40(3). doi:10.1093/sleep/zsx003

119. Ngo HV, Miedema A, Faude I, Martinetz T, Molle M, Born J. Driving sleep slow oscillations by auditory closed-loop stimulation-a self-limiting process. *J Neurosci*. 2015;35(17):6630-6638. doi:10.1523/JNEUROSCI.3133-14.2015

120. Navarrete M, Schneider J, Ngo HV, Valderrama M, Casson AJ, Lewis PA. Examining the optimal timing for closed-loop auditory stimulation of slow-wave sleep in young and older adults. *Sleep*. 2020;43(6). doi:10.1093/sleep/zsz315

121. Ong JL, Patanaik A, Chee N, Lee XK, Poh JH, Chee MWL. Auditory stimulation of sleep slow oscillations modulates subsequent memory encoding through altered hippocampal function. *Sleep*. 2019;42(2). doi:10.1093/sleep/zsy240

122. Papalambros NA, Santostasi G, Malkani RG, et al. Acoustic Enhancement of Sleep Slow Oscillations and Concomitant Memory Improvement in Older Adults. *Front Hum Neurosci*. 2017;11:109. doi:10.3389/fnhum.2017.00109

123. Barham MP, Enticott PG, Conduit R, Lum JA. Transcranial electrical stimulation during sleep enhances declarative (but not procedural) memory consolidation: Evidence from a meta-analysis. *Neurosci Biobehav Rev*. 2016;63:65-77. doi:10.1016/j.neubiorev.2016.01.009

124. Marshall L, Helgadottir H, Molle M, Born J. Boosting slow oscillations during sleep potentiates memory. *Nature*. 2006;444(7119):610-613. doi:10.1038/nature05278

125. Marshall L, Molle M, Hallschmid M, Born J. Transcranial direct current stimulation during sleep improves declarative memory. *J Neurosci*. 2004;24(44):9985-9992. doi:10.1523/JNEUROSCI.2725-04.2004

126. Cellini N, Shimizu RE, Connolly PM, et al. Short Duration Repetitive Transcranial Electrical Stimulation During Sleep Enhances Declarative Memory of Facts. *Front Hum Neurosci*. 2019;13:123. doi:10.3389/fnhum.2019.00123

127. Sahlem GL, Badran BW, Halford JJ, et al. Oscillating Square Wave Transcranial Direct Current Stimulation (tDCS) Delivered During Slow Wave Sleep Does Not Improve Declarative Memory More Than Sham: A Randomized Sham Controlled Crossover Study. *Brain Stimul*. 2015;8(3):528-534. doi:10.1016/j.brs.2015.01.414

128. Cordi MJ, Rasch B. How robust are sleep-mediated memory benefits? *Curr Opin Neurobiol*. 2021;67:1-7. doi:10.1016/j.conb.2020.06.002

129. Aeschbach D, Cutler AJ, Ronda JM. A role for non-rapid-eye-movement sleep homeostasis in perceptual learning. *J Neurosci*. 2008;28(11):2766-2772. doi:10.1523/JNEUROSCI.5548-07.2008

130. Siapas AG, Wilson MA. Coordinated interactions between hippocampal ripples and cortical spindles during slow-wave sleep. *Neuron*. 1998;21(5):1123-1128. doi:10.1016/s0896-6273(00)80629-7

131. Bergmann TO, Born J. Phase-Amplitude Coupling: A General Mechanism for Memory Processing and Synaptic Plasticity? *Neuron*. 2018;97(1):10-13. doi:10.1016/j.neuron.2017.12.023

132. Fell J, Axmacher N. The role of phase synchronization in memory processes. *Nat Rev Neurosci*. 2011;12(2):105-118. doi:10.1038/nrn2979

133. Helfrich RF, Mander BA, Jagust WJ, Knight RT, Walker MP. Old Brains Come Uncoupled in Sleep: Slow Wave-Spindle Synchrony, Brain Atrophy, and Forgetting. *Neuron*. 2018;97(1):221-230 e4. doi:10.1016/j.neuron.2017.11.020

134. Cox R, Mylonas DS, Manoach DS, Stickgold R. Large-scale structure and individual fingerprints of locally coupled sleep oscillations. *Sleep*. 2018;41(12). doi:10.1093/sleep/zsy175

135. Calais JB, Ojopi EB, Morya E, Sameshima K, Ribeiro S. Experience-dependent upregulation of multiple plasticity factors in the hippocampus during early REM sleep. *Neurobiol Learn Mem*. 2015;122:19-27. doi:10.1016/j.nlm.2015.01.002

136. Nishida M, Pearsall J, Buckner RL, Walker MP. REM sleep, prefrontal theta, and the consolidation of human emotional memory. *Cereb Cortex*. 2009;19(5):1158-1166. doi:10.1093/cercor/bhn155

137. Blumberg MS. Developing Sensorimotor Systems in Our Sleep. *Curr Dir Psychol Sci*. 2015;24(1):32-37. doi:10.1177/0963721414551362

138. Dooley JC, Blumberg MS. Developmental “awakening” of primary motor cortex to the sensory consequences of movement. *Elife*. 2018;7. doi:10.7554/eLife.41841

139. Poe GR. Sleep Is for Forgetting. *J Neurosci*. 2017;37(3):464-473. doi:10.1523/JNEUROSCI.0820-16.2017

140. Mednick S, Nakayama K, Stickgold R. Sleep-dependent learning: a nap is as good as a night. *Nat Neurosci*. 2003;6(7):697-698. doi:10.1038/nn1078

141. Ribeiro S, Shi X, Engelhard M, et al. Novel experience induces persistent sleep-dependent plasticity in the cortex but not in the hippocampus. *Front Neurosci*. 2007;1(1):43-55. doi:10.3389/neuro.01.1.1.003.2007

142. Zhang Y, Ren R, Sanford LD, et al. Sleep in posttraumatic stress disorder: A systematic review and meta-analysis of polysomnographic findings. *Sleep Med Rev*. 2019;48:101210. doi:10.1016/j.smrv.2019.08.004

143. Ackermann S, Rasch B. Differential effects of non-REM and REM sleep on memory consolidation? *Curr Neurol Neurosci Rep*. 2014;14(2):430. doi:10.1007/s11910-013-0430-8

144. Fischer S, Hallschmid M, Elsner AL, Born J. Sleep forms memory for finger skills. *Proc Natl Acad Sci U A*. 2002;99(18):11987-11991. doi:10.1073/pnas.182178199

145. Zhou Y, Lai CSW, Bai Y, et al. REM sleep promotes experience-dependent dendritic spine elimination in the mouse cortex. *Nat Commun*. 2020;11(1):4819. doi:10.1038/s41467-020-18592-5

146. Mednick SC, Arman AC, Boynton GM. The time course and specificity of perceptual deterioration. *Proc Natl Acad Sci U A*. 2005;102(10):3881-3885. doi:10.1073/pnas.0407866102

147. Daan S, Beersma DG, Borbely AA. Timing of human sleep: recovery process gated by a circadian pacemaker. *Am J Physiol-Regul Integr Comp Physiol*. 1984;246(2):R161-R183. doi:10.1152/ajpregu.1984.246.2.R161

148. Krueger JM, Huang YH, Rector DM, Buysse DJ. Sleep: a synchrony of cell activity-driven small network states. *Eur J Neurosci*. 2013;38(2):2199-2209. doi:10.1111/ejn.12238

149. Goel N, Abe T, Braun ME, Dinges DF. Cognitive Workload and Sleep Restriction Interact to Influence Sleep Homeostatic Responses. *Sleep*. 2014;37(11):1745-1756. doi:10.5665/sleep.4164

150. Rodriguez AV, Funk CM, Vyazovskiy VV, Nir Y, Tononi G, Cirelli C. Why Does Sleep Slow-Wave Activity Increase After Extended Wake? Assessing the Effects of Increased Cortical Firing During Wake and Sleep. *J Neurosci Off J Soc Neurosci*. 2016;36(49):12436-12447. doi:10.1523/JNEUROSCI.1614-16.2016

151. Plante DT, Goldstein MR, Cook JD, et al. Effects of partial sleep deprivation on slow waves during non-rapid eye movement sleep: A high density EEG investigation. *Clin Neurophysiol Off J Int Fed Clin Neurophysiol*. 2016;127(2):1436-1444. doi:10.1016/j.clinph.2015.10.040

152. Chennaoui M, Vanneau T, Trignol A, et al. How does sleep help recovery from exercise-induced muscle injuries? *J Sci Med Sport*. 2021;24(10):982-987. doi:10.1016/j.jsams.2021.05.007

153. Tkachenko O, Dinges DF. Interindividual variability in neurobehavioral response to sleep loss: A comprehensive review. *Neurosci Biobehav Rev*. 2018;89:29-48. doi:10.1016/j.neubiorev.2018.03.017

154. Lazar AS, Lazar ZI, Dijk DJ. Circadian regulation of slow waves in human sleep: Topographical aspects. *Neuroimage*. 2015;116:123-134. doi:10.1016/j.neuroimage.2015.05.012

155. De Gennaro L, Marzano C, Fratello F, et al. The electroencephalographic fingerprint of sleep is genetically determined: a twin study. *Ann Neurol*. 2008;64(4):455-460. doi:10.1002/ana.21434

156. Goel N. Genetic Markers of Sleep and Sleepiness. *Sleep Med Clin*. 2017;12(3):289-299. doi:10.1016/j.jsmc.2017.03.005

157. Tucker AM, Dinges DF, Van Dongen HP. Trait interindividual differences in the sleep physiology of healthy young adults. *J Sleep Res*. 2007;16(2):170-180. doi:10.1111/j.1365-2869.2007.00594.x

158. Gander P, Signal L, Van Dongen HPA, Muller D, Van Den Berg M. Stable inter-individual differences in slow-wave sleep during nocturnal sleep and naps. *Sleep and biological rhythms*. Published online 2010. Accessed July 29, 2021. https://onlinelibrary.wiley.com/doi/abs/10.1111/j.1479-8425.2010.00454.x

159. Erwin JA, Skeiky L, Satterfield BC, et al. Robustness of inter-individual differences in slow wave sleep for daytime sleep periods after total sleep deprivation with or without caffeine administration: potential implications for around-the-clock operations. *Chronobiol Int*. 2020;37(9-10):1465-1468. doi:10.1080/07420528.2020.1817931

160. Buckelmuller J, Landolt HP, Stassen HH, Achermann P. Trait-like individual differences in the human sleep electroencephalogram. *Neuroscience*. 2006;138(1):351-356. doi:10.1016/j.neuroscience.2005.11.005

161. Tarokh L, Rusterholz T, Achermann P, Van Dongen HP. The spectrum of the non-rapid eye movement sleep electroencephalogram following total sleep deprivation is trait-like. *J Sleep Res*. 2015;24(4):360-363. doi:10.1111/jsr.12279

162. Tan X, Campbell IG, Feinberg I. Internight reliability and benchmark values for computer analyses of non-rapid eye movement (NREM) and REM EEG in normal young adult and elderly subjects. *Clin Neurophysiol*. 2001;112(8):1540-1552. doi:10.1016/s1388-2457(01)00570-3

163. Rusterholz T, Achermann P. Topographical aspects in the dynamics of sleep homeostasis in young men: individual patterns. *BMC Neurosci*. 2011;12(1):84. doi:10.1186/1471-2202-12-84

164. Rusterholz T, Dürr R, Achermann P. Inter-individual differences in the dynamics of sleep homeostasis. *Sleep*. 2010;33(4):491-498. doi:10.1093/sleep/33.4.491

165. Ong JL, Lo JC, Patanaik A, Chee MWL. Trait-like characteristics of sleep EEG power spectra in adolescents across sleep opportunity manipulations. *J Sleep Res*. 2019;28(5):e12824. doi:10.1111/jsr.12824

166. Beckner ME, Conkright WR, Eagle SR, et al. Impact of simulated military operational stress on executive function relative to trait resilience, aerobic fitness, and neuroendocrine biomarkers. *Physiol Behav*. 2021;236:113413. doi:10.1016/j.physbeh.2021.113413

167. Palmer CJ, Bigelow C, Van Emmerik REA. Defining soldier equipment trade space: load effects on combat marksmanship and perception–action coupling. *Ergonomics*. 2013;56(11):1708-1721. doi:10.1080/00140139.2013.832805

168. Biggs AT, Hamilton JA, Jensen AE, et al. Perception during use of force and the likelihood of firing upon an unarmed person. *Sci Rep*. 2021;11(1):13313. doi:10.1038/s41598-021-90918-9

169. Tong J, Maruta J, Heaton KJ, Maule AL, Ghajar J. Adaptation of visual tracking synchronization after one night of sleep deprivation. *Exp Brain Res*. 2014;232(1):121-131. doi:10.1007/s00221-013-3725-8

170. Smith CD, Cooper A, Merullo DJ, et al. Sleep restriction and cognitive load affect performance on a simulated marksmanship task. *J Sleep Res*. 2019;28(3). doi:10.1111/jsr.12637

171. Head J, Tenan MS, Tweedell AJ, et al. Prior Mental Fatigue Impairs Marksmanship Decision Performance. *Front Physiol*. 2017;8:680. doi:10.3389/fphys.2017.00680

172. Tenan MS, LaFiandra ME, Ortega SV. The Effect of Soldier Marching, Rucksack Load, and Heart Rate on Marksmanship. *Hum Factors*. 2017;59(2):259-267. doi:10.1177/0018720816671604

173. Tikuisis P, Keefe AA, McLellan TM, Kamimori G. Caffeine restores engagement speed but not shooting precision following 22 h of active wakefulness. *Aviat Space Environ Med*. 2004;75(9):771-776.

174. McLellan TM, Kamimori GH, Bell DG, Smith IF, Johnson D, Belenky G. Caffeine maintains vigilance and marksmanship in simulated urban operations with sleep deprivation. *Aviat Space Environ Med*. 2005;76(1):39-45.

175. Hornsby JH, Johnson BL, Meckley DP, et al. Effects of Heart Rate Biofeedback, Sleep, and Alertness on Marksmanship Accuracy during a Live-fire Stress Shoot. *Int J Exerc Sci*. 2021;14(6):123-133.

176. Kamimori GH, McLellan TM, Tate CM, Voss DM, Niro P, Lieberman HR. Caffeine improves reaction time, vigilance and logical reasoning during extended periods with restricted opportunities for sleep. *Psychopharmacology (Berl)*. 2015;232(12):2031-2042. doi:10.1007/s00213-014-3834-5

177. Thompson AG, Swain DP, Branch JD, Spina RJ, Grieco CR. Autonomic response to tactical pistol performance measured by heart rate variability. *J Strength Cond Res*. 2015;29(4):926-933. doi:10.1519/JSC.0000000000000615

178. Rognum TO, Vartdal F, Rodahl K, et al. Physical and mental performance of soldiers on high- and low-energy diets during prolonged heavy exercise combined with sleep deprivation. *Ergonomics*. 1986;29(7):859-867. doi:10.1080/00140138608967198

179. Vaara JP, Oksanen H, Kyrolainen H, Virmavirta M, Koski H, Finni T. 60-Hour Sleep Deprivation Affects Submaximal but Not Maximal Physical Performance. *Front Physiol*. 2018;9:1437. doi:10.3389/fphys.2018.01437

180. Knapik J, Daniels W, Murphy M, Fitzgerald P, Drews F, Vogel J. Physiological factors in infantry operations. *Eur J Appl Physiol*. 1990;60(3):233-238. doi:10.1007/BF00839165

181. Guezennec CY, Satabin P, Legrand H, Bigard AX. Physical performance and metabolic changes induced by combined prolonged exercise and different energy intakes in humans. *Eur J Appl Physiol*. 1994;68(6):525-530. doi:10.1007/BF00599524

182. Keramidas ME, Gadefors M, Nilsson LO, Eiken O. Physiological and psychological determinants of whole-body endurance exercise following short-term sustained operations with partial sleep deprivation. *Eur J Appl Physiol*. 2018;118(7):1373-1384. doi:10.1007/s00421-018-3869-0

183. Tomczak A, Dąbrowski J, Mikulski T. Psychomotor performance of Polish Air Force cadets after 36 hours of survival training. *Ann Agric Environ Med AAEM*. 2017;24(3):387-391. doi:10.5604/12321966.1232762

184. Tomczak A. Coordination Motor Skills of Military Pilots Subjected to Survival Training. *J Strength Cond Res*. 2015;29(9):2460-2464. doi:10.1519/JSC.0000000000000910

185. Lieberman HR, Bukhari AS, Caldwell JA, et al. Two Days of Calorie Deprivation Induced by Underfeeding and Aerobic Exercise Degrades Mood and Lowers Interstitial Glucose but Does Not Impair Cognitive Function in Young Adults. *J Nutr*. 2017;147(1):110-116. doi:10.3945/jn.116.238246

186. Matsangas P, Shattuck NL. Discriminating Between Fatigue and Sleepiness in the Naval Operational Environment. *Behav Sleep Med*. 2018;16(5):427-436. doi:10.1080/15402002.2016.1228645

187. Bonnet MH. The effect of varying prophylactic naps on performance, alertness and mood throughout a 52-hour continuous operation. *Sleep*. 1991;14(4):307-315. doi:10.1093/sleep/14.4.307

188. Shattuck NL, Matsangas P. Psychomotor vigilance performance predicted by Epworth Sleepiness Scale scores in an operational setting with the United States Navy. *J Sleep Res*. 2015;24(2):174-180. doi:10.1111/jsr.12243

189. Basner M, Rao H, Goel N, Dinges DF. Sleep deprivation and neurobehavioral dynamics. *Curr Opin Neurobiol*. 2013;23(5):854-863. doi:10.1016/j.conb.2013.02.008

190. Basner M, Dinges DF. Maximizing sensitivity of the psychomotor vigilance test (PVT) to sleep loss. *Sleep*. 2011;34(5):581-591. doi:10.1093/sleep/34.5.581

191. Chua EC, Sullivan JP, Duffy JF, et al. Classifying attentional vulnerability to total sleep deprivation using baseline features of Psychomotor Vigilance Test performance. *Sci Rep*. 2019;9(1):12102. doi:10.1038/s41598-019-48280-4

192. Drummond SP, Bischoff-Grethe A, Dinges DF, Ayalon L, Mednick SC, Meloy MJ. The neural basis of the psychomotor vigilance task. *Sleep*. 2005;28(9):1059-1068.

193. Gorgoni M, Ferlazzo F, Ferrara M, et al. Topographic electroencephalogram changes associated with psychomotor vigilance task performance after sleep deprivation. *Sleep Med*. 2014;15(9):1132-1139. doi:10.1016/j.sleep.2014.04.022

194. Hudson AN, Van Dongen HPA, Honn KA. Sleep deprivation, vigilant attention, and brain function: a review. *Neuropsychopharmacology*. 2020;45(1):21-30. doi:10.1038/s41386-019-0432-6

195. Van Dongen HP, Dinges DF. Sleep, circadian rhythms, and psychomotor vigilance. *Clin Sports Med*. 2005;24(2):237-249, vii-viii. doi:10.1016/j.csm.2004.12.007

196. Lo JC, Groeger JA, Santhi N, et al. Effects of partial and acute total sleep deprivation on performance across cognitive domains, individuals and circadian phase. *PLoS One*. 2012;7(9):e45987. doi:10.1371/journal.pone.0045987

197. Skornyakov E, Shattuck NL, Winser MA, et al. Sleep and performance in simulated Navy watch schedules. *Accid Anal Prev*. 2017;99:422-427. doi:10.1016/j.aap.2015.11.021

198. Krause AJ, Simon EB, Mander BA, et al. The sleep-deprived human brain. *Nat Rev Neurosci*. 2017;18(7):404-418. doi:10.1038/nrn.2017.55

199. Ma N, Dinges DF, Basner M, Rao H. How acute total sleep loss affects the attending brain: a meta-analysis of neuroimaging studies. *Sleep*. 2015;38(2):233-240. doi:10.5665/sleep.4404

200. Nir Y, Andrillon T, Marmelshtein A, et al. Selective neuronal lapses precede human cognitive lapses following sleep deprivation. *Nat Med*. 2017;23(12):1474-1480. doi:10.1038/nm.4433

201. Andrillon T, Burns A, Mackay T, Windt J, Tsuchiya N. Predicting lapses of attention with sleep-like slow waves. *Nat Commun*. 2021;12(1):3657. doi:10.1038/s41467-021-23890-7

202. Ferguson SA, Lamond N, Kandelaars K, Jay SM, Dawson D. The impact of short, irregular sleep opportunities at sea on the alertness of marine pilots working extended hours. *Chronobiol Int*. 2008;25(2):399-411. doi:10.1080/07420520802106819

203. Davids K, Button C, Araujo D, Renshaw I, Hristovski R. Movement models from sports provide representative task constrains for studying adaptive behavior in human movement systems. *Adapt Behav*. 2006;14(1):73-95.

204. Gibson JJ. The Theory of Affordances. In: *The Ecological Approach to Visual Perception*. ; 1979.

205. Cordovil R, Araújo D, Pepping GJ, Barreiros J. An ecological stance on risk and safe behaviors in children: The role of affordances and emergent behaviors. *New Ideas Psychol*. 2015;36:50-59. doi:10.1016/j.newideapsych.2014.10.007

206. Bootsma RJ, Bakker FC, van Snippenberg FJ, Tdlohreg CW. The effects of anxiety on perceiving the reachability of passing objects. *Ecol Psychol*. 1992;4:1-16.

207. Pijpers JR, Oudejans RRD, Bakker FC, Beek PJ. The Role of Anxiety in Perceiving and Realizing Affordances. *Ecol Psychol*. 2006;18(3):131-161. doi:10.1207/s15326969eco1803_1

208. Johnson CD, Eagle SR, Nindl BC, et al. The effects of fatiguing exercise and load carriage on the perception and initiation of movement. *Eur J Sport Sci*. 2021;21(1):36-44. doi:10.1080/17461391.2020.1725137

209. Eagle SR, Kontos AP, Pepping GJ, et al. Increased Risk of Musculoskeletal Injury Following Sport-Related Concussion: A Perception-Action Coupling Approach. *Sports Med*. 2020;50(1):15-23. doi:10.1007/s40279-019-01144-3

210. Eagle SR, Nindl BC, Johnson CD, Kontos AP, Connaboy C. Does Concussion Affect Perception-Action Coupling Behavior? Action Boundary Perception as a Biomarker for Concussion. *Clin J Sport Med*. Published online February 27, 2019. doi:10.1097/JSM.0000000000000731

211. Palmer CJ, van Emmerik REA. Constraints of Load and Posture on Coordination Variability and Marksmanship Performance. *Motor Control*. 2020;24(3):435-456. doi:10.1123/mc.2019-0082

212. Lim J, Palmer CJ, Busa MA, et al. Additional helmet and pack loading reduce situational awareness during the establishment of marksmanship posture. *Ergonomics*. 2017;60(6):824-836. doi:10.1080/00140139.2016.1222001

213. LaGoy AD, Sinnott AM, Ambarian M, et al. Differences in affordace-based behaviors within an isolated and confined environment are related to sleep, emotional health and physiological parameters. *Acta Astronaut*. 2020;176:238-246. doi:10.1016/j.actaastro.2020.06.034

214. Mednick SC, Nakayama K, Cantero JL, et al. The restorative effect of naps on perceptual deterioration. *Nat Neurosci*. 2002;5(7):677-681. doi:10.1038/nn864

215. De Gennaro L, Ferrara M, Urbani L, Bertini M. Oculomotor impairment after 1 night of total sleep deprivation: a dissociation between measures of speed and accuracy. *Clin Neurophysiol*. 2000;111(10):1771-1778. doi:10.1016/s1388-2457(00)00393-x

216. McClelland LE, Pilcher JJ, Moore DD. Oculomotor measures as predictors of performance during sleep deprivation. *Aviat Space Env Med*. 2010;81(9):833-842. doi:10.3357/asem.2653.2010

217. Gais S, Koster S, Sprenger A, Bethke J, Heide W, Kimmig H. Sleep is required for improving reaction times after training on a procedural visuo-motor task. *Neurobiol Learn Mem*. 2008;90(4):610-615. doi:10.1016/j.nlm.2008.07.016

218. Poudel GR, Innes CR, Jones RD. Distinct neural correlates of time-on-task and transient errors during a visuomotor tracking task after sleep restriction. *Neuroimage*. 2013;77:105-113. doi:10.1016/j.neuroimage.2013.03.054

219. Aguiar SA, Barela JA. Adaptation of sensorimotor coupling in postural control is impaired by sleep deprivation. *PLoS One*. 2015;10(3):e0122340. doi:10.1371/journal.pone.0122340

220. Cheng S, Ma J, Sun J, et al. Differences in sensory reweighting due to loss of visual and proprioceptive cues in postural stability support among sleep-deprived cadet pilots. *Gait Posture*. 2018;63:97-103. doi:10.1016/j.gaitpost.2018.04.037

221. Mah CD, Sparks AJ, Samaan MA, Souza RB, Luke A. Sleep restriction impairs maximal jump performance and joint coordination in elite athletes. *J Sports Sci*. 2019;37(17):1981-1988. doi:10.1080/02640414.2019.1612504

222. Mantua J, Bessey AF, Ritland BM, et al. Sleep loss is related to unstable stationary balance in U.S. Army soldiers in an operationally-relevant context. *Sleep Med*. 2020;73:130-134. doi:10.1016/j.sleep.2020.04.011

223. Ritland BM, Naylor JA, Bessey AF, et al. Transitioning from daytime to nighttime operations in military training has a temporary negative impact on dynamic balance and jump performance in U.S. Army Rangers. *J Sci Med Sport*. Published online February 2021:S1440244021000499. doi:10.1016/j.jsams.2021.02.013

224. Tomczak A, Różański P, Jówko E. Changes in Coordination Motor Abilities of Naval Academy Cadets During Military Survival Training. *Aerosp Med Hum Perform*. 2019;90(7):632-636. doi:10.3357/AMHP.5302.2019

225. Whitney P, Hinson JM, Nusbaum AT. A dynamic attentional control framework for understanding sleep deprivation effects on cognition. *Prog Brain Res*. 2019;246:111-126. doi:10.1016/bs.pbr.2019.03.015

226. Honn KA, Hinson JM, Whitney P, Van Dongen HPA. Cognitive flexibility: A distinct element of performance impairment due to sleep deprivation. *Accid Anal Prev*. Published online March 14, 2018. doi:10.1016/j.aap.2018.02.013

227. Goel N. Neurobehavioral Effects and Biomarkers of Sleep Loss in Healthy Adults. *Curr Neurol Neurosci Rep*. 2017;17(11):89. doi:10.1007/s11910-017-0799-x

228. Yamazaki EM, Goel N. Robust stability of trait-like vulnerability or resilience to common types of sleep deprivation in a large sample of adults. *Sleep*. 2020;43(6):zsz292. doi:10.1093/sleep/zsz292

229. Rupp TL, Wesensten NJ, Balkin TJ. Trait-Like Vulnerability to Total and Partial Sleep Loss. *Sleep*. 2012;35(8):1163-1172. doi:10.5665/sleep.2010

230. Dennis LE, Wohl RJ, Selame LA, Goel N. Healthy Adults Display Long-Term Trait-Like Neurobehavioral Resilience and Vulnerability to Sleep Loss. *Sci Rep*. 2017;7(1):14889. doi:10.1038/s41598-017-14006-7

231. Casale CE, Yamazaki EM, Brieva TE, Antler CA, Goel N. Raw scores on subjective sleepiness, fatigue, and vigor metrics consistently define resilience and vulnerability to sleep loss. *Sleep*. Published online September 9, 2021:zsab228. doi:10.1093/sleep/zsab228

232. Brieva TE, Casale CE, Yamazaki EM, Antler CA, Goel N. Cognitive throughput and working memory raw scores consistently differentiate resilient and vulnerable groups to sleep loss. *Sleep*. Published online August 1, 2021:zsab197. doi:10.1093/sleep/zsab197

233. Yamazaki EM, Casale CE, Brieva TE, Antler CA, Goel N. Concordance of multiple methods to define resiliency and vulnerability to sleep loss depends on Psychomotor Vigilance Test metric. *Sleep*. Published online October 8, 2021:zsab249. doi:10.1093/sleep/zsab249

234. Ramakrishnan S, Laxminarayan S, Wesensten NJ, Kamimori GH, Balkin TJ, Reifman J. Dose-dependent model of caffeine effects on human vigilance during total sleep deprivation. *J Theor Biol*. 2014;358:11-24. doi:10.1016/j.jtbi.2014.05.017

235. Reifman J, Kumar K, Wesensten NJ, Tountas NA, Balkin TJ, Ramakrishnan S. 2B-Alert Web: An Open-Access Tool for Predicting the Effects of Sleep/Wake Schedules and Caffeine Consumption on Neurobehavioral Performance. *Sleep*. 2016;39(12):2157-2159. doi:10.5665/sleep.6318

236. Vital-Lopez FG, Ramakrishnan S, Doty TJ, Balkin TJ, Reifman J. Caffeine dosing strategies to optimize alertness during sleep loss. *J Sleep Res*. 2018;27(5):e12711. doi:10.1111/jsr.12711

237. Arnal PJ, Sauvet F, Leger D, et al. Benefits of Sleep Extension on Sustained Attention and Sleep Pressure Before and During Total Sleep Deprivation and Recovery. *Sleep*. 2015;38(12):1935-1943. doi:10.5665/sleep.5244

238. Mah CD, Mah KE, Kezirian EJ, Dement WC. The effects of sleep extension on the athletic performance of collegiate basketball players. *Sleep*. 2011;34(7):943-950. doi:10.5665/SLEEP.1132

239. Rupp TL, Wesensten NJ, Bliese PD, Balkin TJ. Banking sleep: realization of benefits during subsequent sleep restriction and recovery. *Sleep*. 2009;32(3):311-321. doi:10.1093/sleep/32.3.311

240. Swinbourne R, Miller J, Smart D, Dulson DK, Gill N. The Effects of Sleep Extension on Sleep, Performance, Immunity and Physical Stress in Rugby Players. *Sports Basel Switz*. 2018;6(2):E42. doi:10.3390/sports6020042

241. Silva AC, Silva A, Edwards BJ, et al. Sleep extension in athletes: what we know so far - A systematic review. *Sleep Med*. 2021;77:128-135. doi:10.1016/j.sleep.2020.11.028

242. LaGoy AD, Ferrarelli F, Sinnott AM, Eagle SR, Johnson CD, Connaboy C. You Snooze, You Win? An Ecological Dynamics Framework Approach to Understanding the Relationships Between Sleep and Sensorimotor Performance in Sport. *Sleep Med Clin*. 2020;15(1):31-39. doi:10.1016/j.jsmc.2019.11.001

243. Patterson PD, Weaver MD, Hostler D, Guyette FX, Callaway CW, Yealy DM. The shift length, fatigue, and safety conundrum in EMS. *Prehosp Emerg Care*. 2012;16(4):572-576. doi:10.3109/10903127.2012.704491

244. Dinges DF, Orne MT, Whitehouse WG, Orne EC. Temporal placement of a nap for alertness: contributions of circadian phase and prior wakefulness. *Sleep*. 1987;10(4):313-329.

245. Lumley M, Roehrs T, Zorick F, Lamphere J, Roth T. The alerting effects of naps in sleep-deprived subjects. *Psychophysiology*. 1986;23(4):403-408. doi:10.1111/j.1469-8986.1986.tb00653.x

246. Brooks A, Lack L. A brief afternoon nap following nocturnal sleep restriction: which nap duration is most recuperative? *Sleep*. 2006;29(6):831-840. doi:10.1093/sleep/29.6.831

247. Philip P, Taillard J, Moore N, et al. The effects of coffee and napping on nighttime highway driving: a randomized trial. *Ann Intern Med*. 2006;144(11):785-791. doi:10.7326/0003-4819-144-11-200606060-00004

248. Waterhouse J, Atkinson G, Edwards B, Reilly T. The role of a short post-lunch nap in improving cognitive, motor, and sprint performance in participants with partial sleep deprivation. *J Sports Sci*. 2007;25(14):1557-1566. doi:10.1080/02640410701244983

249. Keramidas ME, Siebenmann C, Norrbrand L, Gadefors M, Eiken O. A brief pre-exercise nap may alleviate physical performance impairments induced by short-term sustained operations with partial sleep deprivation - A field-based study. *Chronobiol Int*. 2018;35(10):1464-1470. doi:10.1080/07420528.2018.1490316

250. Hilditch CJ, McHill AW. Sleep inertia: current insights. *Nat Sci Sleep*. 2019;11:155-165. doi:10.2147/NSS.S188911

251. Groeger JA, Lo JC, Burns CG, Dijk DJ. Effects of sleep inertia after daytime naps vary with executive load and time of day. *Behav Neurosci*. 2011;125(2):252-260. doi:10.1037/a0022692

252. Hilditch CJ, Centofanti SA, Dorrian J, Banks S. A 30-Minute, but Not a 10-Minute Nighttime Nap is Associated with Sleep Inertia. *Sleep*. 2016;39(3):675-685. doi:10.5665/sleep.5550

253. Boukhris O, Abdessalem R, Ammar A, et al. Nap Opportunity During the Daytime Affects Performance and Perceived Exertion in 5-m Shuttle Run Test. *Front Physiol*. 2019;10:779. doi:10.3389/fphys.2019.00779

254. Chung F, Abdullah HR, Liao P. STOP-Bang Questionnaire: A Practical Approach to Screen for Obstructive Sleep Apnea. *Chest*. 2016;149(3):631-638. doi:10.1378/chest.15-0903

255. Saunders JB, Aasland OG, Babor TF, de la Fuente JR, Grant M. Development of the Alcohol Use Disorders Identification Test (AUDIT): WHO Collaborative Project on Early Detection of Persons with Harmful Alcohol Consumption--II. *Addiction*. 1993;88(6):791-804. doi:10.1111/j.1360-0443.1993.tb02093.x

256. Dempster P, Aitkens S. A new air displacement method for the determination of human body composition. Published 1995. Accessed July 14, 2021. https://oce-ovid-com.pitt.idm.oclc.org/article/00005768-199512000-00017/HTML

257. Fields DA, Goran MI, McCrory MA. Body-composition assessment via air-displacement plethysmography in adults and children: a review. *Am J Clin Nutr*. 2002;75(3):453-467. doi:10.1093/ajcn/75.3.453

258. Buysse DJ, Reynolds CF, Monk TH, Berman SR, Kupfer DJ. The Pittsburgh sleep quality index: A new instrument for psychiatric practice and research. *Psychiatry Res*. 1989;28(2):193-213. doi:10.1016/0165-1781(89)90047-4

259. Matsangas P, Mysliwiec V. The utility of the Pittsburgh Sleep Quality Index in US military personnel. *Mil Psychol*. 2018;30(4):360-369. doi:10.1080/08995605.2018.1478547

260. Rice VJB, Schroeder PJ. Self-Reported Sleep, Anxiety, and Cognitive Performance in a Sample of U.S. Military Active Duty and Veterans. *Mil Med*. 2019;184(Suppl 1):488-497. doi:10.1093/milmed/usy323

261. Morin CM. *Insomnia: Psychological Assessment and Management*. Guilford Press; 1993:xvii, 238.

262. Bastien CH, Vallières A, Morin CM. Validation of the Insomnia Severity Index as an outcome measure for insomnia research. *Sleep Med*. 2001;2(4):297-307. doi:10.1016/s1389-9457(00)00065-4

263. Johns MW. A new method for measuring daytime sleepiness: the Epworth sleepiness scale. *Sleep*. 1991;14(6):540-545. doi:10.1093/sleep/14.6.540

264. Johns MW. Reliability and factor analysis of the Epworth Sleepiness Scale. *Sleep*. 1992;15(4):376-381. doi:10.1093/sleep/15.4.376

265. Green BL. Trauma History Questionnaire. In: Stamm BH, ed. *Measurement of Stress, Trauma and Adaptation*. Sidran Press; 1996:366-369.

266. Connor KM, Davidson JR. Development of a new resilience scale: the Connor-Davidson Resilience Scale (CD-RISC). *Depress Anxiety*. 2003;18(2):76-82. doi:10.1002/da.10113

267. McNair D. *Profile of Mood States, POMS. Educational and Industrial Testing Service.* Educational and Industrial Testing Service; 1971.

268. Connaboy C Johnson, CD, LaGoy, AD, Pepping, GJ, Simpson, RJ, Eagle, SR, Flanagan, SD, Deng, Z, Ma, L, Bower, JL and Alfano, CA. Intersession Reliability and Within-Session Stability of a Novel Perception-Action Coupling Task. *Aerosp Med Hum Perform*. 2019;90(2):77-83.

269. Reifman J, Kumar K, Khitrov MY, Liu J, Ramakrishnan S. PC-PVT 2.0: An updated platform for psychomotor vigilance task testing, analysis, prediction, and visualization. *J Neurosci Methods*. 2018;304:39-45. doi:10.1016/j.jneumeth.2018.04.007

270. Vasko RC Jr, Brunner DP, Monahan JP, et al. Power spectral analysis of EEG in a multiple-bedroom, multiple-polygraph sleep laboratory. *Int J Med Inf*. 1997;46(3):175-184. doi:10.1016/s1386-5056(97)00064-6

271. Brunner DP, Vasko RC, Detka CS, Monahan JP, Reynolds CF 3rd, Kupfer DJ. Muscle artifacts in the sleep EEG: automated detection and effect on all-night EEG power spectra. *J Sleep Res*. 1996;5(3):155-164. doi:10.1046/j.1365-2869.1996.00009.x

272. Doman J, Detka C, Hoffman T, et al. Automating the sleep laboratory: implementation and validation of digital recording and analysis. *Int J Biomed Comput*. 1995;38(3):277-290. doi:10.1016/s0020-7101(05)80010-8

273. Koo TK, Li MY. A Guideline of Selecting and Reporting Intraclass Correlation Coefficients for Reliability Research. *J Chiropr Med*. 2016;15(2):155-163. doi:10.1016/j.jcm.2016.02.012

274. Landis JR, Koch GG. The measurement of observer agreement for categorical data. *Biometrics*. 1977;33(1):159-174.

275. Kuznetsova A, Brockhoff P, Christensen R %J J of SS. lmerTest Package: Tests in Linear Mixed Effects Models. 2017;82:1-26.

276. Barr DJ. Random effects structure for testing interactions in linear mixed-effects models. *Front Psychol*. 2013;4:328. doi:10.3389/fpsyg.2013.00328

277. Jaccard J, Turrisi R. *Interaction Effects in Multiple Regression*. 2nd ed. Sage; 2003.

278. Lenth R. emmeans: Estimated Marginal Means, aka Least-Squares Means. *R Package Version 153*. Published online 2020. https://CRAN.R-project.org/package=emmeans

279. Piantoni G, Poil SS, Linkenkaer-Hansen K, et al. Individual differences in white matter diffusion affect sleep oscillations. *J Neurosci*. 2013;33(1):227-233. doi:10.1523/jneurosci.2030-12.2013

280. Piantoni G, Halgren E, Cash SS. The Contribution of Thalamocortical Core and Matrix Pathways to Sleep Spindles. *Neural Plast*. 2016;2016:3024342. doi:10.1155/2016/3024342

281. Gais S, Mölle M, Helms K, Born J. Learning-dependent increases in sleep spindle density. *J Neurosci Off J Soc Neurosci*. 2002;22(15):6830-6834. doi:20026697

282. Dolezal BA, Neufeld EV, Boland DM, Martin JL, Cooper CB. Interrelationship between Sleep and Exercise: A Systematic Review. *Adv Prev Med*. 2017;2017:1364387. doi:10.1155/2017/1364387

283. Straus LD, Drummond SP, Nappi CM, Jenkins MM, Norman SB. Sleep variability in military-related PTSD: a comparison to primary insomnia and healthy controls. *J Trauma Stress*. 2015;28(1):8-16. doi:10.1002/jts.21982

284. Mascaro L, Phillips AJK, Clark JW, Straus LD, Drummond SPA. Diurnal Rhythm Robustness in Individuals With PTSD and Insomnia and The Association With Sleep. *J Biol Rhythms*. Published online January 20, 2021:748730420984563. doi:10.1177/0748730420984563

285. Insana SP, Kolko DJ, Germain A. Early-life trauma is associated with rapid eye movement sleep fragmentation among military veterans. *Biol Psychol*. 2012;89(3):570-579. doi:10.1016/j.biopsycho.2012.01.001

286. Green KT, Calhoun PS, Dennis MF, Mid-Atlantic Mental Illness Research E, Clinical Center W, Beckham JC. Exploration of the resilience construct in posttraumatic stress disorder severity and functional correlates in military combat veterans who have served since September 11, 2001. *J Clin Psychiatry*. 2010;71(7):823-830. doi:10.4088/JCP.09m05780blu

287. Windle G, Bennett KM, Noyes J. A methodological review of resilience measurement scales. *Health Qual Life Outcomes*. 2011;9:8. doi:10.1186/1477-7525-9-8

288. Conkright WR, Beckner ME, Sinnott AM, et al. Neuromuscular performance and hormonal responses to military operational stress in men and women. *J Strength Cond Res*.

289. National Academies of Sciences E and MD of B and SS and EB on C Youth and Families, Committee on the Well Being of Military Families. Demographic and Military Service Characteristics of Military Families. In: Le Menestrel S, Kizer K, eds. *Strengthening the Military Family Readiness System for a Changing American Society*. National Academies Press; 2019.

290. Bezdjian S, Schneider KG, Burchett D, Baker MT, Garb HN. Resilience in the United States Air Force: Psychometric properties of the Connor-Davidson Resilience Scale (CD-RISC). *Psychol Assess*. 2017;29(5):479-485. doi:10.1037/pas0000370

291. Kirschen GW, Jones JJ, Hale L. The Impact of Sleep Duration on Performance Among Competitive Athletes: A Systematic Literature Review. *Clin J Sport Med Off J Can Acad Sport Med*. 2020;30(5):503-512. doi:10.1097/JSM.0000000000000622

292. Ritland BM, Simonelli G, Gentili RJ, et al. Effects of sleep extension on cognitive/motor performance and motivation in military tactical athletes. *Sleep Med*. 2019;58:48-55. doi:10.1016/j.sleep.2019.03.013

293. Chang SP, Chen YH. Relationships between sleep quality, physical fitness and body mass index in college freshmen. *J Sports Med Phys Fitness*. 2015;55(10):1234-1241.

294. Crowley SK, Rebellon J, Huber C, Leonard AJ, Henderson D, Magal M. Cardiorespiratory fitness, sleep, and physiological responses to stress in women. *Eur J Sport Sci*. 2020;20(10):1368-1377. doi:10.1080/17461391.2020.1716855

295. Lee AJY, Lin WH. Association between sleep quality and physical fitness in female young adults. *J Sports Med Phys Fitness*. 2007;47(4):462-467.

296. Kisiolek JN, Smith KA, Baur DA, et al. Sleep Duration Correlates With Performance in Ultra-Endurance Triathlon. *Int J Sports Physiol Perform*. Published online October 9, 2021:1-8. doi:10.1123/ijspp.2021-0111

297. Antunes BM, Campos EZ, Parmezzani SS, Santos RV, Franchini E, Lira FS. Sleep quality and duration are associated with performance in maximal incremental test. *Physiol Behav*. 2017;177:252-256. doi:10.1016/j.physbeh.2017.05.014

298. Roberts SSH, Teo WP, Aisbett B, Warmington SA. Extended Sleep Maintains Endurance Performance Better than Normal or Restricted Sleep. *Med Sci Sports Exerc*. 2019;51(12):2516-2523. doi:10.1249/MSS.0000000000002071

299. Shapiro CM, Warren PM, Trinder J, et al. Fitness facilitates sleep. *Eur J Appl Physiol*. 1984;53(1):1-4. doi:10.1007/BF00964680

300. Rao MN, Blackwell T, Redline S, et al. Association between sleep architecture and measures of body composition. *Sleep*. 2009;32(4):483-490. doi:10.1093/sleep/32.4.483

301. Edinger JD, Morey MC, Sullivan RJ, et al. Aerobic fitness, acute exercise and sleep in older men. *Sleep*. 1993;16(4):351-359. doi:10.1093/sleep/16.4.351

302. Melancon MO, Lorrain D, Dionne IJ. Sleep depth and continuity before and after chronic exercise in older men: electrophysiological evidence. *Physiol Behav*. 2015;140:203-208. doi:10.1016/j.physbeh.2014.12.031

303. Driver HS, Meintjes AF, Rogers GG, Shapiro CM. Submaximal exercise effects on sleep patterns in young women before and after an aerobic training programme. *Acta Physiol Scand Suppl*. 1988;574:8-13.

304. Meintjes AF, Driver HS, Shapiro CM. Improved physical fitness failed to alter the EEG patterns of sleep in young women. *Eur J Appl Physiol*. 1989;59(1-2):123-127. doi:10.1007/BF02396589

305. Kitamura E, Kawasaki Y, Kasai T, et al. The relationship between body composition and sleep architecture in athletes. *Sleep Med*. 2021;87:92-96. doi:10.1016/j.sleep.2021.08.028

306. Paxton SJ, Trinder J, Shapiro CM, Adam K, Oswald I, Gräf KJ. Effect of physical fitness and body composition on sleep and sleep-related hormone concentrations. *Sleep*. 1984;7(4):339-346. doi:10.1093/sleep/7.4.339

307. Montgomery I, Trinder J, Paxton S, Harris D, Fraser G, Colrain I. Physical exercise and sleep: the effect of the age and sex of the subjects and type of exercise. *Acta Physiol Scand Suppl*. 1988;574:36-40.

308. Dattilo M, Antunes HKM, Medeiros A, et al. Sleep and muscle recovery: Endocrinological and molecular basis for a new and promising hypothesis. *Med Hypotheses*. 2011;77(2):220-222. doi:10.1016/j.mehy.2011.04.017

309. Mônico-Neto M, Dáttilo M, Ribeiro DA, et al. REM sleep deprivation impairs muscle regeneration in rats. *Growth Factors*. 2017;35(1):12-18. doi:10.1080/08977194.2017.1314277

310. Stepan ME, Altmann EM, Fenn KM. Slow Wave Sleep During a Brief Nap is Related to Reduced Cognitive Deficits During Sleep Deprivation. *Sleep*. Published online June 22, 2021:zsab152. doi:10.1093/sleep/zsab152

311. Froelicher VF, Thompson AJ, Davis G, Stewart AJ, Triebwasser JH. Prediction of maximal oxygen consumption. Comparison of the Bruce and Balke treadmill protocols. *Chest*. 1975;68(3):331-336. doi:10.1378/chest.68.3.331

312. Borg G. *Borg's Perceived Exertion and Pain Scales*. Human Kinetics; 1998:viii, 104.

313. Friedman JH, Hastie T, Tibshirani R. Regularization Paths for Generalized Linear Models via Coordinate Descent. *J Stat Softw*. 2010;33:1-22. doi:10.18637/jss.v033.i01

314. McNeish DM. Using Lasso for Predictor Selection and to Assuage Overfitting: A Method Long Overlooked in Behavioral Sciences. *Multivar Behav Res*. 2015;50(5):471-484. doi:10.1080/00273171.2015.1036965

315. Soehner AM, Bertocci MA, Levenson JC, et al. Longitudinal Associations Between Sleep Patterns and Psychiatric Symptom Severity in High-Risk and Community Comparison Youth. *J Am Acad Child Adolesc Psychiatry*. 2019;58(6):608-617. doi:10.1016/j.jaac.2018.09.448

316. Laventure S, Fogel S, Lungu O, et al. NREM2 and Sleep Spindles Are Instrumental to the Consolidation of Motor Sequence Memories. *PLoS Biol*. 2016;14(3):e1002429. doi:10.1371/journal.pbio.1002429

317. Kong D, Asplund CL, Ling A, Chee MWL. Increased Automaticity and Altered Temporal Preparation Following Sleep Deprivation. *Sleep*. 2015;38(8):1219-1227. doi:10.5665/sleep.4896

318. Romdhani M, Hammouda O, Smari K, et al. Total Sleep Deprivation and Recovery Sleep Affect the Diurnal Variation of Agility Performance: The Gender Differences. *J Strength Cond Res*. 2021;35(1):132-140. doi:10.1519/JSC.0000000000002614

319. Mysliwiec V, Walter RJ, Collen J, Wesensten N. Military Sleep Management: An Operational Imperative. *US Army Med Dep J*. 2016;(2-16):128-134.

320. Franchak JM, van der Zalm DJ, Adolph KE. Learning by doing: action performance facilitates affordance perception. *Vis Res*. 2010;50(24):2758-2765. doi:10.1016/j.visres.2010.09.019

321. Fitts PM. The information capacity of the human motor system in controlling the amplitude of movement. *J Exp Psychol*. 1954;47(6):381-391.

322. Chua ECP, Yeo SC, Lee ITG, et al. Sustained Attention Performance during Sleep Deprivation Associates with Instability in Behavior and Physiologic Measures at Baseline. *Sleep*. 2014;37(1):27-39. doi:10.5665/sleep.3302

323. Patanaik A, Zagorodnov V, Kwoh CK, Chee MWL. Predicting vulnerability to sleep deprivation using diffusion model parameters. *J Sleep Res*. 2014;23(5):576-584. doi:10.1111/jsr.12166

324. Yeo BTT, Tandi J, Chee MWL. Functional connectivity during rested wakefulness predicts vulnerability to sleep deprivation. *NeuroImage*. 2015;111:147-158. doi:10.1016/j.neuroimage.2015.02.018

325. Xu J, Zhu Y, Fu C, et al. Frontal metabolic activity contributes to individual differences in vulnerability toward total sleep deprivation-induced changes in cognitive function. *J Sleep Res*. 2016;25(2):169-180. doi:10.1111/jsr.12354

326. Riontino L, Cavallero C. Individual differences in working memory efficiency modulate proactive interference after sleep deprivation. *Psychol Res*. 2021;85(2):480-490. doi:10.1007/s00426-020-01292-6

327. Leproult R, Colecchia EF, Berardi AM, Stickgold R, Kosslyn SM, Van Cauter E. Individual differences in subjective and objective alertness during sleep deprivation are stable and unrelated. *Am J Physiol Regul Integr Comp Physiol*. 2003;284(2):R280-290. doi:10.1152/ajpregu.00197.2002

328. Dinges DF, Pack F, Williams K, et al. Cumulative sleepiness, mood disturbance, and psychomotor vigilance performance decrements during a week of sleep restricted to 4-5 hours per night. *Sleep*. 1997;20(4):267-277.

329. Franzen PL, Siegle GJ, Buysse DJ. Relationships between affect, vigilance, and sleepiness following sleep deprivation. *J Sleep Res*. 2008;17(1):34-41. doi:10.1111/j.1365-2869.2008.00635.x

330. Hansen DA, Ramakrishnan S, Satterfield BC, et al. Randomized, double-blind, placebo-controlled, crossover study of the effects of repeated-dose caffeine on neurobehavioral performance during 48 h of total sleep deprivation. *Psychopharmacology (Berl)*. 2019;236(4):1313-1322. doi:10.1007/s00213-018-5140-0

331. Stepan ME, Altmann EM, Fenn KM. Caffeine selectively mitigates cognitive deficits caused by sleep deprivation. *J Exp Psychol Learn Mem Cogn*. Published online May 20, 2021. doi:10.1037/xlm0001023

332. Hilditch CJ, Dorrian J, Banks S. A review of short naps and sleep inertia: do naps of 30 min or less really avoid sleep inertia and slow-wave sleep? *Sleep Med*. 2017;32:176-190. doi:10.1016/j.sleep.2016.12.016

333. Horne JA, Reyner LA. Counteracting driver sleepiness: effects of napping, caffeine, and placebo. *Psychophysiology*. 1996;33(3):306-309. doi:10.1111/j.1469-8986.1996.tb00428.x

334. Martin-Gill C, Barger LK, Moore CG, et al. Effects of Napping During Shift Work on Sleepiness and Performance in Emergency Medical Services Personnel and Similar Shift Workers: A Systematic Review and Meta-Analysis. *Prehospital Emerg Care Off J Natl Assoc EMS Physicians Natl Assoc State EMS Dir*. 2018;22(sup1):47-57. doi:10.1080/10903127.2017.1376136

335. Arnal PJ, Lapole T, Erblang M, et al. Sleep Extension before Sleep Loss: Effects on Performance and Neuromuscular Function. *Med Sci Sports Exerc*. 2016;48(8):1595-1603. doi:10.1249/MSS.0000000000000925

336. della Monica C, Johnsen S, Atzori G, Groeger JA, Dijk DJ. Rapid Eye Movement Sleep, Sleep Continuity and Slow Wave Sleep as Predictors of Cognition, Mood, and Subjective Sleep Quality in Healthy Men and Women, Aged 20–84 Years. *Front Psychiatry*. 2018;9:255. doi:10.3389/fpsyt.2018.00255

337. Zinke K, Noack H, Born J. Sleep augments training-induced improvement in working memory in children and adults. *Neurobiol Learn Mem*. 2018;147:46-53. doi:10.1016/j.nlm.2017.11.009

338. McHugh ML. Interrater reliability: the kappa statistic. *Biochem Medica*. 2012;22(3):276-282.

339. Frey DJ, Badia P, Wright KP. Inter- and intra-individual variability in performance near the circadian nadir during sleep deprivation. *J Sleep Res*. 2004;13(4):305-315. doi:10.1111/j.1365-2869.2004.00429.x

340. Saletin JM, Goldstein-Piekarski AN, Greer SM, Stark S, Stark CE, Walker MP. Human Hippocampal Structure: A Novel Biomarker Predicting Mnemonic Vulnerability to, and Recovery from, Sleep Deprivation. *J Neurosci Off J Soc Neurosci*. 2016;36(8):2355-2363. doi:10.1523/JNEUROSCI.3466-15.2016

341. Ayala V, Martínez-Bebia M, Latorre JA, et al. Influence of circadian rhythms on sports performance. *Chronobiol Int*. 2021;38(11):1522-1536. doi:10.1080/07420528.2021.1933003

342. López-Samanes Á, Moreno-Pérez D, Maté-Muñoz JL, et al. Circadian rhythm effect on physical tennis performance in trained male players. *J Sports Sci*. 2017;35(21):2121-2128. doi:10.1080/02640414.2016.1258481