Managing Sleep and Alertness to Sustain Performance in the Operational Environment

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ABSTRACT

Among the challenges inherent in integrating the human into a system of systems is the fact that human capabilities and performance vary across time. In continuous operations, this variance is to a large extent a function of sleep loss and circadian desynchrony. To minimize the risks associated with sleep loss and to optimize performance during continuous operations, we are developing a comprehensive system to manage operator sleep and alertness. This system will support human performance by facilitating informed decisions regarding the administration of pharmacological fatigue countermeasures (choice of drug, timing, and dose), the scheduling of recovery sleep opportunities (e.g., duration and timing), and other behavioral countermeasures (e.g., application of environmental stimuli such as light) in the operational environment. The main components of this system include (a) wrist actigraphy for objective determination of the operators' recent sleep/wake history; (b) fatigue countermeasures; and most importantly (c) a mathematical model in which the relationship between sleep, the circadian rhythm of alertness, and various aspects of performance have been quantified. The latter serves as the lynchpin of the sleep management system, and is a necessary component of strategies to achieve human system integration during continuous operations. This model provides the performance capability predictions necessary for making appropriate demands upon personnel resources over time.

Of the three main components of the sleep and alertness management system, wrist actigraphy is the most advanced—having been shown in several previous studies to be a valid and reliable means of distinguishing sleep from wakefulness. Next in terms of maturity is the effort to evaluate the efficacy of different fatigue countermeasures. However, our recent studies [in which the effects and efficacy of modafinil, d-amphetamine, and caffeine were compared in a head-to-head manner] show that each restores a unique subset of cognitive abilities, and none restores all of those aspects of cognitive performance that are decremented by sleep loss. This suggests the need for further research on the use of alternative and/or supplemental agents during continuous operations (e.g., new stimulants and/or cognitive enhancers). The least developed component—and the primary focus of our current research program—is the sleep performance/prediction model. The current version of this model predicts average performance on a psychomotor vigilance task during total sleep loss. However, its utility in the operational environment will ultimately depend on its ability to predict (a) the effects of sleep loss on individuals; (b) the effects of fatigue countermeasures; (c) the effects of sleep restriction versus total sleep deprivation; and (d) the amount of sleep needed to recover from a period of sleep loss (i.e., to specify optimal recycle rates).

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1.0 ROLE OF THE OPERATOR IN THE OPERATIONAL ENVIRONMENT

Technological advancements are continually improving the efficiency and productivity of human operators engaged in military, manufacturing, communications, and transportation sectors. As this trend continues, individual operators are performing more (with broader ranges of responsibilities and attendant increases in information processing loads) within each operational 'loop.' For example, U.S. Navy destroyers are currently manned by approximately 300 sailors. However, in a few years the Navy will be launching a new destroyer, the DD-21 that will be deployed with a crew of less than 100 sailors— a crew size reduction of roughly 66%. Since it can be presumed that this reduction in manpower will not result in any reduction in functional capabilities, the average level and number of responsibilities for those individuals manning the new ship—in terms of information processing, decision making, and possibly also work shift durations—must increase accordingly. As individual responsibility and decision making requirements increase within an operational loop, so does the probability that the weakest links in those systems will become the human operators, for whom comparable diagnostics and prognostics capabilities have not yet been developed. This is particularly important in environments that include sophisticated automation and mechanized components with built-in 'diagnostics and prognostics' capabilities (e.g., gauges that report the functional status of a component and provide notification of impending component failure but require corrective actions to be taken by the human operator before system failures occur).

1.1 The Nature of Performance Deficits in the Operational Environment

It is difficult to develop means to measure, monitor, and predict operator functional state because human performance is determined by multiple factors. These factors include individual traits of the operator such as intelligence level, physical strength, visual and auditory acuity as well as the state of the individual operator (motivation level, mood, internal distractions such as headache, thirst, etc.). Additionally, factors reflecting interactions of the operator with the operational environment (e.g. time on task or environmental factors) play an important role. Further, the nature of the task itself can influence the probability of operator error and performance failure. Also the operator's perception of the task may increase the likelihood of performance failure. For example, sleepiness may be unmasked during performance of tasks perceived as 'boring' [1]. Therefore, human performance is the product of complex interactions involving the operator's internal milieu of traits and states and the nature of the task being performed.

1.2 Multiple Factors Impact Performance in the Operational Environment

Ultimately, the capacity to perform a particular task depends on the underlying capacity and readiness of the brain as well as the body to perform that task. Normal performance over extended periods of time typically reflects and signifies a normal underlying level of brain functioning. Also, normal performance typically involves some variability—with, for example, predictable circadian and ultradian rhythms evident for most performance measures. But, on the other hand, poor performance does not necessarily reflect compromised brain functioning. This is because performance deficits can result from factors such as inattentiveness due to boredom, reduced mood, momentary distractions, thirst, pain, etc. There are an infinite number of events and circumstances that can affect performance without impacting brain function, and without suggesting that the underlying capacity of the brain to perform the task at hand is in any way compromised.

In those cases in which brain functioning actually is compromised, overall performance will generally be reduced to an extent that corresponds to the level of the underlying brain dysfunction. Again, the correspondence may not be perfect or linear since compensatory mechanisms such as increased mental effort may help maintain performance at nominally adequate levels [2], at least temporarily. But extended monitoring of performance will typically reveal deficits that reflect the compromised brain state.

2. SLEEPINESS AS A DETERMINANT OF OPERATOR FUNCTIONAL STATE

Sleepiness constitutes one such state of compromised cognitive functioning. It has long been known that sleep deprivation has a negative effect on a wide variety of tasks (the first scientific study of sleep deprivation on humans was conducted by Patrick and Gilbert in 1896 [3]). But it is also clear that all tasks are not equally sensitive to sleep loss [4]. In general, tasks involving mental performance are especially sensitive to sleep loss, whereas tasks requiring mostly physical performance (e.g., measures of strength and endurance) are resistant to the effects of sleep loss.

Jobs involving continuous (24 hour-per-day) operations in the manufacturing, service, military, communications, and transportation sectors also increase the demand placed on human operators. It is likely that the modern pressures to increase commercial activities to 24 hour-per-day operations, at least partly, accounts for findings from epidemiological studies showing that the nightly, average number of hours of sleep obtained by adults in the U.S. has decreased substantially within the past century [5,6]. It has long been known that the combination of sleep loss and circadian desynchrony from shiftwork leads to deficits in alertness and performance. It has been suggested that human error compounded by sleepiness and fatigue may have contributed to several tragic disasters such as Chernobyl, Three Mile Island, and Bhopal [7]. However, again, the rapid expansion of such 24 hour-per-day operations has not been matched by comparable progress toward effective measurement, prediction, or monitoring of functional state in the operational environment—even in those industries or operations for which the consequences of human error and performance failure are potentially catastrophic.

2.1 The Physiological Basis of Sleepiness-Related Performance Deficits

Earlier work by Wilkinson found that [4] performance on tasks that are themselves sleep-conducive (by virtue of their long duration, boredom-inducing pace etc.) are especially sensitive to the effects of sleep loss. However, more recently it has also been shown that tasks measuring higher order mental abilities—abilities such as logical reasoning, judgment, problem solving and creativity that are mediated by prefrontal cortices and commonly thought to be unique to human beings--are also especially sensitive to sleep loss [8,9]. Because tests of higher order cognitive abilities can be stimulating and interesting, it is unlikely that they are sleep-conducive in the same way as those tasks identified by Wilkinson [4], and it is less likely that sleepiness-related deficits in performance on these relatively stimulating tests are simply a result of ‘lapses’ in performance associated with microsleep episodes [10]. Rather, these tests suggest that sleep loss results in a *state* of impaired alertness and decremented cognitive ability—a reduced mean level of functioning around which alertness and performance levels fluctuate on a moment-to-moment basis. Previous work at the Walter Reed Army Institute of Research laboratory [11] has established that this state of reduced alertness and impaired cognitive ability is characterized by reduced brain activation (i.e., hypometabolism), with global reductions of about 7 percent following 24 hours of continuous wakefulness. Brain regions most affected include the thalamus and anterior cingulate cortex (which, in addition to other functions, mediate general arousal and directed attention), as well as heteromodal association areas in prefrontal and parietal cortices (which also mediate some aspects of attention, as well as the higher-order mental abilities such as foresight, planning, problem solving, and perseverance) [12]. Therefore, it is possible that the sensitivity to sleep loss of long-duration, boring tasks (i.e., the types of tasks identified by

Wilkinson [4]) largely reflect hypometabolism in the thalamus and anterior cingulate (i.e., difficulty maintaining attention and alertness), whereas deficits in higher-order mental abilities (such as those identified by Horne [8], Feuerstein et al. [13], and Harrison and Horne [9]) reflect sleep-loss-induced hypometabolism in the prefrontal and parietal heteromodal association cortices.

3. A STRATEGY TO MONITOR VARIATIONS IN OPERATOR FUNCTIONAL STATE AS A PRODUCT OF SLEEPINESS

To this point, it has been argued that (a) sleepiness is a common and significant determinant of operator functional state; (b) sleepiness is characterized by a specific pattern of regional brain deactivation; (c) sleepiness produces specific performance deficits; but (d) there are several additional factors that potentially mediate performance in the operational environment. Given this state of affairs, how does one monitor alertness/sleepiness and then predict operator functional state (i.e., the ability of the operator to perform his duties in the operational environment)? We propose a multiple component system that includes each of the following:

Component 1: A Sleep/Wake Monitor/Recorder. As indicated previously, sleep loss is only one of many potential antecedents/causes for performance deficits in the operational environment. If the operationally relevant performance measure indicates a trend toward degraded performance, the next question is 'What is the underlying cause of this performance degradation?' In order to determine the likelihood that the observed degradation is due to sleepiness, it is necessary to have data regarding the adequacy of the operator's most recent sleep (i.e., duration of prior sleep and elapsed time since that sleep period). Wrist actigraphy is a well-validated method [e.g., 15,16,17,18,19] for measuring and monitoring sleep/wake history (i.e., sleep duration and timing) in the operational environment, over several weeks or even months. Also, it has the added advantage of being unobtrusive—wrist actigraphs are essentially wear-and-forget devices. This is especially important because the utility of a device or measure in the operational environment is as much dependent upon its 'ease of use' as it is upon its validity.

Component 2: Performance Measures. Until all of the factors that can potentially impact operational performance are identified, monitored, and modeled; there will be a need to actually monitor operationally relevant performance (e.g., with embedded performance measures or with minimally intrusive tasks that correlate well with operational performance). These measures should reflect degradations in cognitive abilities and alertness well before the operationally relevant performance deteriorates to the extent that effectiveness and safety are compromised (i.e., early enough that effective countermeasures can be implemented). One example of such a performance measure would be the use of lane tracking devices to identify steering patterns in truck drivers that suggest reduced attentiveness (e.g., fewer steering corrections per minute, but of increasing magnitude).

When embedded measures cannot be identified or obtained, the next best option is to introduce performance measures from which existing operational performance capability can be inferred—i.e., measures that reflect performance in the operational setting. Quantification of performance in turn makes possible the construction of scales for determining the adequacy of performance following sleep loss, or the efficacy of interventions. Addidionally, quantify performance permits the development of mathematical models to describe the relationship between performance and factors that impact performance in order to predict performance.

There are several factors to consider when choosing a performance measure for use in the operational environment [14]. Although not an exhaustive list, some of the most salient factors to be considered include:

- *Sensitivity.* Of utmost importance, the performance measure must be maximally sensitive to the effects of sleep loss. This provides the potential to "map" measured performance onto performance of actual operational tasks that may be less sensitive to the effects of sleep loss—thus providing the potential for accurate prediction of performance decrements before they become manifest during the actual operation.

- *Reliability*. The measure should be "repeatable" and not subject to "learning" effects (i.e., performance does not improve with repeated administration of the measure) and thus accurately reflect changes in the factor of interest—in this case, sleep loss-induced decrements in the ability to perform operationally relevant tasks.
- *Content Validity*. This refers to the specificity with which the selected measure reflects sleep history-related changes in operationally relevant performance. Although it is not possible to quantify the relative content validity of various measures (i.e., the extent to which fluctuations in these measures reflect fluctuations in general cognitive abilities versus operationally relevant abilities), it is possible to rate purely physiological measures. For example, measures such as blood pressure or oculomotor activity have relatively low content validity in comparison with the psychomotor measures in which response speed is measured. In this context "cognitive processing speed" is a relevant determinant of performance in a wide array of operationally relevant tasks.
- *Intrusiveness.* From a practical standpoint, it is essential that the selected measure be non- or only minimally intrusive. Optimal measurement procedures should result in minimal/inconsequential interference in the performance of operationally-relevant tasks.
- *Cumbersomeness.* Measurement procedures must also be compatible with the operational environment and require minimal expenditures in terms of cost, time, individual effort required for data collection; and ease with which data can be compiled, processed, and interpreted. Like intrusiveness, this factor represents a practical consideration in the utility of a measure in the operational environment, and is akin to the "Ease of Use" factors identified by Dinges and Mallis [14].

Component 3: A Validated Sleep/Performance Model. In order to interpret the sleep/wake data in a manner that is operationally useful it is necessary to have a model that specifies the relationship between sleepiness and operationally relevant performance. The application of such a model can be used to determine when countermeasures should be applied; what those countermeasures should be; and at what 'dose' levels the countermeasures should be applied. Examples of such countermeasures include caffeine, modafinil or strategically placed nap intervals. Thus an on-line performance measure could indicate that an operator's current performance is nominally adequate at 0200 hours. However, based on that operator's existing level of performance, his/her accumulating level of sleep debt, and his/her circadian rhythm of performance, a sleep/performance model might predict that without application of an intervention (such as 200 mg caffeine or a 20-minute nap), performance would degrade to an unacceptable level by 0300 hours.

Several such models are currently in development, including a model by the U.S. Department of Defense, called the "Sleep, Activity, Fatigue and Task Effectiveness" (SAFTE) Model. The SAFTE model includes mathematical functions to describe the decrementing effect of continuous wakefulness, recovery of cognitive abilities and alertness during subsequent sleep, the short term post-awakening performance deficits known as "sleep inertia" effects, and the influence of circadian rhythms:

- *Wake/Decrement Function.* A wake/decrement function is a mathematical formula describing the rate at which cognitive performance declines during continuous wakefulness. In the SAFTE model, the wake decrementing function was constructed based on the following assumptions that were derived from the relevant literature: (a) cognitive performance is maintained at a steady state across days when individuals obtain 8 hours of sleep each night; (b) cognitive performance declines by approximately 25 percent for every 24 hours of total sleep deprivation, with some variation depending on the particular cognitive task being studied [20]; and (c) a single, daily 30-minute nap over 85 hours of sleep deprivation has substantial recuperative value, slowing the rate of performance decline from 25 percent to 17 percent per day [21].

- *Sleep/Recovery Function.* The sleep/restoration function is a mathematical formula describing the rate at which restoration of alertness and cognitive ability accrues during sleep. In the SAFTE model, this rate is determined by: (a) the individual's sleep debt at the time of sleep onset, and (b) the amount of time spent asleep. Thus, the rate at which recuperation occurs during sleep varies concomitantly with existing sleep debt—so recuperation at the beginning of the sleep period (when sleep debt is relatively high) accrues at a faster rate than at the end of the sleep period (when sleep debt is relatively low). [Previous studies suggest that recuperation accrues during sleep in a nonlinear manner [e.g., 22] with a high rate of recuperation during the first few hours of sleep that gradually wanes (approaches an asymptote) as the sleep period is extended—until the benefit realized from additional sleep becomes negligible [9].
- *Sleep Inertia Function*. The sleep inertia function is a mathematical formula that describes the gradual (over approximately 20 minutes) restoration of normal performance and alertness levels that occurs upon awakening from sleep. It is therefore a function that describes performance for a relatively restricted period of time each day. It is based on both performance [for a review of sleep inertia effects, see 23] and positron emission tomography data [24] showing that those brain regions known to mediate cognitive performance are relatively deactivated immediately upon awakening from sleep.
- *Circadian Rhythm.* The time-of-day function is based on empirical data showing that, under constant routine and/or total sleep deprivation conditions (i.e., with sleep/wake history controlled), cognitive performance oscillates between approximately 5 and 20 percent peak to peak over a 24-hour period. Although there is typically a lag of an hour or more, alertness and performance tend to track the core body temperature rhythm with a nadir in the early morning hours, and increase across the day (except for a dip in the afternoon), and a peak in the evening hours, prior to sleep onset [see 25,26].

Component 4: A Device for Monitoring Moment-to-Moment Fluctuations in Alertness. Alertness and performance are influenced by sleep debt status and follow a predictable circadian rhythm, but predictions derived from these factors should be considered estimates of a probability range of alertness and performance levels rather than precise points; with substantial moment-to-moment variations possible (perhaps due to ultradian rhythms, variations in motivation and 'effort', etc.). In fact, it has been suggested that the primary effect of sleep loss on performance and alertness is not so much a 'general reduction in functioning" as it is an 'increased variability in functioning' [27]. Thus, for occupations in which even momentary lapses in alertness and performance can have serious consequences (e.g., air traffic controllers, sonar operators, and truck drivers) it would be prudent to add a fourth component to the system—one in which momentary fluctuations in alertness are identified in real time (or better yet, predicted in a timely manner so that appropriate interventions—such as alerting stimuli— can be applied before performance and alertness deteriorate to dangerous levels). The need for such devices has long been recognized, and several attempts to develop them have been made.

The characteristics that such a device must possess to be of use in the operational environment are obvious. Again, like any measure, it must be valid (i.e., it must truly reflect rapid fluctuations in alertness) and reliable (it must consistently provide accurate measures of alertness over time). Unique to such a device, however, is that in order for it to reflect rapid changes, the sampling rate would need to be quite high. This latter requirement obviates the use of performance measures like the PVT, since they would need to be administered continuously and would therefore interfere with performance of operationally-relevant tasks. However, continuous performance measures that are embedded in the operators' actual task (like automatic lane tracking devices on the trucks of commercial drivers) would be appropriate, if they could be devised.

Because it is not possible to devise embedded performance measures for every occupation, and because the requirement that alertness be monitored continuously necessitates a high sampling rate, the focus in this area has often been development of alertness monitoring devices that unobtrusively measure some aspect of physiology (e.g., EEG) or behavior (e.g., eyeblinks) that correlates with alertness [e.g., see 28]. However, none of these devices have yet been validated to the extent that they have generated widespread interest or acceptance within the scientific or operational communities.

4. STATE OF THE ART

Wrist actigraphy is an unobtrusive method for monitoring operator effectiveness. The Walter Reed Army Institute of Research has been actively involved in the development, testing and fielding of this wrist actigraphy technology. Wrist worn actigraphs provide information on the wearer's level of sleep debt, circadian rhythm phase, and provides a resulting prediction of the wearer's capacity to perform cognitive work (based on laboratory studies of PVT performance during sleep loss). The 'sleep watch' effectively combines two of the four previously described components needed for a comprehensive sleep management/ performance prediction system. It contains a central processing unit, random access memory, and an accelerometer. Each minute, the Sleep Watch records whether and how much movement activity has occurred, and uses this information to determine sleep/wake status using a sleep-scoring algorithm [29]. Also built into some versions of the Sleep Watch is a sleep/performance model (similar to the SAFTE described in the previous section). The model takes the output of the sleep-scoring algorithm (the wearer's sleep/wake history) and uses this information to predict changes in performance in real time. The Sleep Watch that includes the sleep/performance model has a display that includes both an analog and digital "fuel gauge" to predict current or real-time performance. Several models of the watch include a light sensor. The timing of light exposure determines the circadian rhythm acrophase (i.e., peak), so it is anticipated that future versions of the Sleep Watch will include a function that adjusts the circadian rhythm for time-zone changes based on actual history of light exposure.

Currently, the mathematical model is "one size fits all" with respect to the effect of any given amount of sleep on subsequent performance (i.e., based on group mean effects of sleep loss on performance). In the future, through the use of an embedded performance measure (e.g., a modified version of the Psychomotor Vigilance Task developed by Dinges and Powell [30]), it is anticipated that the embedded performance prediction model will be made to 'learn' to adjust itself in a manner that accurately predicts performance based on the individual wearer's sensitivity to the effects of sleep loss. If and when this performance measure is incorporated, then the Sleep Watch will include three of the four previously described components of a comprehensive sleep management/performance prediction system.

Although wrist actigraphy is a well-validated tool for measuring the timing and duration of sleep and wakefulness in the operational environment for extended periods (weeks or months), the usefulness of wrist actigraphy in actual operational scenarios is just beginning to be explored. For example, we are currently endeavouring to collaborate with the 3rd Infantry Division in Iraq to evaluate the predictive validity of data collected using wrist actigraphs worn by military aviators.

5. CONCLUSIONS

Factors that cannot be measured and quantified cannot be managed or predicted. In the operational setting, management of alertness and optimization of performance requires the ability to measure sleep and/or alertness in the operational setting, and the ability to measure operationally-relevant performance. Once these requirements are met, it becomes possible to mathematically model the relationship between sleep, alertness, and operationally relevant performance. Therefore, the optimal system for managing sleep/alertness and predicting operator effectiveness will have four components: (a) a valid performance measure that reflects operator effectiveness ; (b) the means for objectively and unobtrusively determining recent sleep/wake history in the operational environment (such as wrist actigraphy); (c) a mathematical model that describes the relationship between sleep/wake history and operationally relevant performance; and (d) for some operators whose duties require it, an unobtrusive (and possibly physiologically-based) device for monitoring moment-to-moment fluctuations in alertness. Although each component individually provides operationally relevant data regarding operator functional state, optimal management of alertness and alertness-mediated performance will be achieved by integrating the information provided from each component of such a system.

The applicability of a system to monitor sleep/alertness and predict performance is broad. The implementation of such a system will enhance safety and productivity through optimal application of appropriate interventions (e.g., on-the-fly work shift schedule changes and optimally-timed administration of pharmacologic agents). Applications can be envisioned for virtually any operational setting in which the possibility exists that operator performance could be impacted by sleep loss--including military operations, long-haul trucking, shiftwork in the manufacturing industries, power plant operations, police and firefighting operations, and many others.

6. REFERENCES

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