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The Fatigue Avoidance Scheduling Tool: Modeling to Minimize the Effects of Fatigue on Cognitive Performance

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ABSTRACT

Operator fatigue and time-of-day induced variations in cognitive effectiveness can lead to lapses in attention, slowed reactions, and impaired reasoning and decision-making that has been shown to contribute to accidents, incidents and errors in a host of industrial and military settings. During the past three years, the US Air Force has sponsored the development of a model of human fatigue and circadian variation and a scheduling tool based upon the model that will be used to minimize aircrew fatigue. The initial test version of the tool has passed review by the operational wings of the AF and a final operational product is in advanced development and validation. The software was developed by SAIC and NTI and is called the Fatigue Avoidance Scheduling Tool (FAST™). This fatigue forecasting system is being developed and tested by NTI under a small business innovative research (SBIR) grant from the US Air Force, now in the third year of a three-year program. Fatigue predictions are derived from the Sleep, Activity, Fatigue, and Task Effectiveness (SAFTE™) model invented by Dr. Steven Hursh of SAIC. The patented SAFTE™ model has received a broad scientific review and the DoD considers it the most complete, accurate, and operationally practical model currently available to aid operator scheduling. The Department of Transportation is in the second phase of a three-phase project to validate and calibrate the model for avoiding excessive fatigue in transportation operations. The FAST scheduling tool uses the model to compare schedules in terms of predicted performance effectiveness. FAST allows easy entry of proposed schedules and generates graphical predictions of performance along with tables of estimated effectiveness scores for objective comparison. Optimal schedules may be selected based on average effectiveness for proposed work periods or mission critical events. The tool may also be used for retrospective analysis of fatigue related factors that may have contributed to an accident, error or safety related incident. In this mode, information on the work and sleep schedules of operators prior to the event may be entered into the tool and a projection of performance effectiveness at the time of the event is determined. In combination with other information, this analysis can project the combined effects of time of day and sleep history as a contributing factor to safety related events.

INTRODUCTION

The purpose of the FAST development effort has been to develop a user-friendly, computerized tool for operational planners and schedulers based on a highly researched and recognized model of human sleep and cognitive performance. The Fatigue

Avoidance Scheduling Tool (FAST) allows a user to predict cognitive performance efficiency for periods up to three weeks based on the timing and amount of sleep an individual or team receives prior to and during the period. For military applications, FAST provides the planner the ability to optimize performance under conditions of limited sleep and minimizes the need for pharmacological aids.

SUMMARY OF COMPLETED WORK

The effort has built on a newly developed model of sleep and performance invented by Dr. Steven Hursh of SAIC called the Sleep, Activity, Fatigue, and Task Effectiveness (**SAFTE**) Model [1]. This model predicts human cognitive performance based on 20 years of sleep and circadian rhythm research. Dr. Hursh invented the first sleep and performance model for the Walter Reed Army Institute of Research and the current model is an advanced modification of that Army model. The current version of the model makes valid predictions of performance under a broad range of schedule conditions, from minimal to complete sleep deprivation, at any time of day and for normal adult subjects ranging in age from the early twenties to mid-fifties. The model is homeostatic and adjusts its predictions of future performance based on the recent sleep history of the projected population or specific individuals. In the model, a circadian process influences both performance and sleep regulation. Sleep regulation is dependent on hours of sleep, hours of wakefulness, current sleep debt, the circadian process and sleep fragmentation (awakenings during a period of sleep) that reduce sleep quality. Performance is dependent on the current balance of the sleep regulation process, the circadian process, and sleep inertia. An additional benefit of **SAFTE** is that it can be easily enhanced by future studies to refine fatigue effects on specific subject populations, specific aspects of operator performance, and the effects of interventions, such as stimulants, sedatives, and naps.

The initial phase of the ***FAST*** development effort incorporated the **SAFTE** Model into a software tool for scheduling pilots and crews that permits mission planners to evaluate alternative schedules for their effects on performance capacity, as degraded by fatigue and circadian variation. The tool incorporates interpretive tools for visualizing performance changes over time and the capability to simultaneously compare multiple schedules on the basis of predicted changes in cognitive capacity. The current product can be easily installed from a CD-ROM on any Windows-based computer. ***FAST*** allows the user to view the effects of pre-programmed and user-defined sleep/wake schedules on predicted performance effectiveness. The tool provides a simple, user interface enabling rapid visual and quantitative estimates of the effects of a variety of factors on the cognitive performance of aircrew members. Figure 1 shows an actual screen from the current ***FAST*** program comparing two schedules simultaneously. Schedules may be viewed in a window, and two or more windows may be overlaid or tiled for comparison. They may be copied to another program or directly printed. The tool allows the user to load pre-programmed sleep schedules, edit them using keyboard and mouse commands, and save edited schedules.

Figure 1: This is a screen image of the ***FAST*** *main window and shows performance by a railroad engineer based on a log of sleep and on-duty time. The top window shows predicted performance based on actual sleep. The bottom window shows potential improved performance based on the addition of increased sleep during off-duty periods. The top of each graph shows the performance effectiveness at the day and time indicated by the vertical cursor.*

Effectiveness, as predicted by the ***FAST*** model, is displayed for a user-selectable interval ranging from 6 hours to over 30 days. The program allows simultaneous editing and comparison of any number of sleep schedules.

A standard Windows menu structure has been implemented, along with export to other programs, such as a spreadsheet or presentation.

One valuable option to aid comparison of several schedules is the overlay of a table of interval statistics. This table shows the average “Performance Effectiveness” for successive hours while awake and while working. These tables, when selected, are displayed as an overlay on the graphic display and can be moved to any position that is convenient for simultaneous viewing of the graph and the table. These tables can be printed or copied to the clipboard for inclusion in a briefing or report.

SAIC has created an algorithm for shift-work phase adjustment and transmeridian relocation within the **SAFTE** model. The model contains logic to detect the change in work/sleep patterns and to readjust the phase of the circadian rhythm depending on whether the new pattern is indicative of a change in time zone or shift in work schedule (shift rotations).

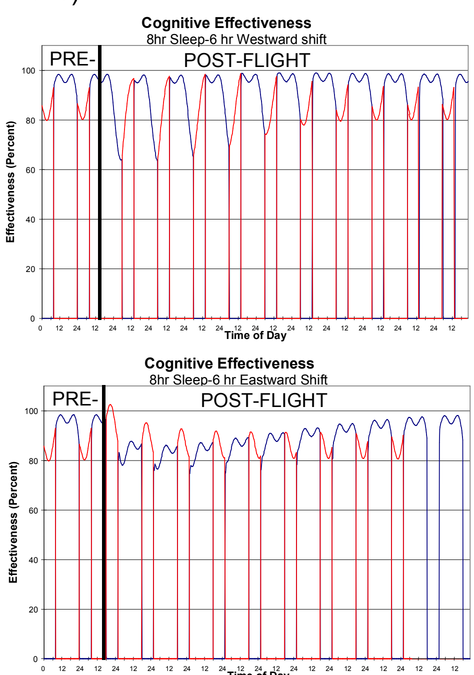

Figure 2: Disruptions of performance following westward (upper panel) and eastward (lower panel) travel across 6 time zones. Note that the model predicts greater on the job disruptions (blue line) following eastward travel and a longer period of adjustment.

Dr. Hursh developed a unique method to trigger shifts in the circadian process that can predict “Jet Lag” based on travel from east to west and west to east, illustrated in Figure 2. This new feature of the model is now incorporated in the ***FAST*** software. This feature also permits the software to properly adjust the circadian rhythm for shift-work schedules typical of many industrial operations.

The product currently under development will provide the AF with a crew scheduling tool to anticipate fatigue effects on performance, thus allowing the military planner to take action to reduce or mitigate the effects of fatigue or to alter the schedule to maintain performance without fatigue. The anticipated product will not only provide a graphic display of performance effects of multiple schedules, it will also provide a Mission Timeline to guide the crew during the performance of the mission.

Current Status:

An initial version ***FAST*** was used to validate the use of in-flight naps to maintain performance of Air Force bomber crews conducting 30 and 45 hr missions and to guide the design of night training exercises. In 2002, the Army, Air Force, and Navy convened a meeting to discuss fatigue modeling and the **SAFTE** Model was accepted as the base model for continued DOD development. Other organizations have also expressed an interest in using ***FAST***. The Federal Railroad Administration is using the tool to assess fatigue as a possible contributing factor to major rail accidents and the FAA and NTSB are monitoring progress in the development effort for potential applications for schedule assessment and accident investigations. Recently, the Federal Railroad Administration has initiated a program to validate and calibrate the tool for fatigue management and accident investigation in rail operations. Several commercial companies are committed to pursuing studies to calibrate the scheduling tool to manage fatigue in the rail environment, including Burlington Northern and Santa Fe Railway and Union Pacific Railroad. The program has lead to the development of a specialized version of ***FAST,*** called ***FAST-TR,*** that incorporates all the earlier features of ***FAST*** plus the ability to compute likely sleep patterns based on a work schedule, an algorithm called **AutoSleep**. The product is currently being used to analyze railroad accidents to determine if fatigue may have played a role in causing human errors.

The Army and Air Force are conducting studies on novel fatigue countermeasures: stimulants and sleep aids. These studies will provide significant parameters to the underlying **SAFTE** Model and provide planners with quantitative data to compare alternative courses of fatigue remediation. For Air Force applications, the product will allow input of information directly from the flight plan (take off, waypoints, air refuelings, landing, etc.), include information on the light/dark cycle throughout the mission, and provide multiple time scales (home, Zulu, mission-elapsed, and destination) along with a plot of performance efficiency. Additionally, the tool has been enhanced to intelligently decide when sleep "typically" would occur during non-duty time.

Details of the SAFTE Model:

The general architecture of the current **SAFTE**™ model is shown in Figure 3. A circadian process influences both performance and sleep regulation. Sleep regulation is dependent on hours of sleep, hours of wakefulness, current sleep debt, the circadian process, and fragmentation (awakenings during a period of sleep). Performance is dependent on the current balance of the sleep regulation process, the circadian process, and sleep inertia. Although developed independently, the resulting model has structural similarity to the scheme suggested by Acherman and Borbely [2] and when the simulation is integrated over time approximates (ignoring circadian influences in the model) the mathematics of the homeostatic model of Folkard and Akerstedt [3]. However, the new model has been optimized to predict changes in cognitive performance and incorporates features not included in any prior comprehensive model. These features are: a multi-oscillator circadian process, a circadian sleep propensity process, a sleep fragmentation process, and a circadian phase adjusting feature for time zone changes. Each component will be discussed in detail, with supporting data.

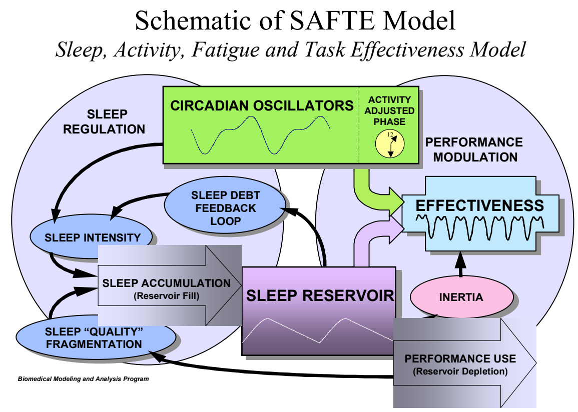

Figure 3: Block diagram of SAFTE™ Model.

Components of the Model

Circadian Oscillators: Performance while awake and the drive to sleep are both controlled, in part, by a circadian process [4], [3]. Performance and alertness reach a major peak in the early evening, about 2000 hours, and fall to a minimum at about 0400 hours. There is a secondary minimum in the early afternoon, about 1400 hours, and a secondary morning peak at about 1000 hours. Correlated with this pattern is a rising tendency to fall asleep that reaches a peak at about the same time performance and alertness reach their minima. The existence of both a major and a minor peak in performance and two corresponding minima at other times suggest that at least two oscillators are involved in the circadian process.

The sleep and performance model incorporates a circadian process that is composed of the sum of two cosine waves, one with a period of 24 hours and one with a period of 12 hours. This arousal oscillator drives both variations in predicted cognitive effectiveness and sleep propensity. These two translations of the oscillator have identical frequency and phase components and differ only in amplitude and sign; a rise in arousal produces an increase in performance and a decrease in propensity to sleep. The circadian process is depicted in the large rectangle shown in the diagram of the **SAFTE**™ model, Figure 3. In addition, based on observations that the amplitude of circadian variation increased with hours of sleep deprivation, the amplitude of the performance rhythm is a linear function that increases from a minimum to a maximum depending on the level of sleep debt (reservoir capacity minus current reservoir level).

Activity Adjusted Circadian Phase: When subjects move to another time zone or alter work patterns so that sleep and work occur at different times of day, the internal circadian oscillator that controls body temperature and alertness shifts to this new schedule. During the period of adjustment, subjects experience performance degradation, disrupted mood and feelings of dysphoria, called circadian desynchronization or "jet lag" [5], [6], [7]. The model mimics this process and automatically adjusts the phase of the circadian rhythm to coincide with the activity pattern of the subject. This feature is critical for the accurate prediction of the effects of moving to a new time zone or changing to a new and regular work pattern, such as changing from the day shift to the night shift. When ones moves to a new work schedule or a new time zone, the change in average awake time (relative to a reference time zone) is detected and a new "target phase" is computed. For example, when moving from the central US time zone to Germany, the awake time of the subject advances six hours. Instead of waking at, say, 0600 Central Time, the subject awakens at 0000 Central Time, which is 0600 German time. This causes a shift of 6 hours in the "target phase" of the subject. The model adjusts to the new "target phase" gradually over the course of 9 days. During that time, the performance of the subject will show degradation due to the desynchronization of the internal circadian rhythm from the new rhythm of work and sleep. Likewise, westerly travel causes a phase delay in the circadian rhythm and research shows that phase delays take less time for adjustment, about one day per hour of shift, or six days for a six hour time change (Klein and Wegman, 1980; Haus and Halberg, 1980).

The Sleep Reservoir and Homeostatic Sleep Regulation: The control of sleep and its influence on cognitive capacity is a homeostatic process (see [8], [9]). At the core of this process is a sleep reservoir, diagrammed as a rectangle at the center of the diagram in Figure 3. The model simulates the underlying processes that govern the capacity to perform. A fully rested person has a certain performance capacity indicated as the reservoir capacity, R_c. While awake, units of this reservoir are depleted each minute according to a linear performance use function, indicated by the arrow leaving the reservoir. While asleep, units of capacity are added to the reservoir each minute to replenish the reservoir and the capacity to perform and be alert. The rate of accumulation for each minute of sleep is called sleep intensity and is driven by two factors: 1) the circadian variation in sleep propensity, and 2) the current sleep deficit, which is the reservoir capacity R_c , minus the current level of the reservoir at time *t,* R_t. This deficit is constantly changing as one sleeps and replenishes the reservoir, or is awake and depleting the reservoir. The oscillation in the reservoir level is called the sleep-wake cycle and reflects the current reservoir deficit. Note that sleep accumulation does not start immediately upon retiring to sleep. Following an awakening there is a minimal delay of about 5 min required to achieve a restful sleep state. This factor accounts for the penalty during recuperation that is caused by sleep in an environment that leads to frequent interruptions (sleep fragmentation). These components of the sleep accumulation function are indicated as ellipses in the diagram (Figure 3) to the left of the sleep reservoir feeding into the sleep accumulation function. Since the model is a simulation, it can easily accommodate a complex pattern of sleep and waking. While asleep, the simulation adds to the reservoir; while awake the simulation depletes the reservoir. A schedule can oscillate between these states as often as once a minute and the simulation will keep account of the net effects on performance capacity as the balance in the reservoir, like the balance in a check book.

Cognitive Effectiveness: Consistent with the approach proposed by [4] and [2], the **SAFTE™** model stipulates that cognitive effectiveness and alertness are primarily dependent on variations in the two processes just described: the endogenous circadian rhythm (reflected in oral temperature) and current sleep reservoir balance resulting from the sleep-wake cycle, as diagrammed in Figure 4. A third factor, not shown in Figure 4, is the temporary disturbance in performance that often occurs immediately following awakening, called sleep inertia, see [9]. The predictions of the model are normally in terms of changes from cognitive effectiveness, expressed as percent of baseline performance when well rested. This measure corresponds to performance of a standard serial add-subtract task or the average of a range of standard cognitive tests. In addition, the parameters of the performance calculation can be adjusted to predict other components of performance, such as vigilance speed, reaction time, lapses in attention, and target error.

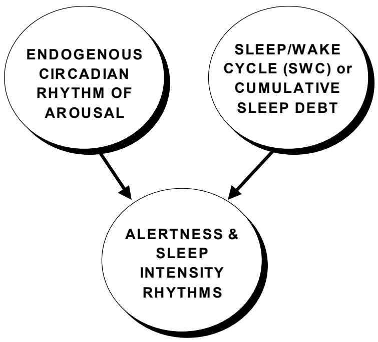

Figure 4: Major drivers of alertness and sleep regulation (after [10]).

Predictions of the Model.

*Performance and Alertnes*s: The average person is assumed to require eight hours of sleep per day to be fully effective and to avoid accumulation of sleep debt. Based on the joint interaction of the endogenous circadian oscillator and the sleep-wake cycle, performance is predicted to have two peaks in percent effectiveness at approximately 1000 hours and 2000 hours, a minor dip in performance at about 1400 hours, and a major trough in effectiveness during the early morning hours when the person is normally asleep. This pattern is shown in Figure 5. The nighttime pattern reveals a major trough in performance at about 0300 hours. The predicted pattern corresponds with the results of [11]. The average alertness scores for a study group of shift workers reflected subjective alertness around the clock without accumulated sleep debt. The pattern of alertness closely parallels the prediction of the model with two peaks in alertness, a mid-afternoon dip in alertness, and a major trough in alertness at 0600 hours.

A number of studies have confirmed the bimodal pattern of performance shown in Figures 5. Lavie [12] reported that traffic accidents in Israel between 1984 and 1989 reveal two peaks in sleep related accidents, a major peak at about 0300 hours, and a minor peak at about 1500 hours in the afternoon. These correspond to the dips in performance predicted by the model in Figure 5. Similarly, Voigt, et al., [13] report acoustical reaction time as a function of time of day and, again, there are two peaks (slowing) of reaction time, a major one at about 0200 hours and a minor one at about 1400 hours. Finally, Folkard and Monk [14] summarized results from industrial settings showing two dips in performance, one at about 0300 hours and a second at about 1400 hours.

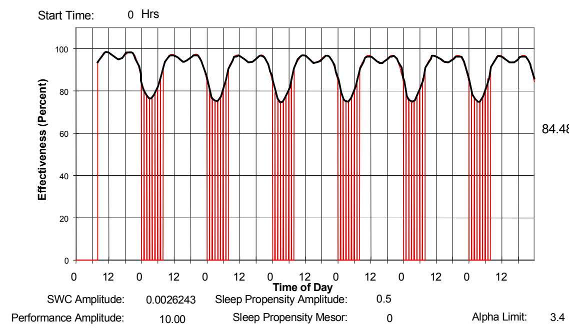

Figure 5: Predicted cognitive effect as a function of time of day (see text).

Sleep Propensity and Sleep Intensity: The intensity of sleep is the sum of two processes, as well [12]. As described earlier, the circadian process produces an oscillation in sleep propensity. This rhythm is the negative of the arousal rhythm and scaled in sleep units. Sleep propensity combines with the current sleep debt resulting from the sleep-wake cycle to generate a prediction of *sleep intensity*. For a person taking a normal 8 hours sleep from midnight to 0800 hours, sleep is most intense in the early morning at about 0300 hours. There is a mid-afternoon increase in sleep propensity at about 1600 hours that coincides with the mid-afternoon dip in alertness and consistent with the observation of increases in sleep related traffic accidents [12].

Equilibrium States: A homeostatic representation of sleep regulation leads to an important implication seldom recognized, even by those proposing a sleep debt responsive exponential sleep process, [3], [15]. If a subject is scheduled to take less than an optimal amount of sleep each night, for example, four hours per day, the reservoir initially loses more units during the awake period than are made up during the sleep period. This results in a sleep debt at the end of the sleep period that accumulates over days. However, since the rate of sleep accumulation increases with sleep debt, eventually, the rate of sleep accumulation increases such that four hours of sleep makes up for twenty hours awake. At this point, the reservoir reaches an equilibrium state and no further debt is accumulated, although the initial deficit remains as long as the person remains on this schedule. By the sixth day of the restricted sleep schedule, cognitive performance oscillates about a stable level well below the baseline level achieved with 8 hours of sleep. Minimum effectiveness is about 64% on the seventh day.

Progressive Sleep Debt under Extreme Schedules: The sleep homeostat is not infinitely elastic; there is a limit to the rate of sleep accumulation (sleep intensity). Any schedule that provides less than 4 hours of sleep per day (for the average person) will not reach an equilibrium state and performance capacity will gradually deplete to zero, although the rate of depletion slows over the first week of restriction as sleep intensity rises to its maximum level. Under a schedule of only 2 hours of sleep per day, minimum performance declines to about 19% on the seventh day.

Sleep Timing: The model is sensitive to the time of day of the sleep period. For an individual given eight hours of sleep per day, starting at 1200 hours (noon) each day, performance reaches a peak of 100 % at the start of each work period (2000 hours); performance then rapidly declines during the late night and early morning hours to a strong dip at about 0500 hours. Minimum predicted performance under this schedule is predicted to be as low as 66% compared to minimum performance under a normal sleep schedule of 86%. This alteration in pattern results from two factors. First, sleep intensity is initially less for sleep periods starting at noon. This results in a small accumulated debt that is quickly offset by the homeostatic sleep mechanism. The second, more persistent effect is the circadian oscillator of performance that reaches its minimum in the early morning hours. This pattern has strong implications for performance under shift schedules that require daytime sleep. It is well documented that most mistakes on the night shift occur during the early morning hours ([16], [17], and [18]) and the model predicts this outcome.

Validation of the SAFTE™ Model

The **SAFTE™** model incorporates a number of improvements compared to the prior models. In general, those changes discussed above were designed to improve conformance with the underlying principles that form the basis of performance predictions. As discussed above, the model includes a realistic representation of the underlying circadian processes, a sophisticated routine governing the intensity of sleep as a function of time of day, and includes consideration of sleep inertia. To validate the model, the predictions of the model for the effects of total sleep deprivation were compared to an independent set of data reported by Angus and Heslegrave [19].

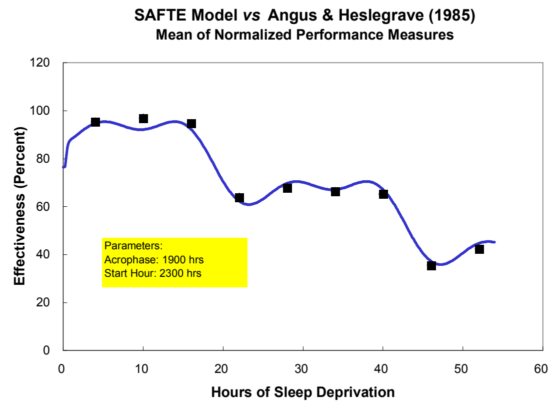

Figure 6: SAFTE™ Model predictions for cognitive performance under total sleep deprivation (solid line) compared to mean normalized cognitive performance (filled squares) reported by Angus & Heslegrave (1985).

Their results were plotted against the predictions of the sleep model and are shown in Figure 6. All parameters within the model were set to the default values with the acrophase (peak of the 24-hr circadian rhythm) and start time as indicated in the legend. The **SAFTE™** Model predictions for the actual data are exceptionally good with an R^2 of 0.98.

Often demanding military and civilian schedules provide less than the optimal eight hours of sleep a day for extended periods of time. These schedules provided chronic restricted amounts of sleep. A recent study of chronic sleep restriction conducted at the Walter Reed Army Institute of Research in cooperation with the Department of Transportation provided data on schedules of seven, five, and three hours of time in bed over seven days [20]. The latest version of the **SAFTE** Model is able to predict both the performance degradation effects and rate of recovery from those schedules with an R^2 of 0.94.

Extrapolations to Performance of Military Tasks.

The sleep and performance model has been optimized to predict changes in cognitive capacity as measured by standard laboratory tests of cognitive performance. It is assumed that these tests measure changes in the fundamental capacity to perform a variety of tasks that rely, more or less, on the cognitive skills of discrimination, reaction time, mental processing, reasoning, and language comprehension and production. However, specific military tasks vary in their reliance on these skills, and deficits in cognitive capacity may not produce identical reductions in the capacity to perform all military tasks. It is reasonable to assume, however, that the changes in military task performance would be correlated with changes in the underlying cognitive capacity. In other words, if one were to plot changes in military task performance as a function of measured changes in cognitive capacity, there would be a monotonic relationship between the two variables. Therefore, if these two sets of data were available from a test population subjected to sleep deprivation, linear (or non-linear) regression techniques could be applied to derive a transform function; this transform translates predicted cognitive changes into changes in military task performance. Based on this reasoning, the model can be extended to predict variations in any task or component of a task (given appropriate test data) using the generalized Task Effectiveness expression.

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