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Engineering Sleep Architecture for Better Performance Under Combat Stress

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Summary

The next generation of rotary-wing aircraft are anticipated to have advanced capabilities that will require aviators to fly for longer durations and impose a high demand in terms of cognitive workload. Given unavoidable stress and loss of sleep in the operational environment, we anticipate that this will increase the likelihood and prevalence of overloaded and fatigued aviators in the cockpit. The best method of counteracting fatigue induced by loss of sleep or circadian rhythm disruption is to have sufficient and good quality, preferably night-time, sleep. This is not always possible to achieve in aviation, however, especially during military deployments, as sleep in the field is often of less quality and duration than sleep at home (Kelley et al., 2018).

Moreover, performing operations at night and during sequentially long hours with limited opportunities of layover, pre-flight or in-flight rest may be tactically necessary. This is why new technologies for improving sleep efficiency, including through short naps, during military deployments may be a key strategy in boosting cognitive functions and operational readiness and eventually saving lives in the rotary-wing environment. The overall objective of this study is to review the recent promising advances in sleep stage engineering that may enhance the quality of deep sleep and lead to enhanced human cognitive performance. Day-time pre-flight naps, controlled in-flight rest on the flight deck, or short in-seat cockpit naps are promising means of performance enhancement for aviators.

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Introduction

Recent scientific advances are clarifying the neurophysiological mechanisms of memory consolidation in sleep. If sleep is disrupted, such as by chronic anxiety in combat, or even stressful combat training, cognitive performance may degrade progressively as a function of the length of the exposure. This cognitive degradation may be a primary factor in what is known as the fog of war. Improving the efficiency of sleep, through combining both cognitive behavioral training and electrical neuromodulation of sleep neurophysiology, may hold the prospect of improved cognitive performance in demanding military operations. Improving technologies for efficient sleep under stress may be a key strategy for contributing to the Warfighter Brain Health Initiative (Department of Defense [DoD], 2021).

Sleep is a fundamental element of brain health and function, supporting the processes of learning and memory consolidation, maintenance and repair, and waste clearance. Acute sleep deprivation (SD), a frequent operational necessity among Warfighters, significantly impairs attention, vigilance, processing speed, executive function, motor coordination and memory (Alhola & Polo-Kantola, 2007; Goel et al., 2009). Chronic sleep restriction, a condition common among Service Members during combat deployments and operations, causes mood swings, erodes cognitive and physical performance and is a major limitation on sustained operational readiness (Krueger, 1991; Miller et al., 2011). The damaging effect of sleep loss in the U.S. military in general is documented by the March 2021 Pentagon report, “Study on Effects of Sleep Deprivation on Readiness of Members of the Armed Forces.” More specifically, recent systematic surveys have shown high levels of sleep loss during combat deployment. In Operation Enduring Freedom, a survey of 3,175 U.S. Navy personnel found that more than half were classified as sleep deficient. Furthermore, those reporting greater sleep disruption were at significantly higher risk for post-traumatic stress disorder, generalized anxiety disorder, and major depressive disorder (Taylor et al., 2014). High levels of chronic sleep loss were reported in troops in Afghanistan (LoPresti et al., 2016) with 15% of Soldiers reporting accidents that affected combat missions, half of which they attributed to sleepiness. Fewer hours of sleep predicted significantly greater likelihood of accidents or errors affecting mission performance (LoPresti et al., 2016). Therefore, the development of countermeasures that improve the biological efficiency of sleep and compensate for the temporary lack of sleep may preserve cognitive function and readiness and eventually save lives in the rotary-wing environment (Fletcher et al., 2022).

The best method of counteracting fatigue induced by loss of sleep or circadian rhythm disruption is to have sufficient and good quality, preferably night-time, sleep. This is not always possible to achieve in aviation, however, especially during military deployments, as sleep in the field is often of lesser quality and duration than sleep at home (Kelley et al., 2018). Moreover, performing operations at night and during sequentially long hours with limited opportunities of layover, pre-flight or in-flight rest may be tactically necessary. This is why improving technologies for efficient sleep during military deployments may be a key strategy for contributing to the Warfighter Brain Health Initiative (DoD, 2021).

Cognitive Performance Under Combat Stress and Sleep Loss

One classical measure of the operational effectiveness of troops in battle is the number of own troops killed or injured versus the number of enemy casualties inflicted. Although many military reports have claimed 2% or so casualties from friendly fire, a systematic review of historical records in several U.S. conflicts by Steinweg, 1994 has documented that casualties from friendly fire are 10 to 15% as high as casualties inflicted on the enemy, emphasizing the high cost to the U.S. military and civilian population of what is traditionally described as the fog of war (Steinweg, 1994).

The obvious explanation for these serious combat mistakes is that the Warfighter's cognitive and behavioral performance becomes severely degraded under the stress of combat. An important set of empirical studies by Lieberman and associates (Lieberman et al., 2002) examined cognitive performance with a battery of structured tasks in military personnel in combat training. These tasks included a simple four-choice visual reaction time test, a demanding visual vigilance task, a pattern matching test assessing both vigilance and working memory, a motor acquisition test assessing both attention and working memory, and a grammatical (sequence) reasoning test. In addition, they completed the Profile of Mood States survey, assessing Tension, Depression, Anger, Vigor, Fatigue, and Confusion subscales.

One combat training exercise was during Hell Week of the U.S. Navy SEAL Training at the Naval Special Warfare Training Center, Coronado, CA. The mean age of volunteers was 24, with an average of 3 years in the military. Cognition and mood were assessed prior to the exercise and after 73 hours of training, during which volunteers had 1 hour of sleep and were exposed to cold water conditions as well as continuous intense physical exertion. Not only were there significant impairments of mood states, but the objective measures of all cognitive tasks showed significant impairment on at least one performance measure on each task ($p < .007$).

A common assumption is that “seasoned” or experienced troops become more resistant to confusion under combat stress. Another combat training exercise was examined by Lieberman and associates with an experienced Army Ranger unit (all rank of Captain, average age 32, averaging 9 years of active-duty) in a hot and humid environment. The total time of the exercise was about 72 hours, with 53 hours in the field, during which participants had little more than 3 hours sleep in short naps. The physical stress was indicated by an average weight loss (primarily water) of 9 pounds. Immediately following the exercise, cognitive performance on all tasks was impaired, with significant impairment on at least one outcome measure observed in all tasks (typically $p < .001$). Similarly, there were significant decreases in self-reported vigor, and increases in fatigue, depression, anger, and confusion.

While the study involved multiple concurrent stressors (including physical exertion, caloric deficit, dehydration, and environmental heat), sleep loss was identified as the primary, most devastating driver of cognitive decline. Lieberman et al. demonstrated that simulated combat stress—primarily driven by acute SD—produces severe, global cognitive degradation across all domains (vigilance, reaction time, memory, and reasoning). The magnitude of these cognitive deficits was found to be greater than those produced by legal alcohol intoxication (0.10% blood-alcohol content), sedating drugs, or clinical hypoglycemia.

Neural Mechanisms of Anxiety and Cognitive Performance

Beyond general degradation of memory and cognition, there are qualitative changes in cognitive performance under stress. Both military observations and psychological experiments show stress and anxiety cause "tunnel vision"—a focus on central information at the expense of peripheral events (Cornsweet, 1969; Easterbrook, 1959; Tucker et al., 1978; Tucker & Derryberry, 1992). The result can be a loss of situational awareness and mistakes in operational decisions (Luu et al., 2014; Luu et al., 2010).

Current evidence and theory in cognitive neuroscience provide a rationale for the cognitive deficits under the psychological stress of combat. The key issue is how different forms of emotional arousal influence the neural systems that contribute to specific capacities of memory and cognition. Spatial, contextual memory is supported by dorsal corticolimbic networks (regulated by the Papez limbic circuit including the hippocampus, septum, and cingulate cortex) which handle cognitive processing of spatial, contextual information.

In contrast, focal object memory is mediated by ventral corticolimbic networks (including the amygdala, insula, and interconnections through the striatum) that are important to object memory and the ability to focus attention on specific objects (Luu et al., 2007; Tucker & Luu, 2012; Ungerleider & Mishkin, 1982; Yonelinas, 2006). Under severe stress, such as high perceived threat to life, the phenomenon of tunnel vision can be explained as the effect of anxiety (based in primitive fight-flight mechanisms) in enhancing the ventral limbic focus on objects at the expense of dorsal limbic contextual cognition (Cornsweet, 1969; Easterbrook, 1959; Leon, 1989). The result may be the loss of situational awareness. Standard practice in military training recognizes the effect of anxiety and stress in impairing flexibility in adapting to new situations, whereas well-practiced responses are retained (Luu et al., 2014). The well-known adage is, "Train like you fight. Fight like you train." In addition to these immediate effects of stress and anxiety on waking cognitive performance, the chronic anxiety of facing combat danger may introduce progressive impairment of cognitive capacity through disrupting sleep.

How Stress-Impaired Sleep May Lead to Specific Deficits in Cognitive Performance

Recent progress in the scientific understanding of the functions of sleep is not only characterizing basic neurophysiological mechanisms but is yielding insight into how specific stages of sleep are required for the consolidation of specific forms of memory. When sleep is disrupted by chronic stress over days, weeks, and months, the result may be the severe deficits in cognition and effective behavior observed under combat conditions (Lieberman et al., 2002; Shapiro, 2005). Furthermore, the recent evidence suggests that, because forms of memory are consolidated in specific stages of sleep, a better scientific understanding of the effects of stress on sleep may help to explain how specific cognitive deficits may worsen with chronic sleep disruption.

Impaired Retention of Explicit Memory

Although it has long been proposed that sleep, including short power naps (George et al., 2024), may have a restorative function for the brain, and sleep may therefore contribute to the consolidation or strengthening of memory (Jouvet, 1980; Roffwarg et al., 1966), only recently

has the specific contribution of the neurophysiological stages of sleep started to become clear. For many years, scientific attention was directed to paradoxical or rapid eye movement (REM) sleep, during which vivid dreams occur. This was described as *paradoxical* sleep because the electroencephalogram (EEG) shows a desynchronized pattern that is typical of waking (Rechtschaffen & Kales, 1968).

However, a burgeoning research field over the last several decades has determined that the consolidation of explicit memory, often described as declarative memory, is achieved not in REM sleep, but in the non-REM (NREM) stages of sleep, marked by the frequent spindles of stage N2 and the large slow oscillations (SOs) of stage N3 (Diekelmann & Born, 2010). In fact, a current theoretical model is that the NREM neurophysiology is important to the initial retention of recent events of the day, whereas REM sleep may be more important to the consolidation of these events within lifelong memory schemas (Born & Wagner, 2004; Diekelmann & Born, 2010; Rasch & Born, 2013). Because situational awareness in combat often requires accurate monitoring of recent events, a degradation of memory for recent events could be a major contributor to the fog of war (Steinweg & Bowman, 1994). A reduction in glymphatic clearance, and thus toxic metabolite buildup, may be a source of impaired cognition during extended periods of sleep restriction. Although, SOs can be enhanced pharmacologically (Krueger et al., 1986), non-pharmacological means of boosting deep sleep may be advantageous.

Options for Therapeutic Intervention

Civil aviation does not endorse using pharmacological aids like hypnotics for sleep, chronobiotics to adjust circadian rhythms, or stimulants to enhance alertness. However, the Air Forces in many countries do allow for such interventions (Wingelaar-Jagt et al., 2021). Positive effects of hypnotics in facilitating and improving night-time sleep, as well as initiating naps of moderate and short durations and treating sleep-onset difficulties had been well documented in the military aviation context (Caldwell et al., 2003; Fry et al., 2000; Caldwell et al., 2009). Restorative effects of stimulants, such as caffeine, dextroamphetamine, or modafinil following prolonged wakefulness after SD have been demonstrated both in civil medicine (Gill et al., 2006) and research focused on military aviation applications (Caldwell & Caldwell, 2005; Estrada et al., 2008, 2012). However, these measures can be considered as only temporarily fixing a problem and have not been implemented on daily basis. The lack of wide-scale implementation is also for reasons such as the potential for addiction, tolerance and withdrawal symptoms, other well-known side effects such as feelings of nervousness, loss of appetite, anxiety, agitation, and insomnia (Matthews & Schnyer, 2019). Societal objection due to the ethical and regulatory challenges have also played a role in minimizing their implementation (Russo, 2007; Kelley et al., 2018; Brunyé et al., 2020). Finally, relationships between performance metrics in different tasks and arousal (stress) induced by caffeine or other stimulant intake may be nonlinear resembling inverted U-shaped curves (Yerkes & Dodson 1908; Hebb 1955), thus, an optimal individualized dosage becomes extremely important. Given the deleterious effects that can occur within operational settings due to acute SD and/or chronic sleep restriction, other safe and effective methods to sustain alertness are still sought out.

In particular, the crew rest schedule exists on long flights to mitigate the occurrence of acute fatigue instances. Controlled rest in aviation, often called a "cockpit nap," is a highly structured, short nap (around 20-45 minutes) for one pilot, taken in-seat during low-workload

cruise flight, while the other pilot remains fully awake and in control, using strict procedures like seat adjustment, cabin crew alerts, and recovery time to combat fatigue safely (Jackman, 2018). It is a fatigue countermeasure, not a scheduling tool, used as a safety net for unexpected fatigue on long flights, allowing for brief, effective rest without requiring a full crew rest bunk. It is commonly used globally, but the Federal Aviation Administration (FAA) in the U.S. traditionally restricts it, favoring duty-hour limits and dedicated rest facilities, though debate continues.

The FAA does not authorize "controlled rest" for pilots in U.S. cockpits, unlike many international regulators (European Union Safety Administration, Canada, Australia) that permit it. The FAA prefers relying on strict duty-hour limits, fatigue risk management systems, and, for long-haul flights, crew augmentation (additional crew) to allow for rest in designated bunks, not the cockpit seat. Despite evidence that short, 25–30-minute naps can significantly increase alertness (Leong et al., 2023), the FAA currently prohibits this in-seat practice for commercial air transport in the U.S. It is an even more debated issue in the military, in particular rotary-wing aviation.

One of the new non-pharmacological methods may be the use of transcranial electrical stimulation (tES) to enhance sleep processes (Kelley et al., 2019; Feltman et al., 2020; McIntire et al., 2014, 2017, 2020). The EEG SO of < 1 hertz (Hz) frequency has been thought to play a crucial role in major sleep functions, igniting an emerging interest in SO enhancement strategies by electrical (Dondé et al., 2021) and acoustical (Grimaldi et al., 2020; Shade et al., 2020) stimulation. In an influential early study, Marshall et al. (2006) demonstrated that 25 minutes of a slow oscillatory form of transcranial direct current stimulation (SO-tDCS) applied at the typical frequency (0.75 Hz) during early nocturnal non-rapid-eye-movement (NREM, stage N3) sleep potentiates memory, consistent with a proposed role for the SO in sleep-related memory consolidation. Several groups confirmed this effect (Grimaldi et al., 2020). Another proposed function of the SO is synaptic downscaling, hypothesized to constitute the physiological basis for satisfying the homeostatic drive for sleep, per the synaptic homeostasis hypothesis (Tononi & Cirelli, 2006).

Yet another suggested role of SOs in deep sleep is rooted in glymphatic brain cleansing. Described initially between 2012-2014 by Nedergaard and colleagues (Iliff et al., 2012; Xie et al., 2013), the glymphatic system supports the rapid exchange of fluid through brain tissue during sleep, facilitating the clearance of wastes that accumulate through the course of waking activity. Increased glymphatic clearance occurs in the deepest (slow wave, N3) stage of sleep and is facilitated by the dynamic enlargement of the brain's extracellular space during slow wave activity. Sleep-active glymphatic function is postulated to underlie the restorative function of sleep on cognition, and its impairment is proposed to drive the cognitive impacts of sleep disruption. This suggests that improving glymphatic function, whether pharmacologically or by means of a device, could ameliorate the cognitive effects of acute SD and chronic sleep restriction. Therefore, it might be beneficial to use noninvasive electrical or acoustical stimulation to enhance SOs to improve quality of sleep and subsequently cognitive performance as both are closely related. More than that low frequency (~ 5 Hz) transcranial alternating current stimulation was reported as promoting onset of sleep in daytime naps (Gorgoni et al., 2020; Xie et al., 2021).

In the recent Walter Reed Army Institute of Research (WRAIR) studies by Hughes et al. (2021, 2026) open loop SO-tDCS with 50 minutes at 0.75 Hz was used to enhance the restorative properties of sleep, by enhancing SO activity, during the second hour of a restricted 2-hour nocturnal sleep opportunity by assessing performance during a subsequent period of SD and recovery. They essentially followed the stimulation protocol of Marshall et al. (2006). Performance was assessed using the Psychomotor Vigilance Test (PVT) approximately every 75 minutes across baseline, SD, and recovery, and memory was assessed by using a Paired Words Associate Task (PWAT). A mixed linear regression revealed significant main effects of day, group, and the interaction between group and day on mean reaction time (RT). Post hoc analysis revealed faster RTs following stimulation on day 2 of SD. It was also found that participants in the stimulation group had fewer major lapses (RTs > 500 milliseconds [ms]) than those in the sham group over the first three days following stimulation. Overall, mean response time on the PVT and the number of RTs greater than 1,000 ms significantly worsened across SD. Participants in the verum condition demonstrated significantly better performance during SD relative to the sham condition. On the PWAT, participants in the sham condition recalled fewer word-pairs upon awakening relative to a pre-nap test. In sharp contrast, performance of participants in the SO-tDCS condition did not deteriorate at 20 minutes, and was improved at 120 minutes after awakening, relative to a pre-nap result. These studies demonstrated that SO-tDCS during a portion of a restricted period of sleep appears to enhance sleep's restorative properties and can additionally enhance sleep-related memory consolidation and as a result improve cognitive performance during subsequent sustained wakefulness. The mechanistic basis for this phenomenon, according to the authors, may be increased SO-induced synaptic renormalization.

How do SOs of N3 sleep contribute to explicit memory consolidation? Although there is no definitive model for the mechanism at this point, recent findings at BEL (Brain Electrophysiology Laboratory Company) have found that the EEG SOs of N3 are not broad traveling waves across the neocortex as has been widely reported, but rather focal discharges from ventral limbic regions, including the anterior medial temporal lobes and orbital frontal cortex (Morgan et al., 2021). These findings may be consistent with a recent report in rodents demonstrating that SOs are synchronized by discharges from the claustrum (closely associated with the amygdala and ventral limbic areas) (Narikiyo et al., 2020). These findings of limbic discharges in SOs do not negate the observations of down states or suppression of neural firing in neocortex: the down states are indicated by direct local field potential recordings from the neocortex, whereas the limbic localization by Morgan and associates show that the large SOs of the EEG are focally, not globally generated (even though local field potentials may be globally synchronized).

The importance of accurate localization of EEG SOs was emphasized in a follow-up all-night sleep study at BEL (Hathaway et al., 2021) demonstrating that improved targeting of the ventral limbic sources of SOs, using a high resolution computational model of head tissue conductivity, resulted in successful enhancement of N3 sleep with TES, using half of the current applied by previous studies (0.5 milliampere [mA] versus 1 mA). It is natural to hypothesize that the better sleep quality will lead to the better cognitive performance of a human operator, including a rotary wing pilot. And it was indeed demonstrated in the most recent studies where a

similar approach to boost SOs during a 2-hour daytime nap results in enhanced performance of sleep deprived subjects in Psychomotor Vigilance Test (Hughes et al., 2026).

Besides the above-mentioned acoustical and tES, there have been also other alternatives for sleep/nap quality improvements, like vestibular stimulation in adult bed rocking (Bayer et al, 2011), peripheral nerve stimulation like smell and touch, aroma therapy for deep sleep (Tononi et al., 2010) as well as earlier studies by Soviets in 1950s and 1960s on electroanesthesia and electrosleep (Wagender, 1970) using temporal interference (TI) of frequency detuned signals in the kHz domain. The similar approach of using temporal interference currents was used later by Grossman et al., 2017 and more recently in the context of entraining SOs (Schaeffer et al., 2026). Schaeffer and associates measured direct changes in brain activity by high-definition EEG. The TI SO stimulation successfully performed by demonstrating a significant increase in Slow Wave Activity (SWA, 0.5–4 Hz). This enhancement outlasted the actual 3-minute stimulation blocks and was significantly greater than pure high-frequency electrical stimulation alone. Concurrently, power in higher frequency bands (sigma and beta) decreased. To evaluate the functional and restorative performance of the intervention, participants provided subjective ratings. The incremental gains in SWA measured from the first night to the final night of the 4-week protocol positively correlated with participants' subjective ratings of restorative sleep.

In the 2025 paper by Ulv Larsen et al. published in *PLOS Biology*, researchers investigated human brain fluid dynamics and cerebral vasomotion following SD using accelerated functional magnetic resonance imaging and synchronous EEG. They administered the adrenergic antagonist carvedilol as a verum pharmacological intervention compared to a placebo control to modulate cerebrovascular pulsatility and vasomotion. To measure cognitive sleep pressure and performance, participants completed the PVT, with improvements in post-nap performance directly correlating with the magnitude of low-frequency cerebrovascular oscillations captured during sleep. Presumably, the same effect would be observed if vasomotion could be driven by tES entraining SWA.

Saddoud et al. (2026) demonstrated that "strategic" 45-minute afternoon naps—specifically timed during the natural circadian dip between 13:00 and 15:00 to facilitate sleep onset without disrupting subsequent nocturnal sleep—provided major cognitive recovery (14.1% improvement in decision-making accuracy and 16.1% faster RTs) but only minor physical performance gains (such as a modest 2.4% increase in vertical jump) in sleep-deprived elite Kung-Fu athletes. This precise duration was strategically selected to allow athletes to access restorative light and slow-wave sleep while strictly avoiding the deep-sleep phases that trigger performance-degrading sleep inertia upon waking, thereby acting as a highly targeted neurological intervention to combat the effects of acute SD.

Impaired Consolidation of Implicit Memory

Recent research on sleep and human memory has shown that, whereas REM sleep is not essential for explicit memory, it does contribute to *implicit* memory. This is memory for information that is not explicitly recalled, but may be important in more intuitive problem-solving, such as in insight problems when a solution is not apparent during the initial effortful search, but then suddenly appears and resolves the problem (Diekelmann & Born, 2010; Rasch & Born, 2013).

Although implicit memory has not been widely appreciated in studies of cognitive performance in military settings, it may contribute to the intuitive apprehension of the context required for situational awareness (Luu et al., 2010). Furthermore, the research on REM sleep has also emphasized the importance of REM sleep to emotional integration (Diekelmann & Born, 2010; Rasch & Born, 2013). It has long been known that REM may be important to processing emotional challenges. This is reflected not only in the common observation that stressful events lead to bad dreams, and in the exaggerated REM sleep (including abnormally short latency to REM) in clinical depression (Kupfer, 1976).

Recent neurophysiological research has shed important light on the limbic mechanisms of REM sleep as well as NREM sleep. High density EEG localization of the sawtooth waves of REM sleep shows these are generated by dorsal limbic regions, including the cingulate cortex (Bernardi et al., 2019). Invasive studies in rodents are consistent with this observation, showing that REM specifically engages dorsal limbic structures, including the hippocampus, cingulate cortex, and septum (Luppi et al., 2017). The implication is that the implicit memory consolidated by REM is integral to the contextual memory of the dorsal limbic division, which may be essential not only to implicit memory, and the creative thinking it supports, but also to the capacity for an intuitive grasp of situational awareness (Luu et al., 2010).

Although the neurophysiological mechanisms for regulating REM sleep are well-known (McCarley et al., 1995), and there is considerable evidence that the time spent in REM sleep is important to various measures of creativity (Cai et al., 2009) there is not the extensive literature on noninvasive tES for improving REM sleep as there is for improving NREM N3 sleep. As a result, creative research exploration may be necessary to understand the modifiability of REM sleep in order to avoid REM sleep restriction under conditions of high stress in military operational settings. Sometimes, REM sleep shows abnormal patterns in timing, disruption, or behavior, for instance in depression or Post-Traumatic Stress Disorder (PTSD). Altered REM sleep patterns—including early or intense REM sleep in some depressed people, or nightmare-related REM sleep disruption in PTSD—may reflect or contribute to disturbed emotional processing. Also, in REM sleep behavior disorder, the normal muscle inhibition is absent or incomplete, so a person may shout, kick, punch, or otherwise enact dreams. This can cause injury and warrants medical assessment and possibly intervention to selectively suppress REM sleep stages by AI-guided closed-loop acoustical stimulation (Bernhard et al., 2026).

Conclusion and Recommendations

In conclusion, sleep stage engineering may enhance the quality of deep sleep and lead to enhanced human cognitive performance. In the context of aviation, day-time pre-flight naps, controlled in-flight rest on the flight deck, or short in-seat cockpit naps (30 to 60 minutes) are promising means for performance enhancement, especially when deep sleep stages are enhanced by closed-loop brain stimulation of SOs. The body of literature establishes strategic daytime napping as an indispensable, non-pharmacological countermeasure against the cognitive and physical degradation caused by sustained military operations and acute SD. When operational windows restrict sleep, technology-augmented brief naps can rapidly restore Warfighter lethality, with performance outcomes highly dependent on nap duration and neurotechnology integration.

Standard 45-minute naps are historically limited because they do not guarantee sufficient time in slow-wave sleep (SWS), the deep sleep stage critical for both metabolic clearing in the brain and physical tissue repair. By utilizing closed-loop auditory stimulation (pink noise bursts aligned with EEG delta waves) or tES, modern tactical medicine can artificially amplify the amplitude and density of SOs (Slow-Wave Activity). This effectively "compresses" the benefits of a 90-minute sleep cycle into a restricted 30-to-45-minute tactical window, maximizing cognitive restoration while preventing awakening from the deep-sleep transition that triggers severe sleep inertia.

The future of military fatigue management lies in closed-loop, wearable neurotechnology integrated into Warfighter helmets or sleep gear. Future research must focus on validating these brain-stimulation napping protocols under multi-day, cumulative sleep debt scenarios, ensuring that augmented slow-wave sleep can sustain high-level executive function and rapid-threat identification over extended, multi-domain operations.

While executing this approach it is necessary to keep in mind the following tactical pitfalls and limitations:

- **The Sleep Inertia Threat:** Warfighters woken abruptly from deep SWS—even if artificially induced—experience temporary cognitive deficits. Missions requiring immediate physical reactivity must build in a 20- to-30-minute cognitive reactivation buffer post-nap.
- **Hardware Tactical Utility:** While closed-loop brain stimulation shows immense laboratory success, ruggedizing EEG/stimulation headwear for austere, high-noise, or active combat environments remains a primary operational hurdle.

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Appendix A. Acronyms and Abbreviations

BEL	Brain Electrophysiology Lab
EEG	Electroencephalography
kHz	Kilohertz
m	Meters
ms	Milliseconds
REM	Rapid Eye Movement
PTSD	Post-Traumatic Stress Disorder
PVT	Psychomotor Vigilance Task
PWAT	Paired Words Associate Task
SD	Sleep Deprivation
SO	Slow Oscillations
tDCS	Transcranial Direct Current Stimulation
tES	Transcranial Electrical Stimulation
USAARL	U.S. Army Aeromedical Research Laboratory

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