The Role of Sleep Deprivation Research in Human Factors

PAUL NAITOH and RICHARD E. TOWNSEND, Navy Medical Neuropsychiatric Research Unit, San Diego, California, and Department of Psychology, Duke University, Durham, North Carolina.

Sleep loss is a ubiquitous phenomenon that occurs on many long-term field missions. The effects of sleep loss are, in general, detrimental to efficient functioning of man-machine systems. To illustrate the effect of sleep loss on task performance, data from four independent research institutes are reviewed. Data are presented relating to the prevention of sleep loss, and to the detection and minimization of sleep loss effects when they occur.

INTRODUCTION

The purpose of this paper is to review and analyze the effects of sleep loss on task performance during unusual and demanding work-rest schedules so that human engineering efforts can be initiated to minimize, detect, and prevent the occurrence of sleep debt. Such efforts should help avoid degeneration of man-machine dynamics due to sleep loss.

The findings of Alluisi, Chiles, and Smith (1964) indicate clearly the critical nature of work-rest-sleep schedules on performance. They found that the work-rest schedules other than 8 hours on duty and 16 hours off (8:16) we are accustomed to disrupted human efficiency and reliability in task performances. For example, extension of a 6:2 work-rest schedule beyond 96 hours resulted in severe degradation of performance. This performance decrement reflects the effect of sleep loss since the subjects under a 6:2 schedule averaged only 4 hours or less sleep per 24-hour period.

In a different study by Hartman and Cantrell (1967), subjects lived for seven days on a work-rest schedule of 8:16, 4:4, or 4:2. They were then totally deprived of total sleep for three consecutive nights. The dual strain of working under the demanding 4:4 or 4:2 work-rest schedule and being totally deprived of sleep was reflected in greater performance degradation of the 4:4 or 4:2 subjects than of the 8:16 subjects.

During long field missions, the logistics of sleep become more complicated. The crew members tend to enter into unpatterned schedules of work and rest. Such aperiodic work-rest schedules result in sleep disturbances and inevitable sleep loss (Hartman and Cantrell, 1967; Naitoh, 1969a; 1969b). Without duey considering the logistics of sleep, the chances of making the operators of equipment sleepy and less vigilant would be higher, thus nullifying much of the effort expended in optimizing man-machine and life-support systems.

What are the effects of excessive sleepiness due to sleep loss on task performances? To illustrate the various types of performance degradation due to sleep debt, a few results obtained from four independent research institutes are described below.

SLEEP LOSS AND TASK PERFORMANCE

The first experiment on sleep loss to be considered employed a reaction time task and was conducted at Walter Reed Army Institute of Research (Williams, Lubin, and Goodnow, 1959). The subjects sat at a table with two lights before them. A click was given to warn them that in 2 sec, either the right or the left light would come on. The task was to turn off the light as quickly as possible by pressing the corresponding right or left response key. A significant (i.e., p ≤ .05) increase in both mean...
and median reaction times was observed during sleep loss of 78 hr. After 78 hr. of sleep loss, mean reaction time was roughly twice as long as on the last baseline day.

This slow reaction time does not imply that sleep loss slowed down human reaction time gradually over all of the trials. Rather, the sleep debt slowed down some of the responses a great deal without affecting the others. This effect of sleep loss is shown in Figure 1. With sleep debt increasing, the subjects responded on some of the trials (i.e., the ten fastest responses) at the best performance level observed during the baseline period. However, extremely slow responses appeared more frequently as the hours of sleep loss increased. Thus, sleep debt greatly increased the variability of reaction time.

Figure 1. Effect of total sleep loss on reaction time in a two-choice reaction time task, adapted from Williams, et al., 1959.

The prolonged reaction times are called “blocks” or lapses (Williams, et al., 1959). Occasional lapses within a stretch of otherwise normal reaction times were characteristic of total sleep loss effects on performance. Figure 2 shows the results of plotting mean and median reaction times for the two-choice reaction time task.

Visual, auditory, and vibratory vigilance tasks showed the effects of sleep debt on more complex and tedious tasks (Williams, et al., 1959). The visual vigilance task required the subjects to watch a viewer on which single letters of the alphabet were flashed in a random sequence at the rate of one letter per second. The task was to press a response key whenever the letter “X” appeared on the viewer. The auditory vigilance task was similar to the visual task except that the letters were presented aurally through a speaker and the subject pressed the key when he heard the letter “X.” In the vibratory vigilance task, the subject experienced vibrations on various parts of his body. His task was to detect vibrations on his left wrist or right temple and to report his detections by releasing the response key. In these experiments, sleep debt produced a significant increase in the number of errors of omission, i.e., lapses, in all vigilance tasks, indicating that the effects of sleep loss were not specific to a particular sense modality.

To provide additional insight to human engineers who are searching for psychophysiological measures to indicate an extent of sleep debt, a section of a polygraph record taken from an experiment in progress at the Navy Medical Neuropsychiatric Research Unit, San Diego, is shown in Figure 3. This record shows, from the top, two channels of electroencephalograms (EEG), and one channel each of skin potential, heart rate, finger pulse volume,
Figure 3. Auditory-vigilance and continuous-counting task performances and their physiological correlates.
respiration, key press task performance, and click stimulus. This record was taken 4 min. after the beginning of the task, on the last of four baseline days prior to total sleep deprivation. The occipital EEG shows clear alpha rhythm of roughly 10 Hz.

The subject, J. Y., was lying on a bed in a sound-attenuated room, with his eyes closed. He was engaged in an auditory vigilance task. The subject was also instructed to press each of the nine keys on a keyboard assembly, one at a time, in the sequence of 9, 8, 7, and so on down to 1, then repeat, i.e., a task of "continuous counting." In the vigilance task, single stimulus clicks were presented to the subject randomly. One such click presentation can be seen in Figure 3. When the subject detected the click, he pressed the zero key, which produced the maximum upward deflection on the record; then the subject resumed the counting task. The regularity of counting should be noted.

The record shown in Figure 4 was taken from the same subject, 3.5 min. after the start of the same auditory vigilance-continuous counting tasks, but after one night of sleep loss. This particular record does not include a stimulus (or response) for the vigilance task, but it does show considerable deterioration in task performance for continuous counting. The most obvious change seen in this record is a lack of continuous key pressing. There are no key presses during the first 10 sec. of this record. The experimenter aroused the subject at that point, and the subject counted for roughly 6 sec. before the sleep debt overwhelmed him again. Physiological concomitants of these lapses are, as shown in Figure 4, a change in the background EEG in which alpha rhythm disappears and vertex sharp waves begin to appear (for significance of vertex sharp wave in drowsiness, see Rechtschaffen and Kales, 1968), and change in respiration which is shallower and slower.

The continuous counting task is 50 min. in its duration, and three 10-min. blocks (minutes 1-10, 21-30, and 41-50) are analyzed in terms of total minutes spent in counting. In the 30 min. of data analyzed, 12 subjects spent on the average 298 sec. less time in the counting task after one night of sleep loss in comparison with their average baseline day performance. This reduction in amount of time spent in the task of counting is significant with zero-mu t test for correlated means (Winer, 1962). After two nights of sleep loss, the subjects spend on the average 451 sec. less time, compared with their baseline performance, i.e., highly significant reduction in actual work.

Since the late 1950's, R. T. Wilkinson of the Medical Research Council Applied Psychology Research Unit, Cambridge, England, has contributed a great deal of research on sleep loss and its effects on performance (Wilkinson, 1958; 1961; 1964; 1965; 1968a; 1968b). One of his intriguing findings was that the type of task affected the extent of performance degradation due to sleep loss. He found that "sailors kept awake for 60 hours showed decrements in performance which varied from 0 to 93 percent according to the kind of performance test" (Wilkinson, 1968b, p. 163). Unlike other tasks of serial choice reaction, vigilance, card sorting, and rote learning, the subjects could perform a "battle game" for one hour without performance degradation even after 50 hr. of sleep loss (Wilkinson, 1964; 1968b). The "battle game," which the subject liked very much because of the game's realism and meaningfulness, was a complex game of sea battle involving five symbols to represent five naval units of destroyers, submarines, etc.

Studies considered up to this point have dealt with the effects of sleep loss on tasks requiring discrete responses. What would be the effects of sleep loss on a short continuous task performance, e.g., tracking? Pasnau, Naitoh, Stier, and Kollar (1968) reported a study on the effect of sleep loss on unidimensional compensatory manual tracking. The subjects were required to stand in a semidark, quiet room and view a 5-in. oscilloscope. Also visible on the scope face was a spot of light 2 mm. in diameter, which was driven vertically by a sine-wave generator. The subjects were trained to keep the spot of light at the center of the circle by manipulation of a hand-held thumbwheel. With this compensatory movement of the thumbwheel, the oscilloscope showed only the voltage difference between the tracking signal and tracking response, a moment-to-moment...
Figure 4. Auditory-vigilance and continuous-counting task performances after one night's sleep loss.
display of tracking error. The duration of tracking was 1 min. on each of several preselected forcing function frequencies.

The results of tracking before, during, and after total sleep deprivation of up to 171 hr. are shown in Figure 5. At the top of Figure 5, the first channel shows the tracking signal, the second channel the tracking response of the subject, H.H., after total sleep loss of 123 hr., the straight line indicating the absence of a tracking response due to excessive sleepiness. The tracking error associated with this drowsiness is shown on the third channel. The lower section of Figure 5 shows the tracking errors only of four subjects, from left to right, R.S., H.H., D.G., and J.L. The frequency of the tracking signals used is shown at the top of each individual record, i.e., 0.2 Hz or 0.3 Hz. The hours of total sleep deprivation are indicated at the beginning of the error records.

The results show surprisingly good tracking until sleep loss reaches 99 hr. or more. Tracking became impossible to perform beyond 171 hr. due to excessive sleepiness. Tracking errors after one recovery night sleep of roughly 10 hr., and after two recovery nights, representing 10 and 8 hr., respectively, of sleep duration, are shown in R1 and R2 respectively.

The above review should be sufficient to convince human engineers of the importance of preventing sleep loss in extended field missions. Since sleep loss and sleep disturbances appear to be inevitable in many field missions, however, the obvious question facing human factors engineers concerned with man-machine dynamics would be: What can be done to insure a planned smooth man-machine interaction, despite sleep debt?

The situation is summarized in Table 1. In brief, the human factors engineer can work to
detect sleep loss and take appropriate actions to prevent it, but at the same time he should consider means of minimizing the effects on job performance when sleep loss occurs.

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<td>1. Human-factored habitat (especially berthing area)</td>
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DETECTION OF SLEEP LOSS

Detection of sleep debt has been difficult, because total sleep loss of less than two consecutive nights may not affect crew members' behavior appreciably. The first author of this paper examined a variety of electroencephalographic (EEG), autonomic, biochemical, and behavioral variables in his attempt to determine the effects of total sleep loss, and concluded that the best sleep debt indicator would be the quantity of EEG alpha wave (8-12-Hz, activity) after eye closure with mind kept "blank" (Naitoh, Kales, Kollar, Smith and Jacobson, 1969).

Figure 6 illustrates the effect of sleep loss on EEG measured at different times of day (from Naitoh, et al., 1969). The fitted curves were computed with an IBM 360/75, using a BMD 05R program for orthogonal polynomials. These data suggest a predominantly linear decrease in EEG alpha time as the hours of total sleep loss accumulate, especially when EEG samples are taken at 3 A.M.

Closure of eyes usually results in the appearance of alpha waves in human subjects, and its absence, relative to the individual's normal EEG, may be considered to reflect the extent of sleep debt (Armington and Mitnick, 1959; Bjerner, 1949; Malmo and Surwillo, 1960; Williams, et al., 1959). For those individuals who have low or no alpha waves, the use of a task of two-step addition (Williams and Lubin, 1967) would be recommended.

To detect a very small sleep debt of less than one night, a more extensive behavioral task session is required. Wilkinson (1968a) gave his subjects continuous addition and auditory vigilance tasks in alternate hours from 7:45 A.M. to 10:35 P.M., with usual break periods for meals, to detect reliably the effects of small sleep loss.

PREVENTION OF SLEEP LOSS

Techniques to obtain good sleep in exotic and hostile environments are not sufficiently developed to offer any definitive clues in setting up the physical and psychological conditions surrounding human sleep, e.g., psychological conditions which would be conducive to quick sleep onset, or features of sleeping quarters optimal for good sleep.

Kleitman (1963) pointed out, in his book containing 4,337 references on sleep, that questions concerning beds, bedding, and bedroom conditions are constantly being asked and very few of them can be answered adequately. In this context, no basic progress has been made since then, and only a few tentative suggestions can be offered.

1. Certain types of activity just before bedtime are undesirable for obtaining good sleep. Baekland, Foulkes, and Lasky (1968) showed that viewing a psychologically stressful movie produced more frequent REM-associated awakenings during sleep period. The term REM refers to those stages of sleep involving rapid eye movements, usually equated with a dreaming sleep.
2. The bedcovers and adequate night attire are important factors in controlling the thermal environment and insuring a good sleep. Hellmuth and Dever recorded, according to Kleitman (1963), thigh skin temperature, bed temperature, and movements of the sleepers, and found the level of skin temperature to have little influence on motility (a sign of poor sleep), provided the difference between the bed and skin temperature was not too small. The difference usually amounted to 4-5°C, but if it decreased to 1°C or less, movements increased. On the other hand, too great a difference between these two temperatures prevented early onset of sleep. The importance of thermal comfort for sleep, which has remained undetermined as yet, is well recognized (Hamilton, MacInnis, Noble, and Schreiner, 1966).

3. Other factors, such as sleeping-quarter ventilation, humidity, noise, and illumination have been subjectively known to affect quantity and quality of sleep, but no definitive studies have been conducted to confirm our “common” knowledge.

Other ways of assuring good sleep, aside from construction of suitable sleeping quarters, are (1) through adequate planning of the work-rest cycle, (2) through an electronic device (“sleep machine,” e.g., that described in Achten, Kauko, and Sepälä, 1968), (3) through sleep-inducing drugs, and (4) through training to achieve quick sleep onset. The uses of electro-sleep induction and drugs hold a great deal of promise in sleep logistics.

MINIMIZATION OF SLEEP LOSS EFFECTS

Six parameters of task structure have been confirmed experimentally to aid in minimizing the effects of sleep debt.
1. The duration of the task performance must be short. For example, performance on a continuous visual task lasting two min. will be significantly affected by sleep loss of approximately 70 hr., but the very same task extended to three min. will be detrimentally affected by only 50 hr. of sleep loss (Williams, et al., 1959). Longer task duration means increased susceptibility to sleep loss effect.

2. The task must provide knowledge of results. Wilkinson (1961) found that providing knowledge of results in a 30-min.-long, five-choice test of serial reaction overcame performance decrement produced by 30 hr. of total sleep loss.

3. The work load of the task must be well within the capability of the crew members. The work load may be defined in terms of speed and cognitive and information loading. In general, a task that requires a higher work load is influenced more by sleep loss than a low-work-load task. Williams and Lubin (1967) confirmed the effect of speed loading. They discovered that mental addition at a rate of one addition per 2 seconds did not show effects of two nights of sleep loss, but by increasing the speed to one addition every 1.25 sec., a 38% speed increase, a detrimental effect of two nights of sleep loss was detected.

In the same paper, they reported that a task which had high cognitive loading was very sensitive to sleep loss. The task consisted of mental addition of a pair of digits presented aurally. To increase the cognitive load, the subjects were instructed to add the quantity 8 to each sum just obtained, hence, a “plus-8” task. This two-step addition was so sensitive to sleep debt that a significant increase in processing time was observed after one night's sleep loss.

Another study already cited (Williams, et al., 1959), using a different test, confirmed that increased information load made a task more vulnerable to total sleep loss. The “Pentagon task” consisted of a display panel of five different colored lights, arranged in a pentagon configuration. The subject was instructed to press the response key each time a red light flashed on, and to refrain from pressing for all other colored lights. The rate of light presentation was 1.0 per sec., with 30 lights being grouped as one set of the test. Eight of the 30 light presentations were red signal lights.

Three separate modes of signal presentations were used. In the redundant mode of the pentagon task, the red light was presented 8 times in succession within the 30 light presentations. In the standard mode, the 8 red lights appeared in a fixed sequence mixed with the 22 other colored lights. After practice, the standard-task signal sequence could be learned with some accuracy. In the uncertain mode of the task, the red signal lights were programmed to appear in a completely random fashion. Thus, the standard task contained more information than the redundant task, and the uncertain task contained more information than either of the other tasks. With the increased information loading, sleep loss caused the uncertain task to have the largest percentage of errors of omission after two nights of sleep loss.

4. The task must be self-paced. An example of a self-paced task is the five-choice test of serial reaction. One version of the task consisted of a stimulus panel which had five light disks arranged like a pentagon. During the task performance, one of the five lights was lighted, and the subject's response was to tap with a special stylus the corresponding disk in a similarly arranged response panel. As soon as the subject responded, that light was extinguished and another light in the stimulus pentagon was lighted. No restriction on speed in responding was imposed, and it was up to the subject as to how rapidly he performed the task.

An example of a work-paced task is an auditory vigilance task. The task could be simply to detect the occurrence of a shorter burst of tone amid frequently appearing tone bursts of standard length. Although the mechanism involved in determining the pace of a self-paced task is not known, the self-paced task can withstand sleep loss substantially better than the work-paced tasks (Naitoh, 1969a; Wilkinson, 1965).

5. The task must avoid any extensive use of short-term memory. Williams, et al., (1959), and Williams and Lubin (1967), reported that total sleep loss introduced impairments in short-term memory by its interference with memory trace formation and its storage.
6. The task must be simple. Complex tasks are affected more by sleep loss, provided that the subject's interest does not increase as a result of handling the complex and probably more interesting task (Naitoh, 1969a; Wilkinson, 1965).

Minimization of sleep loss effects on performance can be achieved by restructuring the task, according to the above six guidelines. There are, however, nontask factors in achieving the minimization of sleep loss effects, which are at least as important as adequate structuring of the tasks to be resistant to sleep loss. For example, a carefully structured sleep-loss-resistant task could turn out to be ineffective in combating sleep loss impairment on performance, because the task was so uninteresting that the subject performed it with poor motivation.

Nontask factors include the interest value of the task, motivation of the subjects, and behavioral periodicity. Some solutions for obtaining the optimal nontask factors might be found in the miniature society formed by the members of a work crew. The miniature society could select crew members who found their given tasks to have higher interest, and therefore be highly motivated to perform. Similarly, the miniature society could determine the time of the day at which its individual members function best, so as to capitalize on human behavioral periodicity.

The performance recovery value of naps has been reported in subjective terms; objective data to support such reports is lacking. Naps could not replace the need for a program of regular uninterrupted sleep, as man takes a certain finite time to become fully awake from naps, and nap inertia could lead to human errors in performance. The intake of certain drugs, e.g., dextroamphetamine (Kornetsky, Mirsky, Kessler, and Dorff, 1959), reduces the effects of total sleep loss on performance. Such drugs, however, may have undesirable side-effects which could influence task performance.

SUMMARY AND CONCLUSIONS

Sleep disturbances and sleep loss are an inevitable consequence of living in unfamiliar and hostile environments for an extended period of time. Problems of sleep logistics have been extensively studied under laboratory conditions. The results from four independent research institutes (the Walter Reed Army Institute of Research; the Department of Psychiatry, the University of California, Los Angeles; the Medical Research Council Applied Psychology Unit, Cambridge, England; and the U.S. Navy Medical Neuropsychiatric Research Unit, San Diego) have been reviewed to summarize the effects of sleep disturbances and sleep loss on task performance.

The summarized research confirms the importance of preventing sleep loss in order to sustain a smooth man-machine interaction. Under circumstances where man cannot avoid incurring sleep loss, then it is important to minimize the effects of sleep debt. A few techniques are available for minimizing the effects of sleep loss on performance: tasks can be restructured, and behavioral periodicity and naps can be utilized. Detection and prevention of sleep difficulties are equally desirable.

This review indicates a continuing need for human engineering research to define sleep requirements, and to assure that adequate conditions of sleep can be maintained for men who must work in unfamiliar and hostile environments. Continuing research on sleep and sleep debt should be conducted to enable men to interact with their machines in a more complex manner and for longer periods of time. Such intensive man-machine interaction will be needed in man's future efforts to cope with his extended living space.

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