

Chapter 3

MEASURING AND PREDICTING SLEEP AND PERFORMANCE DURING MILITARY OPERATIONS

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INTRODUCTION

Background and Definitions

It is widely believed that a full night's sleep is an unnecessary, inefficient luxury. However, this belief is even stronger in military and political settings in which a reduced need for sleep is seen often as a badge of honor. Throughout history, it has been reported that many noted individuals (eg, Alexander the Great, Napoleon Bonaparte, and Winston Churchill) only slept a maximum of 4 to 6 hours/day. Whether they slept for a short time every day—and did not get longer sleeps and/or naps regularly—is open for debate. More importantly, whether these individuals performed at an optimal level is another issue for discussion, which leads to the following questions:

- How is sleep assessed quantitatively?
- What measurable performance effects exist?

By addressing these questions, a clearer picture of minimum and optimal sleep needs emerges.

Throughout this chapter, there are specific terms used to describe this process and the performance measures affiliated with it, including:

- sleep,
- sleepiness,
- circadian,
- fatigue, and
- impairment.

At the most basic level, *sleep* is a reversible behavioral state in which there is disengagement from the environment.¹ There are many proposed functions of sleep, including restoration² and memory consolidation.³

Sleepiness is a state of wakefulness in which an individual has an increased inclination to fall asleep.⁴ Both sleep and sleepiness can be measured objectively using standardized methods.⁵ Most people are awake during the day and asleep at night. People who do not work at night—especially between 0000 and 0600 hours—are most likely asleep. This is not surprising because the physical and psychological pressures to sleep at this time are often irresistible, even in people who are motivated to maintain wakefulness. The daily rhythm of wake and sleep states is a result of the *circadian* system, which is a persistent, internal, homeostatic mechanism controlled by the suprachiasmatic nucleus (a distinct group of cells located in the hypothalamus).⁶

Unlike sleepiness, it is not possible to measure fatigue quantitatively.⁷ *Fatigue* relates to both physiological performance decrements and psychological impairments, such as decreased morale, judgment, and mood.⁸ *Impairment* is equally difficult to define because

the degree of impairment depends substantially on the task, the individual's environment, and the level of sleepiness. Operationally, the definition of impairment should encompass the necessary task(s) and the level of acceptable risk for the circumstances.

Operational Context

Success in military operations depends on effective performance at all levels of command and control. Effective performance at the individual level depends on the successful completion of complex cognitive tasks (eg, a commander must maintain near-constant concentration and an awareness of the overall mission goals and progress in the face of competing demands, including detection and management of threats and errors, while successfully firing and maneuvering). There are many factors that shape military effectiveness, including the following:

- battle intensity,
- combat experience,
- training,
- morale,
- hydration,
- nutritional status, and
- sleep.⁹

Falling asleep while on duty in an operational setting can lead to catastrophic accidents. Less well appreciated is the fact that sleep deprivation systematically degrades performance long before people actually fall asleep. There is a cascade of degradation that predictably reflects a decline in mood, communication, reaction speed, reaction accuracy, and physical capacity. The natural endpoint of this spectrum is involuntary sleep. Figure 3-1 shows a representation of this cascade (see also Exhibit 3-1 and accompanying Exhibit Figure E1-1).

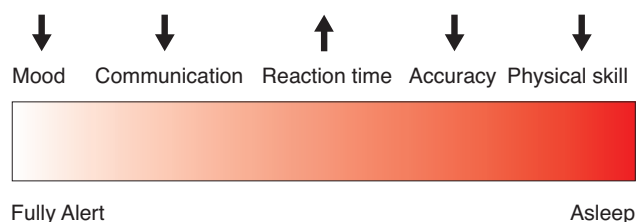


Fig. 3-1. Schematic representation of (from left to right) the psychological and physical degradation associated with increasing sleepiness.

EXHIBIT 3-1**HISTORY OF INADEQUATE SLEEP IN GULF WAR OPERATIONS**

On February 25, 1991, at 1800 hours, during the 100-hour ground war, a platoon of Bradley Fighting Vehicles from the Second Armored Cavalry Regiment (2ACR) was ordered to halt its advance and go into a screen line (Exhibit Figure E1-1a). They were to resume their advance the next morning. They remained awake and monitored their thermal sights for “hot spots,” which indicated a possible Iraqi approach to their position.

About 7 hours later—at approximately 0200 hours—the Bradley crews observed hot spots approaching (Exhibit Figure E1-1b). They were uncertain whether these were friend or foe; regardless, the crews continued to observe. The Iraqis had no thermal sights of their own; therefore, the Iraqis were unaware of the Bradley screen line and proceeded forward. Only when the lead Iraqi vehicles reached the screen line did the Bradley crews realize that these were the enemy. A brief firefight ensued, during which all the Iraqi vehicles were destroyed (Exhibit Figure E1-1c).

During the firefight, the two Bradley crews on the right flank of the screen line had turned to their left; they were no longer parallel to the other Bradley crews, but were instead facing into their own screen line (Exhibit Figure E1-1d). However, the crews of these two Bradleys were unaware that they had turned to face their own screen line. They still believed that they were facing in the correct orientation to the other Bradleys; therefore, they also believed that forward of them was the enemy. Because of this disorientation, the crews mistook the two Bradley crews on the left flank (which were maneuvering around burning Iraqi vehicles) for enemy vehicles and proceeded to enfilade their own line with fire. They destroyed the two Bradley vehicles on the left flank (Exhibit Figure E1-1d).

Because the Bradley Fighting Vehicles were equipped with Kevlar (E. I. Du Pont de Nemours and Company, Wilmington, Delaware) spall curtains and Halon (H3R Performance, Larkspur, California), fire suppression, and the crew members wearing Nomex (E. I. Du Pont de Nemours and Company) fire-retardant suits, all of them escaped without injury. A medical officer with the parent unit of the Bradley platoon was able to assemble the platoon members a few days later and conduct a reconstructive debriefing of this incident.⁽¹⁾ By their own report, the Bradley crews had obtained only 3 to 4 hours of sleep per night over the previous 5 days and would have been performing at a level much lower than their optimal capacity. In addition, the firefight took place during the early morning hours, when the crew members' complex mental operations were naturally waning because of their circadian rhythms.

Data source: (1) Belenky G, Martin JA, Marcy SC. After-action critical incident stress debriefing and battle reconstruction following combat. In: Martin JA, Sparacino LR, Belenky G, eds. *The Gulf War and Mental Health: A Comprehensive Guide*. Westport, Conn: Praeger; 1996: 105–113.

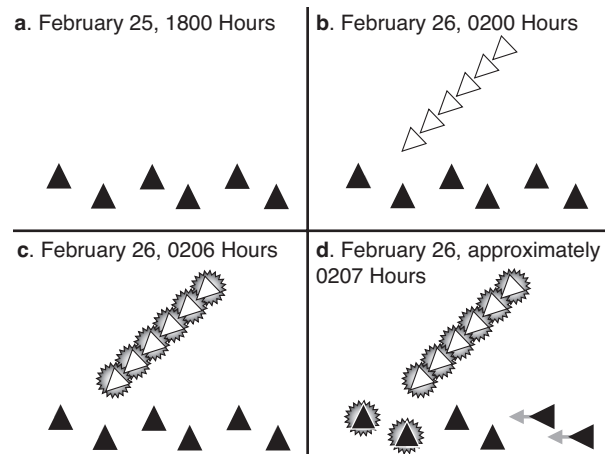


Fig. E1-1. Sequence of events from the 100-hour ground war—friendly fire incident (Gulf War, 1991). **Black triangles** represent US Bradley fighting vehicles. **White triangles** represent enemy vehicles.

MEASURING SLEEP AND PERFORMANCE**Laboratory Sleep Measures**

Behaviorally, it is possible to characterize sleep as a broadly homogeneous state of quiescence and reduced responsivity to sensory stimuli. Physiologically, it is dynamic, with intermittent/phasic changes in brain activity, as well as in endocrine and peripheral nervous system activity. The gold standard for determining

sleep/wake state is polysomnography.

In the sleep scoring system currently accepted as the standard,¹⁰ sleep is divided into five stages—stages 1 to 4 and rapid eye movement (REM)—which are determined visually based on the pattern of polysomnography activity. Stage 1 sleep is characterized by low-amplitude, mixed-frequency electroencephalographic (EEG) activity and is considered a transitional

state between wakefulness and the deeper (and more recuperative) non-REM sleep stages 2 to 4.¹¹ Characteristically, stage 2 sleep has the appearance, in the EEG, of sleep spindles (12- to 14-Hz activity occurring in 0.5- to 2.0-second bursts) and K-complexes (a sharp negative excursion followed by a slower positive excursion and often quickly followed by a sleep spindle).

High-amplitude delta or “slow” waves (slower than 2 Hz, with peak-to-peak amplitude of at least 75 μ V) can emerge during stage 2 sleep. When delta waves comprise 20% to 49% of a 30-second epoch, then that epoch is scored as stage 3 sleep. Epochs composed of 50% or more delta wave activity are scored as stage 4 sleep. Because of the waveforms that characterize sleep stages 3 and 4, these stages are collectively known as slow-wave sleep (SWS) stages.

REM sleep is characterized by a low-amplitude, mixed-frequency EEG (similar to that seen during stage 1); reduced muscle tonus (relative to the other sleep stages, as well as to wakefulness); and intermittent REMs. REM is the sleep stage during which most dreaming occurs.

Until recently, little was known about the neurophysiology underlying the various stages of sleep. The advent of imaging techniques (eg, positron emission tomography) has made it possible to create images of the living human brain during sleep. Recent results show that those brain regions mediating the ability to maintain alertness and vigilance, and so-called executive functions (eg, information assessment, problem-solving, and detection of conflicting information), are deactivated to a greater extent than other brain regions during sleep. This is true regardless of sleep stage; these brain regions deactivate during REM, SWS, and stage 2 sleep, with stage 2 sleep and SWS differing mainly in degree of deactivation (greater deactivation during SWS than during stage 2 sleep).¹² Also, these are the same brain regions most deactivated by sleep deprivation.¹³ On awakening, activity is restored to these regions.¹⁴

The various functions and mechanisms of sleep will continue to be studied and debated. But, in this chapter, we will focus on the apparent role of sleep in the restoration/sustenance of metabolic activity in brain regions that mediate (a) the ability to maintain wakefulness under nonstimulating conditions and (b) executive functions. Questions regarding the extent to which sleep stages are differentially recuperative for performance are obviously important when attempting to quantify the relationship between sleep and subsequent operational function. However, previous experiments have failed to discern stage-dependent differences in the rate that performance recuperation accrues during sleep. This does not mean that sleep-stage-related differences do not exist. Rather, the lack of experimental control over sleep stages has precluded definitive comparisons (ie,

studies have failed generally to compare sleep periods that are equivalent in all potentially relevant respects, except for sleep stage of interest).¹⁵

There are good (albeit nonexperimental) reasons to hypothesize that SWS has greater recuperative value than the other sleep stages. First, stage 3 and stage 4 (SWS) sleep tend to predominate during the first half of the night, whereas REM occupies more of the latter half of the night—an order suggesting that SWS might be the more important stage of sleep. Furthermore, the finding that even relatively brief sleep periods (eg, a 4-hour daily nap following 90 hours of continuous wakefulness) can restore performance to near-normal (presleep deprivation) levels on some tasks¹⁶ suggests that the recuperative benefits of sleep are, to a significant extent, “front-loaded,” in much the same way that SWS is front-loaded within a typical sleep period.

Finally, recovery sleep (ie, sleep following significant sleep loss) is typically characterized by increased (or “rebound”) SWS, both in terms of the percentage and the absolute amounts of SWS obtained. Because normal performance levels are restored recovery sleep periods that include much less sleep time than the amount actually “lost,” the implication is that SWS is likely to be the most “restoratively efficient” sleep.

Accuracy of mathematical models describing the relationship between sleep and subsequent performance—as detailed in the section on Predicting Sleep and Performance—can be enhanced if the relative recuperative powers of the various sleep stages are known and quantified. However, at this time, the importance of determining the relative recuperative value of the various sleep stages is not critical to modeling, because total sleep time is known to impact subsequent performance capacity. Obtaining polysomnography is impractical in most operational environments; and the extent to which sleep stages are differentially recuperative, if they are at all, is unknown.

Field Sleep Measures

Under operational conditions, obtaining adequate sleep can be viewed as a managerial problem similar to other items of logistic resupply (eg, water, food, fuel, and ammunition). For example, to manage fuel consumption effectively, a commander must know (a) how much fuel is on hand and (b) how far that fuel will take the unit, given the anticipated mission profile. This information is critical in planning for timely and adequate resupply. The same is true for sleep.

Historically, commanders had to manage the sleep of their soldiers based primarily on their experience and assessment of the need for sleep relative to other mission requirements. This is at least partly because of the following reasons:

- they did not know objectively how much sleep their soldiers had obtained over the previous days or weeks (ie, they had no means of measuring the relative amounts of sleep state versus the wake state in the field), and
- they were unable to predict how long any sleep obtained would sustain readiness (ie, they had no miles-to-the-gallon equivalent for sleep).

Basic sleep management awareness material has been provided to leaders and soldiers in a card format (Figure 3-2), but recent research will make more sophisticated assistance available to the commanders.

For purposes of managing sleep to sustain performance before and during deployments, the Walter Reed Army Institute of Research (WRAIR) has developed a sleep management system (SMS).^{17,18} This system consists of six components:

1. a wrist-worn activity monitor to continuously record wrist movements,
2. an algorithm to score sleep time versus wake time from recorded activity,
3. a mathematical sleep/performance model to predict real-time performance based on scored sleep,
4. recommendations for stimulant usage to sustain cognitive performance when sleep is not possible,
5. recommendations for the use of sleep-inducing agents to induce recuperative sleep under certain circumstances, and
6. guidelines and doctrine for the sleep management systems to manage sleep, alertness, and performance.

A cornerstone of the SMS is the means for measuring the amount of sleep and wake times under operational conditions. Wrist-mounted actigraphy (developed in the 1970s and 1980s) is a portable, field-use method for estimating sleep and wake amounts based on movement data (Figure 3-3).

When compared with the laboratory-based gold standard for recording sleep/wake times (polysomnography), actigraphy is considered to be a less reliable and valid means of measuring sleep. However, given the substantially cheaper cost, higher portability, and overall level of agreement with polysomnography assessments of sleep, actigraphy is considered practical and useful in operational conditions.¹⁹ Wrist-worn actigraphy presents a practical method for measuring (in a field environment) daily sleep amounts in a large number of individuals for weeks at a time.

The six levels of the Army SMS were designed to



Fig. 3-2. Example of sleep-related guidelines provided to commanders and soldiers.

Photograph: Reproduced from the US Army Center for Health Promotion and Preventive Medicine.

work together to ensure that operational safety and performance were maximized in the field through the management, monitoring, and prediction of a soldier's sleep and alertness levels. The principal function of the SMS is to create the best opportunity for soldiers to sleep successfully, measure their actual sleep, and predict their subsequent performance. This can lead to an overall shift to ensure that more soldiers have capabilities within the optimal part of the performance distribution (Figure 3-4).

Of the stressors affecting warfighter operational effectiveness, sleep loss is the most thoroughly studied in the laboratory. To date, however, no study has been published in which sleep-loss effects have been described under actual combat conditions. In several unpublished studies, sleep-loss effects during field training exercises have been evaluated and detailed. Exhibit 3-2 describes several of these studies.

This information leads to one practical question:



Fig. 3-3. One type of wrist-worn actigraph for the measurement of movement during field operations. From the measurement of activity, it is possible to make predictions of sleep obtained by soldiers using automated sleep-scoring algorithms.

Photograph: Courtesy of the Department of Behavioral Biology, Walter Reed Army Institute of Research.

Given the clear implications of sleep loss on performance, how much sleep is the soldier actually getting? In a series of studies, Colonel Daniel P. Redmond (US Army, Retired) and colleagues at WRAIR used actigraphy to measure sleep/wake amounts during training exercises at the US Army's Ranger School (Fort Benning, Ga) and at the US Army's National Training Center (Fort Irwin, Calif). In the US Army Ranger School exercise, soldiers wore the actigraph continuously throughout the 58 days of training across all phases.

As shown in Figure 3-5, soldiers were significantly sleep-deprived across all phases of training. Inadequate sleep is a deliberate stressor built into the lesson plan in Ranger training. The average sleep amounts for each phase were less than 4 hours/day—an amount inadequate to sustain optimal performance. The WRAIR group also recorded sleep/wake amounts actigraphically in soldiers during another field exercise conducted at the US Army's National Training Center. Figure 3-6 shows average sleep per day across the three training phases, broken down by rank and type of activity.

Soldiers of the lowest rank obtained, on average, more than 8 hours of sleep per night—adequate to

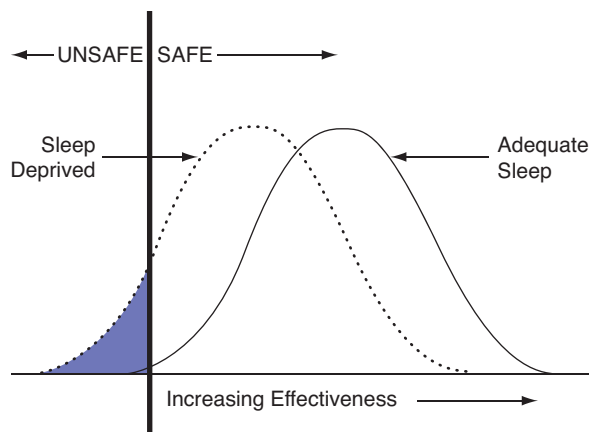


Fig. 3-4. Schematic diagram of the general shift, due to active sleep management, from a less safe/effective distribution of soldier capacity to a more safe/effective one. **Heavy vertical line** distinguishes safe from unsafe effectiveness. **Shaded area** represents the part of the sleep-deprived distribution considered operationally unsafe.

sustain cognitive performance indefinitely. However, the highest ranking individuals, on average, obtained the least sleep: about 5 hours/night—an amount insufficient for sustaining cognitive performance at high levels for the majority of individuals. This discrepancy was particularly noteworthy during the force-on-force training phase. This phase most realistically simulates combat, in that people and machines fought against each other. During this phase, key leaders got inadequate sleep.

Measuring Performance in the Field

In the laboratory, it has been shown that sleep loss directly impairs many cognitive capacities. However, historical attempts to measure capabilities in the field have met with minimal success because of the difficulties in quantifying effective performance in the operational environment. One solution has been to use simple metrics/tests from which operational performance capabilities are inferred. Exhibit 3-3 describes one example of such an application. The Psychomotor Vigilance Task is a simple reaction time task, developed by Dinges and Powell,²⁰ that is usually administered for either 5 or 10 minutes.

PREDICTING SLEEP AND PERFORMANCE

Theoretical Aspects of Prediction

More than 20 years ago, the first theoretical attempts were made to quantify sleep through the construction of mathematical models. Such models typically

conceptualize the timing and duration of sleep as the interaction between prior sleep and wake states. This is referred to as process S^{21} or process H ,²² and the circadian system (typically referred to as process C).

In the original models of sleep regulation, the

EXHIBIT 3-2**STUDIES TO INVESTIGATE THE IMPACT OF SLEEP LOSS ON OPERATIONAL EFFECTIVENESS****Artillery Fire Operations Simulation**

Results from a detailed and realistic simulation of artillery fire operations exemplify the effects of sleep loss on operational effectiveness. In that study, five-person teams were evaluated for their ability to conduct simulated continuous combat operations lasting 36 hours. Each team's task was to (a) plot target locations; (b) derive range, bearing, and angle of gun elevation; (c) charge immediately on receipt of the target; and (d) update situation maps. Across 36 hours of sleep deprivation, each team's ability to derive range, bearing, and gun elevation was unimpaired, as was each team's ability to charge.

However, after approximately 24 hours without sleep, team members stopped updating their situation maps and stopped computing preplanned targets immediately on receipt of new information. As a consequence, the teams disrupted their smooth, accurate flow of work; fired on prohibited targets; and generally lost control of the operation.

Early Call Studies

In a series of studies, Haslam and Abraham⁽¹⁾ evaluated the effects of sleep loss (total or severely restricted) on military relevant aspects of performance. In the first exercise (Early Call I), platoons were assigned to 0, 1.5, or 3.0 hours of sleep per 24 hours (one platoon per sleep group) for 9 days. Shooting, weapon handling, digging, marching, patrolling, and cognitive performance (including map plotting, encoding/decoding, short-term memory, and logical reasoning) were evaluated periodically throughout the exercise.

Haslam and Abraham reported that all soldiers in the 0-hour sleep platoon withdrew from the exercise after four nights without sleep (approximately 96 hours of total sleep deprivation); 39% of the 1.5-hours sleep platoon withdrew after five nights. Just more than half (52%) of the 1.5-hour and 91% of the 3-hour sleep platoons completed the entire 9-day exercise. Encoding performance (number correct) decreased across the exercise in all groups.

The number of on-target deliveries during a 20-minute shooting task decreased across days in all three platoons. Across the last 5 days, performance seemed to drop more precipitously in the 1.5-hour group, compared with the 3-hour group. In contrast to on-target deliveries, "grouping capacity" (the ability to fire five rounds in as small an area as possible) did not vary across days or among sleep groups.

Haslam and Abraham also observed that personal hygiene, self-care, and leadership deteriorated across the exercise. One aspect of leadership deterioration was defined as a change from direct order to exhortation (ie, urging, requesting, or advising), although it was not experimentally tested how lacking in effectiveness this change in communication style actually was. It is, however, possible that the different style was more effective than direct orders for sleep-deprived soldiers and, thus, not a leadership deterioration at all. This specific question would benefit from further assessment.

In the second exercise (Early Call II), 10 experienced infantry soldiers were sleep deprived for 90 hours. This total sleep-deprivation period was then followed for 6 days by 4 hours sleep per 24 hours. Similar to Early Call I, performance on the 20-minute shooting task in this group degraded across the 90-hour sleep deprivation period and showed some rebound during the 4-hour sleep phase. This 10-soldier unit was marked by a high level of unit cohesion and morale. Nonetheless, as the sleep deprivation period continued, the section leader reported increased isolation from his soldiers (who became more docile and more united) and progressive difficulty keeping his soldiers motivated. Based on the results from Early Call I and Early Call II, Haslam and Abraham concluded that soldiers are likely to be militarily ineffective in a defensive role after 48 hours without sleep.

Implications of this case history and field studies are clear: even well-equipped, well-trained, highly motivated soldiers operating within cohesive units with good morale are not resistant to the effects of sleep loss.

Data source: (1) Haslam DR, Abraham P. Sleep loss and military performance. In: Belenky G, ed. *Contemporary Studies in Combat Psychiatry*. Westport, Conn: Greenwood Press; 1987: 167-184.

propensity of sleep at any point in time is the sum of processes S and C .²³ Sleep occurs when process S extends past a high threshold h , and wake-up occurs when process S drops below a low threshold l . The high (h) and low (l) thresholds are "noisy"; they are

not fixed points, but vary over time. These thresholds were determined from sleep/wake structures during internal desynchrony protocols.²⁴

All of these processes (ie, S/H , C , h , and l) are based on physiological parameters that were measured (and

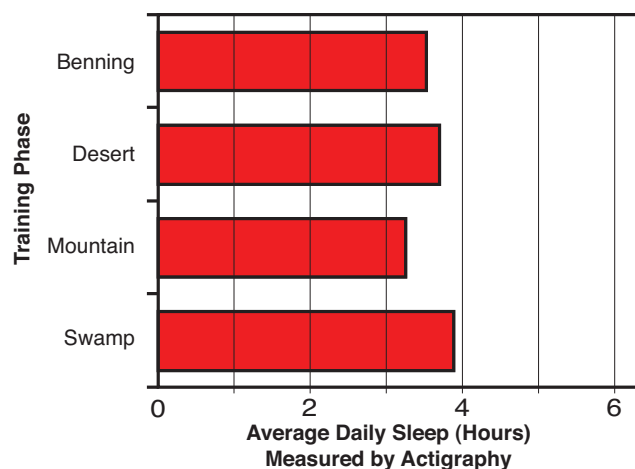


Fig. 3-5. Average daily sleep amounts obtained from soldiers during 58 days of US Army Ranger School (Fort Benning, Ga) broken down by training phase in studies conducted in 1992 and 1993. The current Ranger school curriculum does not include a desert phase. Cognitive function was significantly impaired, but recovered with episodes of sleep. Illustration: Redrawn with permission from Shippee RL, Friedl KE, Kramer T, et al. *Nutritional and Immunological Assessment of Ranger Students with Increased Caloric Intake*. Natick, Mass: US Army Research Institute of Environmental Medicine; December 1994: p. 6-6. Technical Report T95-5. AD-A290252.

subsequently estimated) in a laboratory environment during extended sleep deprivation and internal desynchrony protocols.²⁵⁻³⁰ A schematic diagram of modeled sleep regulation is shown in Figure 3-7 (step 1).

During the late 1980s and early 1990s, the two- and three-process models of sleep regulation and alertness were created based on Borbély's sleep regulation model.^{21,27,31} In the three-process model, a third process (W) was introduced to represent sleep inertia, which typically occurs following waking. Sleep inertia is the feeling of sleepiness or grogginess that occurs after arousal from sleep. According to the creators of the three-process model, modeled sleep inertia symptoms disappear completely after approximately 2 hours.²¹

Recent models have further broadened the scope of the initial sleep regulation models (Figure 3-7, step 2). In particular, such models have since been refined and developed to predict symptoms, for example, changes in subjective alertness^{21,32-34} and fatigue,^{7,35-38} changes in objective vigilance^{27,31} and performance,^{39,40} as well as variations in sleep latency and sleep length.^{39,41,42}

These models have evolved from being used primarily in a laboratory setting where sleep/wake states and other behaviors are closely monitored and controlled, to extensive use in field environments where large variations in all facets of the sleep/wake schedule exist.⁴³ Recent investigations have discovered

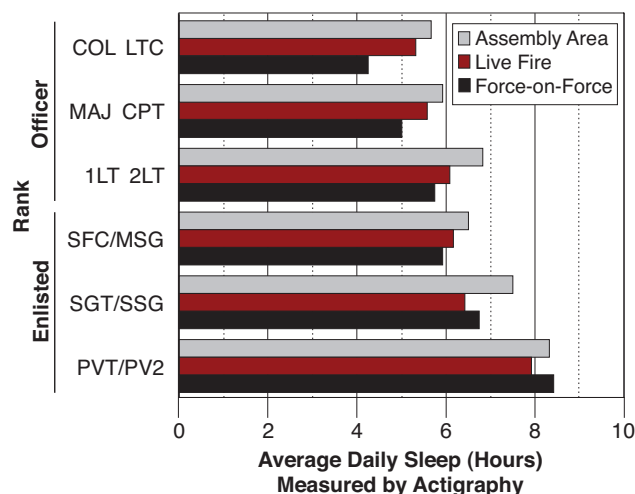


Fig. 3-6. Average daily sleep amounts of military personnel during military exercises conducted at the National Training Center (Fort Irwin, Calif). Data are presented by rank. COL: Colonel; LTC: Lieutenant Colonel; MAJ: Major; CPT: Captain; 1LT: First Lieutenant; 2LT: Second Lieutenant; SFC: Sergeant First Class; MSG: Master Sergeant; SGT: Sergeant; SSG: Staff Sergeant; PVT/PV2: Private; Assembly Area: drawing, repairing, and organizing equipment; Live Fire: firing actual tank and artillery shells while advancing through terrain dotted with simulated enemy targets; Force-on-Force: battle using laser systems to simulate killing and being killed by a live enemy. The discrepancy in sleep obtained between the ranks is most clear in the most operationally realistic phase (Force-on-Force).

Illustration: Courtesy of Colonel (Retired) Greg Belenky, unpublished data.

that there are a number of variations in the specific formulation, input and output variables, and parameterization of each model that are directly related to their application areas.⁴³

Practical Model Use

Models of sleepiness, fatigue, and/or performance are regularly applied in complex field environments. As referenced previously, there is a range of models in the literature that are available for use, with the major differences between these models being related to input requirements. The first group of models^{22,38} are one-step models that use the actual timing of sleep/wake states to predict fatigue (Figure 3-8a). The timing of this sleep/wake state is obtained using polysomnography, actigraphy, or subjective sleep/wake diaries.

One of the strengths of this modeling approach is that accurate predictions of fatigue, performance, or alertness can be made from observed sleep timing, which differs for each individual. However, this one-step technique can only be used retrospectively—post-hoc

EXHIBIT 3-3

THE PSYCHOMOTOR VIGILANCE TASK

The Psychomotor Vigilance Task (PVT) is a simple reaction time task, usually administered for either 5 or 10 minutes, developed by Dinges and Powell.⁽¹⁾ A reaction time test, in its most general form, measures the time it takes for a person to respond to the presentation of new information (usually a visual or auditory stimulus). Because the PVT has demonstrated sensitivity to even slight restrictions in daily sleep amounts well in advance of frank errors and accidents,^(2,3) it has been adapted for field use and has been implemented using a personal digital assistant (PDA).⁽⁴⁾

The handheld PDA version of the PVT is a field-usable test that is sensitive to sleep loss and has a high reliability, due partly to the steep learning curve associated with the reaction time test. Questions regarding the PVT's specificity and validity for operational tasks are not yet fully answered, but initial studies show promise. The PVT involves holding a PDA with a right or left thumb poised over the right or left button (as determined by right- or left-handedness) and when a bull's eye target appears, pressing the button. The score is the time it takes (latency) to press the button after the target appears. Using the PDA-based PVT, McLellan and colleagues⁽⁵⁾ at the Walter Reed Army Institute of Research have shown that speed of responding on the PVT correlates with vigilance shooting on a firing range and vigilance in detecting enemy movement in a Military Operations on Urbanized Terrain (MOUT) field training exercise.

However, can one generalize from performance on the PVT to performance on the battlefield? Although this is an empirical question, strategic and tactical analyses of combat operations—put forward by Colonel John Boyd⁽⁶⁾—suggest that the answer is yes. According to Colonel Boyd, operational success depends on being inside the opponent's decision cycle. In this context, PVT (a measure of reaction speed) seems an appropriate match to the elegant simplicity of Boyd's conception of the basis for operational success at all levels of command and control.

Future work will link PVT metrics to cognitive capabilities underlying the warfighter's ability to rapidly recognize and capitalize on emergent battlefield opportunities in the network-centric environment.⁽⁷⁾ Consider the following scenario:

An M1 tank is engaged in a battle. The commander is scanning for possible targets; finding one, he confirms identity as friend or foe. Once he identifies the target as foe, he passes the target to his gunner. This process involves a positive hand-off in which both commander and gunner confirm to their mutual satisfaction that they are looking at the same thing. The gunner then ranges the target, decides the round, and communicates this to the loader. The loader loads the round. The gunner fires the gun. This entire process takes time, less time when an otherwise well-trained and experienced crew is rested and more time when the crew is sleep deprived.

This process can be broken down into a series of temporal latencies (eg, latency of the commander to acquire a target, latency to pass to the gunner). The sum of these latencies increases the total time taken to execute the task. If for any given target the crew of the M1 is able to complete its series of tasks in less time than it takes for the enemy to do the same, then the outcome will be favorable; thus, the tank crew will operate inside the opponent's decision loop. It should be possible in the simulation environment to correlate PVT performance with the latencies to accomplish these real-world tasks. By predicting and summing these latencies, actual operational performance from the PVT can be predicted. Furthermore, it might be possible to measure these latencies directly in operations and use them as input to a performance prediction model.

Data sources: (1) Dinges DF, Powell JW. Microcomputer analyses of performance on a portable, simple visual RT task during sustained operations. *Behav Res Methods Instrum Comput.* 1985;17:652–655. (2) Belenky G, Wesensten NJ, Thorne DR, et al. Patterns of performance degradation and restoration during sleep restriction and subsequent recovery: a sleep dose-response study. *J Sleep Res.* 2003;12:1–12. (3) Balkin TJ, Bliese PD, Belenky G, et al. Comparative utility of instruments for monitoring sleepiness-related performance decrements in the operational environment. *J Sleep Res.* 2004;13:219–227. (4) Thorne DR, Johnson DE, Redmond DP, Sing HC, Belenky G, Shapiro JM. The Walter Reed palm-held psychomotor vigilance task. *Behav Res Methods.* 2005;37:111–118. (5) 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;76:39–45. (6) Hammond GT. *The Mind of War: John Boyd and American Security.* Washington, DC: Smithsonian Institution Press; 2001. (7) Wesensten NJ, Belenky G, Balkin TJ. Cognitive readiness in network-centric operations. *Parameters.* 2005;Spring:94–105.

rather than as a predictive tool to determine fatigue, performance, and/or alertness—unless there is a reasonable basis for first predicting what the likely sleep pattern will be. Thus, in their most frequently used

form, one-step models are unable to determine whether a work schedule is likely to produce excessive levels of sleepiness/fatigue until after the fact. Such models are useful for analysis of incident/accident investigations

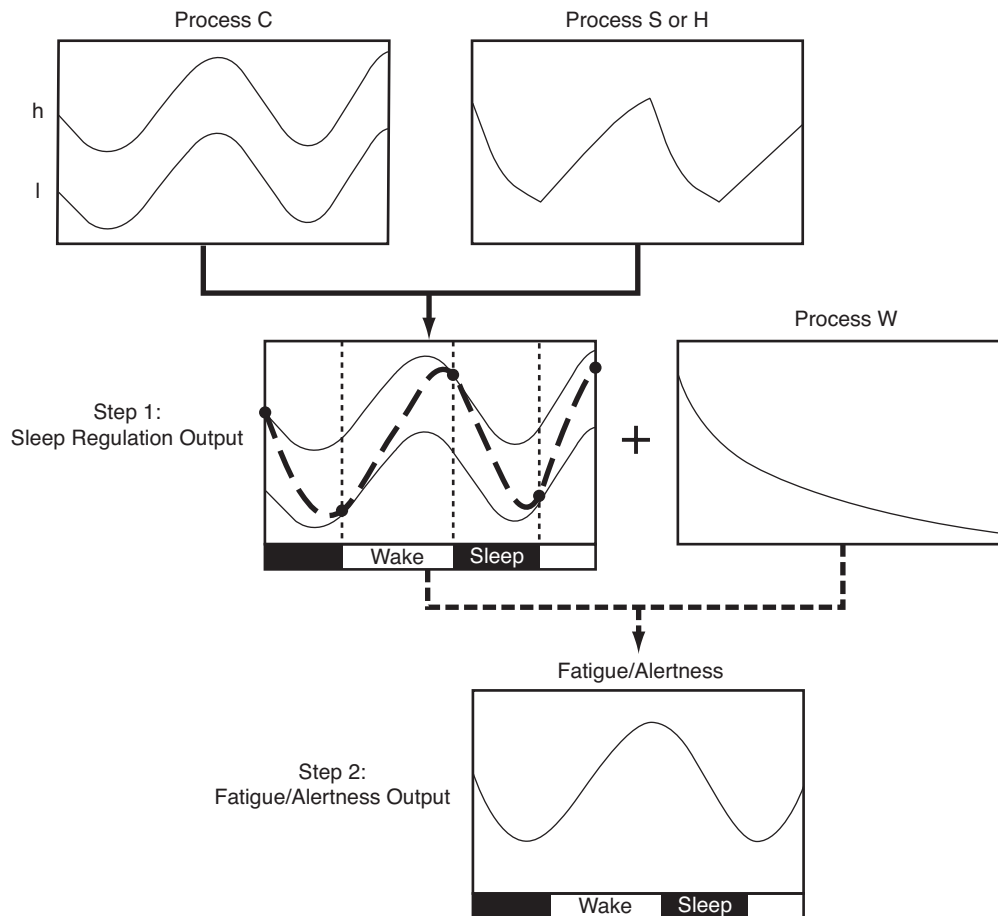


Fig. 3-7. Schematic diagram of the two-process model of sleep regulation and the subsequent fatigue/alertness addition. **Step 1:** Process C modulates the h and l thresholds. Process S/H rises during the wake state and declines during the sleep state. Interaction between these three functions determines the onset and duration of sleep episodes. **Step 2:** Latent alertness is then calculated using these estimated sleep/wake periods and sleep inertia information.

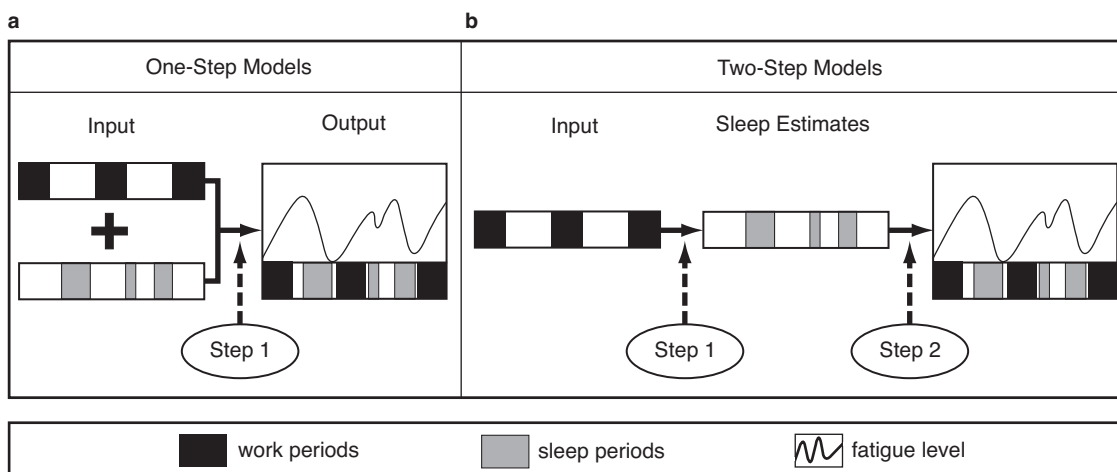


Fig. 3-8. Comparison of the one-step and two-step approaches. (a) One-step models require both work/rest and sleep/wake information as input. (b) Two-step models infer sleep/wake timing either directly or indirectly from the timing of the work/rest state and make subsequent predictions of fatigue, alertness, and/or performance.

in which sleepiness/fatigue was a potential factor and can also be used for testing hypotheses about how the model predictions relate to performance or other meaningful measures. In the future, if real-time activity/sleep data were available, then the utility of one-step models in certain contexts would become significantly more valuable. For example, if soldiers wore wrist actigraphs that allowed assessment of current and near-future status, then the one-step model predictions could be of considerable strategic value to a commander. In environments where collecting data from actigraphy or another objective measure was not possible, such as in civilian shiftwork operations, the potential utility of one-step approaches is therefore low.

The second group of fatigue, performance, and alertness models^{7,21,32,34–37} are two-step models in which the timing of sleep/wake states is inferred either directly or indirectly from the pattern of work (Figure 3-8b). In the first step, the work pattern is used to estimate probabilistic distributions for the timing of sleep/wake cycles and the circadian phase. In the second step, the estimated sleep/wake states are used in a similar manner to the actual sleep/wake states within one-step models.

Unlike their one-step counterparts, the two-step models can prospectively estimate the timing of sleep/wake states and subsequently make predictions of fatigue, alertness, and/or performance. Therefore, these models can be more useful in complex field environments in which the recording of sleep information can be impractical, expensive, and unethical, and, in which fatigue, performance, or alertness predictions are required prior to the task.

Limitations of Current Models

The strengths and limitations of different modeling approaches must consider the context of their development and intended use. For example, some models were developed and validated in the laboratory,²² and other models were developed in the laboratory but later refined to suit organizational settings.^{32,38} As stated previously, most of the current models in the literature predict fatigue, performance, and/or alertness levels in the body based on a combination of circadian and homeostatic components.^{21,22,28,32,38} The circadian component is sinusoidal, and the homeostatic component has been found to be either exponential,²¹ Gaussian (ie, the normal distribution curve),²² or broadly linear (with circadian variation).³⁸ From a physiological perspective, these models contain elements representing many of the processes that control sleep regulation and subsequent levels of fatigue, performance, or alertness.

Unfortunately, none of the models have been exhaustively validated, and published validation studies

have not been typically independent of data used for model development.⁴⁴ Therefore, further validation of models with previously unused datasets, as well as cross-validation between models, is highly desirable. Thus, a 2002 workshop conducted in Seattle, Washington, compared and examined each of the fatigue, alertness, and performance models currently based in the literature using five previously unseen scenarios.⁴⁵ These scenarios ranged from laboratory-based total or partial sleep restriction protocols, to field data collected from locomotive engineers, to a theoretical flight schedule for an ultralong-range flight operation between New York and Hong Kong. Van Dongen's article⁴⁵ gives specific information on these scenarios.

Each of the models used various inputs to estimate fatigue, alertness, and/or performance for the given scenarios. Estimated and actual measures (including various neurobehavioral performance outputs and subjective measurements) were then compared with each model's output generating a "goodness of fit" for each.⁴⁵ Overall, the models produced reasonable goodness-of-fit measures. In general, however, there were relatively small differences between the performances of each model, and there was no model that was consistently better or worse using any of the comparison criteria.⁴⁵

Models developed using laboratory-based data were able to closely fit scenarios based on other laboratory data, but were less reliable when used in the field. Similarly, models derived from field data generally did not perform as well for the laboratory protocols. This highlights the differences between data collected in a laboratory environment (in which factors such as social interaction, sleep strategies, ambient temperature, caffeine consumption, light levels, and tasks undertaken are controlled), compared with data collected in a field environment (in which those same factors are not controlled). These uncontrolled field situations can significantly reduce the amount of sleep obtained during a given break,⁴⁶ compared with laboratory protocols in which the influence of these factors is tightly controlled. Currently, most models used to predict fatigue, alertness, or performance are unable to account for these factors, because they were developed and/or validated in a controlled laboratory environment.

Comparison of current fatigue, alertness, or performance models indicates that there was a tendency to underestimate fatigue in chronic, partial sleep-deprivation protocols.^{45,47} It has been reported that chronic sleep restriction is a major problem encountered by employees in various fields in which shiftwork is prevalent, including individuals in aviation and military settings.^{48,49} Therefore, the inability of current models to accurately predict fatigue and alertness levels during these conditions greatly limits their immediate applicability in a field environment.

EXHIBIT 3-4

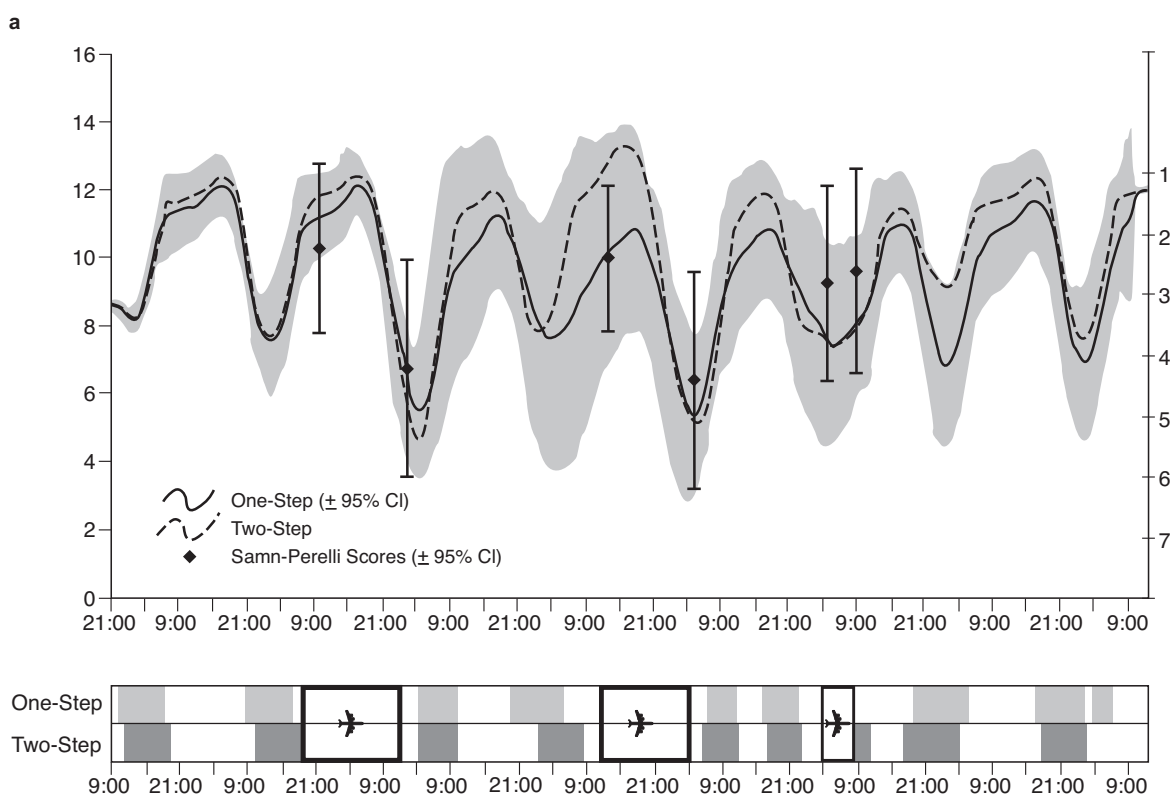
OPERATIONAL EXAMPLE OF INTERINDIVIDUAL DIFFERENCES AND MODELS

Current models used to predict fatigue, sleepiness/alertness, and/or performance do so based on data derived from healthy, young subjects. Recent scientific literature shows that interindividual differences in the neurobehavioral deficits exist and are significant in magnitude.⁽¹⁾ Unfortunately, the present cohort of mathematical fatigue, alertness, and/or performance models lag behind the current literature because they are unable either to account for these large individual differences in deficits or show this variation graphically in their output (eg, through the use of 95% confidence intervals).

This problem is illustrated in the following example taken from a complex aviation setting. Actigraphically derived sleep/wake records of 13 pilots were recorded for a minimum of 15 days, during which time participants were instructed to perform their usual work and social activities. During the recording period, participants were scheduled to complete a routine flight pattern from Sydney, Australia, to Los Angeles, California. After a brief layover in Los Angeles (mean \pm SD, 35.9 \pm 1.2 hours), crews flew to Auckland, New Zealand, where another short layover was undertaken (23.6 \pm 0.95 hours).

A final flight returning to Sydney was then completed. All flight times were similar (SD < 1 hour), as were layover lengths and layover conditions (eg, hotels and lodging). The sleep/wake records were entered into a published one-step model to estimate the alertness of each individual. These individual alertness scores were then compared with the alertness profile obtained when only duty times were entered into the model and the two-step approach was used (Exhibit Figure E4-1). Using the scale of Samn and Perelli,⁽²⁾ self-rated alertness levels recorded preduty and postduty are also included for comparison.

Analysis reveals that a strong relationship exists between the alertness estimated using the one-step and two-step methods ($r = 0.912$, $P \leq 0.0001$; Exhibit Figure E4-1A). Correlations between the one-step and two-step methods and



(Exhibit 3-4 continues)

Exhibit 3-4 continued

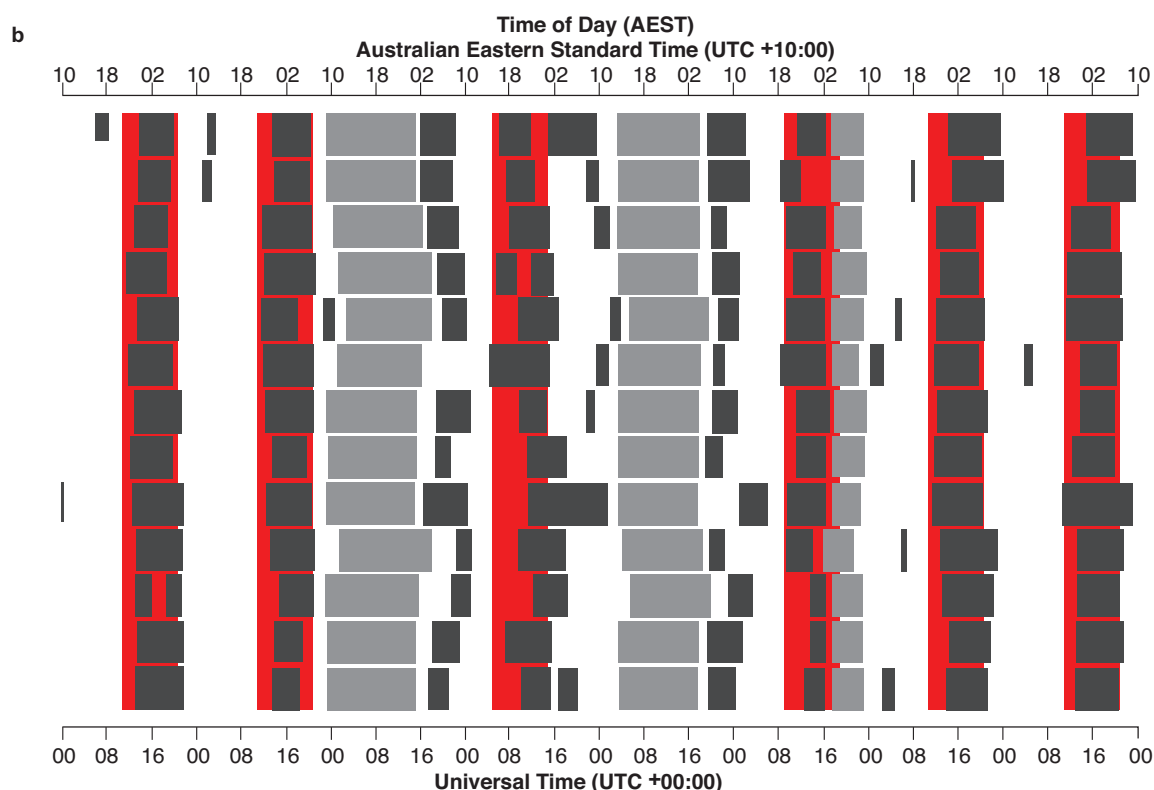


Fig. E4-1. (a) Comparison of one-step and two-step model approaches using data obtained from airline pilots ($n = 13$) flying from Australia to Los Angeles and returning via Auckland, Australia. Included is a comparison of the alertness levels obtained using the one-step approach (with 95% confidence intervals [CIs]), with the two-step approach output and self-rated Samn-Perelli fatigue ratings completed preduty and postduty. The lower schematic diagram compares the periods during each layover where sleep propensity was greater than 33% and sleep estimations were obtained from the two-step approach. (b) Raster plot showing the timing of both sleep (black), duty periods (dark gray), and local night (red) for the 13 flight patterns included in the current analysis in both Australian Eastern Standard Time (AEST) and Universal Time Code (UTC). This plot highlights the differences in sleep strategies among pilots, and the disruption in sleep timing and duration caused by transmeridian travel.

the self-rated scores indicate a strong negative relationship between the fatigue prediction methods (one-step method and Samn-Perelli scale, $r = -0.90$, $P \leq 0.0001$; two-step method and Samn-Perelli scale, $r = -0.85$, $P \leq 0.0001$). The actual sleep/wake data shown in the raster plot of Exhibit Figure E4-1B indicate that each participant's sleep period is disrupted, especially on shorter layovers, thus supporting previously published data on transmeridian travel, which stated that sleep is usually disrupted during the time period when circadian rhythms are resynchronizing.⁽³⁻⁶⁾

Data sources: (1) 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;27:423–433. (2) Samn SW, Perelli LP. *Estimating Aircrew Fatigue: A Technique with Application to Airlift Operations*. Brooks Air Force Base, Tex: US Air Force School of Aerospace Medicine; 1982. No. SAM-TR-82-21. (3) Gander PH, Myhre G, Graeber RC, Andersen HT, Lauber JK. Adjustment of sleep and the circadian temperature rhythm after flights across nine time zones. *Aviat Space Environ Med*. 1989;60:733–743. (4) Samel A, Wegmann HM. Sleep and circadian rhythms of an airline pilot operating on the polar route: a case study. *Aviat Space Environ Med*. 1988;59:443–447. (5) Samel A, Wegmann HM, Summa W, Naumann M. Sleep patterns in aircrew operating on the polar route between Germany and east Asia. *Aviat Space Environ Med*. 1991;62:661–669. (6) Kandelaars KJ, Fletcher A, Eitzen G, Roach GD, Dawson D. Layover prediction for cockpit crews during transmeridian flight patterns. *Aviat Space Environ Med*. 2006;77:145–150.

Recent studies indicate that recovery from chronic sleep restriction can be considerably slower than initially believed.^{48,50} This implies that chronic sleep

restriction can cause relatively longer term changes in brain physiology that are slower to recover. One recent finding suggests that the cumulative effect of

excessive wakefulness should be included in future fatigue and alertness models to account for these effects.⁴⁷⁻⁴⁹ Other findings suggest that the current sleep homeostasis function should be modulated to alter the level of total recovery available during sleep.^{51,52} The findings of both groups are still in their infancy, and further definitive research is required. It is possible that the structure of the existing fatigue, performance, and/or alertness models needs to be altered to fit an updated recovery profile.

Suitability of model use in the field setting versus laboratory setting is not the only factor that can influence model performance. When determining current and future values of a model's proposed application, it is important to distinguish between its performances when the one-step and two-step techniques are used (ie, when the actual sleep/wake state is used as an input versus using estimated sleep/wake times inferred from hours of work). Goodness-of-fit levels are higher when actual sleep/wake data (one-step approach) are input directly.⁴⁵ Furthermore, the output derived from different one-step models is significantly correlated, with little systematic difference observed. Good correlation between models, at the very least, represents convergence of the underlying scientific approaches.

However, marked differences in model outputs are seen when using a two-step approach to estimate the probabilistic distribution of prior sleep/wake states from a work pattern and fatigue.⁴⁵ This discrepancy is caused

by the inability of current models to account for key differences in sleep quality, as well as differences in sleep strategy caused by social interaction during break periods, commuting distances, and family responsibilities.

All current models have been evaluated in terms of their ability to predict average rather than individual levels of fatigue.⁵³ Thus, the general goodness-of-fit for group data does not apply when the model is used to predict individual levels of fatigue, or the likelihood that a single event can be associated with work-related fatigue. This is a significant word of caution for those considering the use of models for individual-level assessment without the perspective of group-level interpretation. This observation points to a further step of development for promising current models, which is to extend the predictions to the individual level.

Another approach that could be applied to field-use models would be to start with a model based on data collected under controlled laboratory conditions, then validate the model, and explore generalizability and limitations using data collected under field conditions. Such an approach would not only limit the amount of inherent noise from field data being incorporated into the model, but also provide guidance for commanders on conditions of use. A model built in this way could also be developed further to account for individual differences or, at the very least, provide an indication of variance in addition to the overall predictions (see Exhibit 3-4 and accompanying Exhibit Figure E4-1).

TACTICAL USE OF SLEEP

In operational settings, where adequate nightly sleep may not be possible, "tactical napping" can be of significant benefit. This confirms the practice of soldiers sleeping whenever they can and as often as possible during extended training or operations. A major reason why naps are a powerful countermeasure is that the improvements that can be gained from a short nap are disproportionately large, compared with a long sleep.⁵⁴ Research studies have illustrated that napping leads to significant benefits of alertness, performance, and communication.⁵⁵⁻⁵⁸

As valuable and efficient as they can be, however, there are specific aspects of napping that need to be addressed in operational environments:

- Scientific studies have shown that naps that last longer than 10 minutes have many benefits.^{59,60}
- The value of a nap is generally dependent on its duration—the longer the nap, usually the more beneficial it is.^{56,61}
- It is equivocal whether the recovery value of a nap depends on the time of day that it is

obtained. Thus, functionally, napping is more important than the time it is taken.⁵⁵

- Some research has found that the time of day does have an effect on the recovery value of a nap (eg, a nap at 0430 hours has higher recovery value than a nap at 2100 hours).⁶²

During the waking process, performance can be impaired.⁶³⁻⁷¹ When awoken from a nap, most individuals experience a 1- to 30-minute period of confusion.^{58,60,72-74} This confusion is sometimes defined as *sleep inertia* or *sleep drunkenness*.⁷⁵⁻⁷⁷ The impact of sleep inertia on performance is similar to reactions observed during sleep deprivation.⁶⁸

In military operational settings, when naps are used tactically, positive benefits are available without sleep inertia risks degrading the nap value. The duration of sleep inertia is typically longer when individuals are:

- awakened from sleep, compared with naturally awaking from sleep,⁷⁸
- awakened from a deep sleep, compared with

- light sleep,^{66,79,80} and
- awakened at a low point of alertness in their biological rhythm.⁷³

Exactly how long sleep inertia lasts remains a contentious issue. The only consensus is that waking up and eliminating sleep inertia are not physiologically or psychologically instantaneous. Military operations that utilize naps should know that napping can also have effects on the quality and quantity of subsequent sleep.^{81–83} Because of these additional factors, managing fatigue in operational settings is a major challenge, even despite the potential benefits of countermeasures (eg, napping).^{84–87}

The capacity of warfighters to obtain sleep/naps in theater also relates to other significant factors not

discussed in this chapter. For example, pharmacological substances taken to sustain alertness during demanding operations are known to influence falling asleep, remaining asleep, remaining awake, and maintaining certain aspects of performance. Each substance has its own pharmacological properties that need to be considered both in terms of their immediate potential benefit, as well as in terms of their subsequent hangover effects. In this context, a hangover can result from a stimulant's impact on an individual's ability to get subsequent sleep or a sleep-inducing agent's impact on the performance capability. In addition, the environment that people have to sleep in (from both the physical and psychological perspectives) plays a role in their capacity to use any recovery opportunities.

SUMMARY

Sleep is a biological need critical to successful operational outcomes. This is true in both military and nonmilitary settings. Under operational conditions, the need to obtain adequate sleep should be viewed as comparable with other requirements of logistic resupply, such as water, food, fuel, and ammunition. From a practical perspective, adequate sleep sustains mental performance; however, less than adequate sleep degrades performance over time.

Commanders are generally aware of the importance of adequate sleep. However, other than their own experience, and limited information/tools, the proactive management of sleep has been a difficult undertaking. There have been technological advances that help to answer key operational questions. The most practical tool available to measure sleep in the field is the wrist-worn actigraph, which measures movement as an index of sleep and wake states. Actigraphy outputs correlate strongly to much more expensive, less practical sleep measures that are usually used in the laboratory, such as PSG. Any data collected using actigraphy in the field are not only useful for mapping the amounts of sleep that all individuals have obtained, but also for estimating the future performance of each individual, groups of individuals, or when data are aggregated.

Quantitatively measuring performance in the field is a more challenging issue than measuring sleep. Principally, this is because the operational demands of engagement must take the highest priority, and, generally, performance is considered acceptable unless an obvious error is made. This retrospective view is not a particularly sensitive process to assess degrading performance under operational conditions; it is only sensitive to failure, which occurs near the impaired end of the performance spectrum. Currently, more simple

tests like the handheld, field-use PVT have been used as surrogate assessments of performance change. Further studies are needed to assess the validity of using surrogate tests to infer performance on operational tasks. Ideally, separate tasks—such as the PVT—would not be necessary because they represent a distraction from a soldier's primary operational task. Thus, automated measures of efficiency and performance using online assessment of primary task performance is an area of significant interest for future studies.

In addition to the currently available tools to measure sleep and performance, there are also mathematical models that predict sleepiness/alertness, fatigue, and performance. Like most tools, these models have strengths and limitations. Therefore, the predictions of such tools are one meaningful input considered in conjunction with other available sources of information. Relevant information includes criticality of planned missions, boundaries of risk tolerance in the operation, self-reports by soldiers, and expected field conditions.

Current evidence suggests that there are potential benefits for efficiency and safety if the sleep of soldiers can be managed in a more proactive way than it has been managed previously, although there is not yet a single, practical strategy to be applied to all circumstances. There is sufficient evidence to support the prediction of sleep timing and amounts, as well as the tracking of actual amounts obtained for missions, gaming, or simulations. Furthermore, the inclusion of sleep deprivation and associated performance loss needs to be considered in risk assessments and in the development of appropriate countermeasures to specific military operations. This occurs because even adequately equipped, well-trained, highly motivated soldiers operating within cohesive units with good

morale are not resistant to sleep loss. Future studies should focus on improving knowledge about the sleep of soldiers and performance behaviors in battle zones.

There is a need to investigate the range of differences between individual-level sleep and performance in such conditions.

Acknowledgments

We thank Colonel Greg Belenky, MD (US Army, Retired) for his detailed and insightful explanations of sleep-loss-related impairment in military operational environments. We also thank Erica Lipizzi for her editing expertise.

REFERENCES

1. Carskadon M, Dement W. Normal human sleep: an overview. In: Kryger M, Roth T, Dement WC, eds. *Principles and Practice of Sleep Medicine*. Philadelphia, Pa: Saunders; 2000: 15–25.
2. Horne J. *Why We Sleep—The Functions of Sleep in Humans and Other Mammals*. Oxford, UK: University Press; 1988.
3. Stickgold R, James L, Hobson JA. Visual discrimination learning requires sleep after training. *Nature*. 2000;3:1237–1238.
4. Dement WC. Sleepiness. In: Carskadon MA, Rechtschaffen A, Richardson G, Roth T, Siegel J, eds. *Encyclopedia of Sleep and Dreaming*. New York, NY: Macmillan Publishing Company; 1993: 554–559.
5. Carskadon M, Dement W. The multiple sleep latency test: what does it measure? *Sleep*. 1982;5:67–72.
6. Dijk DJ, Czeisler CA. Paradoxical timing of the circadian rhythm of sleep propensity serves to consolidate sleep and wakefulness in humans. *Neurosci Lett*. 1994;166:63–68.
7. Fletcher A, Dawson D. A quantitative model of work-related fatigue: empirical evaluations. *Ergonomics*. 2001;44:475–488.
8. Brown ID. Driver fatigue. *Hum Factors*. 1994;36:298–314.
9. Wesensten NJ, Belenky G, Balkin TJ. Cognitive readiness in network-centric operations. *Parameters*. 2005;Spring:94–105.
10. Rechtschaffen A, Kales A, eds. *A Manual of Standardized Terminology, Techniques, and Scoring System for Human Subjects*. Washington, DC: US Government Printing Office; 1968. NIH Publication No. 204.
11. Johnson LC. Are stages of sleep related to waking behavior? *Am Sci*. 1973;61:326–338.
12. Braun AR, Balkin TJ, Wesensten NJ, et al. Regional cerebral blood flow throughout the sleep-wake cycle. An H2(15)O PET study. *Brain*. 1997;120(pt 7):1173–1197.
13. Thomas M, Sing H, Belenky G, et al. Neural basis of alertness and cognitive performance impairments during sleepiness, I: effects of 24 h of sleep deprivation on waking human regional brain activity. *J Sleep Res*. 2000;9:335–352.
14. Balkin TJ, Braun AR, Wesensten NJ, et al. The process of awakening: a PET study of regional brain activity patterns mediating the reestablishment of alertness and consciousness. *Brain*. 2002;125(pt 10):2308–2319.
15. Wesensten NJ, Balkin TJ, Belenky G. Does sleep fragmentation impact recuperation? A review and reanalysis. *J Sleep Res*. 1999;8:237–245.
16. Haslam D. Sleep loss, recovery sleep, and military performance. *Ergonomics*. 1982;25:163–178.
17. Belenky G. *Sleep, Sleep Deprivation and Human Performance in Continuous Operations*. 1997. Available at: <http://www.usafa.af.mil/jscope/JSCOPE97/Belenky97/Belenky97.htm>. Accessed January 1, 2005.

18. Belenky G. *Sustaining Performance During Continuous Operation: The U.S. Army's Sleep Management System*. Paper presented at the International Conference on Managing Fatigue in Transportation; Tampa, Fla; 1997.
19. Balkin T, Thome D, Sing H, et al. *Effects of Sleep Schedules on Commercial Motor Vehicle Driver Performance*. Washington, DC: US Department of Transportation, Federal Motor Carrier Safety Administration; May 2000. Report No. DOT-MC-00-133.
20. Dinges DF, Powell JW. Microcomputer analyses of performance on a portable, simple visual RT task during sustained operations. *Behav Res Methods Instrum Comput*. 1985;17:652–655.
21. Folkard S, Åkerstedt T. A three-process model of the regulation of alertness-sleepiness. In: Broughton R, Wilkinson RT, Ogilvie RD, eds. *Sleep, Arousal and Performance: Problems and Promises*. Boston, Mass: Birkhäuser; 1992: 11–26.
22. Jewett ME, Kronauer RE. Interactive mathematical models of subjective alertness and cognitive throughput in humans. *J Biol Rhythms*. 1999;14:588–597.
23. Daan S, Beersma DG, Borbély AA. Timing of human sleep: recovery process gated by a circadian pacemaker. *Am J Physiol*. 1984;246(2 pt 2):R161–R183.
24. Wever R. *The Circadian System of Man*. Berlin, Germany: Springer-Verlag; 1979.
25. Achermann P. The two-process model of sleep regulation revisited. *Aviat Space Environ Med*. 2004;75(suppl 1):A37–A43.
26. Achermann P, Borbély AA. Combining different models of sleep regulation. *J Sleep Res*. 1992;1:144–147.
27. Åkerstedt T, Folkard S. Validation of the S and C components of the three-process model of alertness regulation. *Sleep*. 1995;18:1–6.
28. Borbély AA. A two process model of sleep regulation. *Hum Neurobiol*. 1982;1:195–204.
29. Borbély AA, Achermann P. Concepts and models of sleep regulation: an overview. *J Sleep Res*. 1992;1:63–79.
30. Borbély AA, Achermann P. Sleep homeostasis and models of sleep regulation. In: Kryger MH, Roth T, Dement WC, eds. *Principles and Practice of Sleep Medicine*. 3rd ed. Philadelphia, Pa: W.B. Saunders Company; 2000: 377–390.
31. Achermann P, Borbély AA. Simulation of daytime vigilance by the additive interaction of a homeostatic and a circadian process. *Biol Cybern*. 1994;71:115–121.
32. Belyavin AJ, Spencer MB. Modeling performance and alertness: the QinetiQ approach. *Aviat Space Environ Med*. 2004;75(suppl 3):A93–A103.
33. Folkard S, Åkerstedt T. Towards the prediction of alertness on abnormal sleep/wake schedules. In: Coblentz A, ed. *Vigilance and Performance in Automatized Systems*. Dordrecht: Kluwer Academic Publishers; 1989: 287–296.
34. Moore-Ede MC, Heitmann A, Guttkuhn R, Trutschel U, Aguirre A, Croke D. Circadian alertness simulator for fatigue risk assessment in transportation: application to reduce frequency and severity of truck accidents. *Aviat Space Environ Med*. 2004;75(suppl 3):A107–A118.
35. Dawson D, Fletcher A. A quantitative model of work-related fatigue: background and definition. *Ergonomics*. 2001;44: 144–163.
36. Fletcher A, Dawson D. A predictive model of work-related fatigue based on hours of work. *J Occup Health Safety Austral NZ*. 1997;13:471–485.
37. Fletcher A, Dawson D. A work-related fatigue model based on hours-of-work. In: Hartley L, ed. *Managing Fatigue in Transportation*. Oxford, UK: Pergamon Press; 1998: 189–208.

38. Hursh SR, Redmond DP, Johnson ML, et al. Fatigue models for applied research in warfighting. *Aviat Space Environ Med.* 2004;75(suppl 3):A44–A53, discussion A54–A60.
39. Åkerstedt T, Folkard S. The three-process model of alertness and its extension to performance, sleep latency, and sleep length. *Chronobiol Int.* 1997;14:115–123.
40. Fletcher A, Lamond N, van den Heuvel C, Dawson D. Prediction of performance during sleep deprivation and alcohol intoxication by a quantitative model of work-related fatigue. *Sleep Res Online.* 2003;5:67–75.
41. Åkerstedt T, Folkard S. Predicting duration of sleep from the three process model of regulation of alertness. *Occup Environ Med.* 1996;53:136–141.
42. Åkerstedt T, Folkard S. Predicting sleep latency from the three-process model of alertness regulation. *Psychophysiology.* 1996;33:385–389.
43. Mallis MM, Mejdal S, Nguyen TT, Dinges DF. Summary of the key features of seven biomathematical models of human fatigue and performance. *Aviat Space Environ Med.* 2004;75(suppl 3):A4–A14.
44. Reifman J, Gander P. Commentary on the three-process model of alertness and broader modeling issues. *Aviat Space Environ Med.* 2004;75(3 suppl):A84–A88, discussion A89.
45. Van Dongen HP. Comparison of mathematical model predictions to experimental data of fatigue and performance. *Aviat Space Environ Med.* 2004;75(suppl 3):A15–A36.
46. Clissold G, Smith P, Accutt B, Di Milia L. A study of female nurses combining partner and parent roles with working a continuous three-shift roster: the impact on sleep, fatigue and stress. *Contemp Nurse.* 2002;12:294–302.
47. Van Dongen HP, Dinges DF. Chronic partial sleep deprivation data point to a novel process regulating waking behavioral alertness. *J Sleep Res.* 2002;11(suppl 1):232.
48. Belenky G, Wesensten NJ, Thorne DR, et al. Patterns of performance degradation and restoration during sleep restriction and subsequent recovery: a sleep dose-response study. *J Sleep Res.* 2003;12:1–12.
49. Van Dongen HP, Maislin G, Mullington JM, Dinges DF. The cumulative cost of additional wakefulness: dose-response effects on neurobehavioral functions and sleep physiology from chronic sleep restriction and total sleep deprivation. *Sleep.* 2003;26:117–126.
50. Van Dongen HP, Dinges DF. Sleep debt and cumulative excess wakefulness. *Sleep.* 2003;26:249.
51. Fletcher A, Johnson ML, Balkin TJ. Recovery from cumulative sleep restriction involves a complex, multi-factor reservoir. *Shiftwork Int Newsletter.* 2005;22:55.
52. Johnson ML, Belenky G, Redmond DP, et al. Modulating the homeostatic process to predict performance during chronic sleep restriction. *Aviat Space Environ Med.* 2004;75(suppl 3):A141–A146.
53. Van Dongen HP, Maislin G, Dinges DF. Dealing with inter-individual differences in the temporal dynamics of fatigue and performance: importance and techniques. *Aviat Space Environ Med.* 2004;75(suppl 3):A147–A154.
54. Stampi C. Evolution, chronobiology, and functions of polyphasic and ultrashort sleep: main issues. In: Stampi C, ed. *Why We Nap. Evolution, Chronobiology, and Functions of Polyphasic and Ultrashort Sleep: Main Issues.* Boston, Mass: Birkhäuser; 1992: 1–20.
55. Dinges DF, Orne MT, Whitehouse WG, Orne EC. Napping can enhance alertness during sustained wakefulness, but the importance of the temporal placement of the nap between days and within the circadian cycle remains controversial. *Sleep.* 1987;10:313–329.
56. Bonnet M. The effect of varying prophylactic naps on performance, alertness and mood throughout a 52-hour continuous operation. *Sleep.* 1991;14:307–315.

57. Bonnet MH, Arand DL. We are chronically sleep deprived. *Sleep*. 1995;18:908–911.
58. Gillberg M, Kecklund G, Axelsson J, Åkerstedt T. The effects of a short daytime nap after restricted night sleep. *Sleep*. 1996;19:570–575.
59. Downey R, Bonnet MH. Performance during frequent sleep disruption. *Sleep*. 1987;10:354–363.
60. Sallinen M, Härmä M, Åkerstedt T, Rosa R, Lillqvist O. Promoting alertness with a short nap during a night shift. *J Sleep Res*. 1998;7:240–247.
61. Bonnet MH, Gomez S, Wirth O, Arand DL. The use of caffeine versus prophylactic naps in sustained performance. *Sleep*. 1995;18:97–104.
62. Gillberg M. The effects of two alternative timings of a one-hour nap on early morning performance. *Biol Psychol*. 1984;19:45–54.
63. Langdon DE, Hartman B. *Performance Upon Sudden Awakening*. Brooks Air Force Base, Tex: 1961: 1–8. SAM Report 62-17.
64. Wilkinson RT, Stretton M. Performance after awakening at different times of night. *Psychon Sci*. 1971;23:283–285.
65. Stones MJ. Memory performance after arousal from different sleep stages. *Br J Psychol*. 1977;68:177–181.
66. Dinges DR, Orne EC, Evans FJ, Orne MT. Performance after naps in sleep-conducive and alerting environments. In: Johnson LC, Tepas DI, Colquhoun WP, Colligan MJ, eds. *Biological Rhythms, Sleep and Shift Work: Advances in Sleep Research*. New York, NY: Spectrum Publications; 1981: 539–552.
67. Dinges DF, Orne MT, Orne EC. Assessing performance upon abrupt awakening from naps during quasi-continuous operations. *Behav Res Meth Instr Comp*. 1985;17:37–45.
68. Balkin TJ, Badia P. Relationship between sleep inertia and sleepiness: cumulative effects of four nights of sleep disruption / restriction on performance following abrupt nocturnal awakenings. *Biol Psych*. 1988;27:245–258.
69. Tassi P, Nicolas A, Dewasmes G, et al. Effects of noise on sleep inertia as a function of circadian placement of a one-hour nap. *Percept Mot Skills*. 1992;75:291–302.
70. Mullington J, Broughton R. Daytime sleep inertia in narcolepsy-cataplexy. *Sleep*. 1994;17:69–76.
71. Achermann P, Werth E, Dijk DJ, Borbély AA. Time course of sleep inertia after nighttime and daytime sleep episodes. *Arch Ital Biol*. 1995;134:109–119.
72. Webb WB, Agnew H. Reaction time and serial response efficiency on arousal from sleep. *Percept Mot Skills*. 1964;18:783–784.
73. Naitoh P, Kelly T, Babkoff H. Sleep inertia: best time not to wake up? *Chronobiol Int*. 1993;10:109–118.
74. Giam GC. Effects of sleep deprivation with reference to military operations. *Ann Acad Med Singapore*. 1997;26:88–93.
75. Lubin A, Hord DJ, Tracy ML, Johnson LC. Effects of exercise, bedrest and napping on performance decrement during 40 hours. *Psychophysiology*. 1976;13:334–339.
76. Dinges DF. Sleep inertia. In: Carskadon MA, Rechtschaffen A, Richardson G, Roth T, Siegel J, eds. *Encyclopedia of Sleep and Dreaming*. New York, NY: Macmillan Publishing Company; 1993: 553–554.
77. Mahowald M. Violence. In: Carskadon MA, Rechtschaffen A, Richardson G, Roth T, Siegel J, eds. *Encyclopedia of Sleep and Dreaming*. New York, NY: Macmillan Publishing Company; 1993: 645–646.

78. Seminara JL, Shavelson RJ. Effectiveness of space crew performance subsequent to sudden sleep arousal. *Aerospace Med.* 1969;40:723–727.
79. Dinges DF. Are you awake? Cognitive performance and reverie during the hypnopompic state. In: Bootzin R, Kihlstrom J, Schacter D, eds. *Sleep and Cognition*. Washington, DC: American Psychological Association; 1990: 159–175.
80. Caldwell JL, Caldwell JA, Sprenger WD, Woodrum LC, Jones HD, Colon J. *Effects of Triazolam on Pilot Performance*. Fort Rucker, Ala: U.S. Army Aeromedical Research Laboratory; 1996. Report No. USAARL-96-11.
81. Åkerstedt T, Torsvall L, Gillberg M. Shift work and napping. In: Dinges DF, Broughton RJ, eds. *Sleep and Alertness: Chronobiological, Behavioural and Medical Aspects of Napping*. New York, NY: Raven Press; 1989: 205–220.
82. Dinges DF. Napping patterns and effects in human adults. In: Dinges DF, Broughton RJ, eds. *Sleep and Alertness: Chronobiological, Behavioural and Medical Aspects of Napping*. New York, NY: Raven Press; 1989: 171–204.
83. Dinges DF. Adult napping and its effects on ability to function. In: Stampi C, ed. *Why We Nap. Evolution, Chronobiology, and Functions of Polyphasic and Ultrashort Sleep: Main Issues*. Boston, Mass: Birkhäuser; 1992: 118–134.
84. Muzet A, Nicolas A, Tassi P, Dewasmes G, Bonneau A. Implementation of napping in industry and the problem of sleep inertia. *J Sleep Res.* 1995;4(suppl 2):67–69.
85. Rosekind MR, Smith RM, Miller DL, et al. Alertness management: strategic naps in operational settings. *J Sleep Res.* 1995;4(suppl 2):62–66.
86. Rosekind MR, Gander PH, Gregory KB, et al. Managing fatigue in operational settings, 1: physiological considerations and countermeasures. *Behav Med.* 1996;21:157–165.
87. Rosekind MR, Gander PH, Gregory KB, et al. Managing fatigue in operational settings, 2: an integrated approach. *Behav Med.* 1996;21:166–170.