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A STUDY OF RECOVERY FUNCTIONS IN MAN

William Harris
James F. O'Hanlon

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William Harris[1]
James F. O'Hanlon[1]

April 1972

APPROVED: John D. Weisz
JOHN D. WEISZ
Director
Human Engineering Laboratory

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[1] Human Factors Research, Inc., 6780 Cortona Drive, Goleta, California

HUMAN ENGINEERING LABORATORY
U. S. Army Aberdeen Research & Development Center
Aberdeen Proving Ground, Maryland

ABSTRACT

Concepts of sustained and continuous military operations were examined with respect to relevant literature. In particular, the objectives were to predict behavioral and biological impairments which might result in those operations; and to determine whether the period necessary for recovery following a sustained operation can be ascertained from the literature. It was concluded that those objectives could not be met due to inadequate information. Nonetheless, the literature did provide data which suggest that certain severe impairments may be experienced by soldiers engaging in sustained and continuous operations. It also provided guidelines for the design of studies to collect the required information. Finally, this review led to a call for serious reevaluation of the current concepts of continuous operations.

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INTRODUCTION

The military commander faces many problems in the field. Perhaps the most important one is how to maintain a relatively constant level of performance effectiveness with the forces at his disposal. If the commander is to solve this problem, he must know, at least, how long men can effectively perform given tasks under various field conditions. In earlier times, the commander's primary concern was with maintaining effectiveness during daylight hours. Most battles were fought during the day, and most other field activities were done in daylight. The dark hours were "reserved" for rest, regrouping, and preparations for daylight peak activities. The development of new weapons and sensors, particularly night-viewing devices, may introduce new requirements. With the aid of new devices, men may be able to perform some tasks at night that before could only be performed effectively in daylight. The commander of the future may have the problem of maintaining performance effectiveness around-the-clock, at all hours of the day and night.

If equipment can provide the *capability* for men to perform effectively night and day, why not take advantage of this and maintain an effective 24-hour fighting force? In response to this question, a concept of "continuous" operations, as contrasted to "sustained" operations, has been proposed by the Army (e.g., Marks, 1969). The concept of continuous operations implies that the performance of a field unit be maintained at a constant level of effectiveness not only over a 24-hour day but for many days on end. In the past, military units have often engaged in sustained operations: 48 hours, 72 hours, or even longer periods of continual or nearly continual fighting and related activities without relief. But these operations generally were not planned; battlefield circumstances or the need to achieve limited objectives forced the sustained activities. Continuous operations, though, would be the result of command decisions. If continuous operations are to be implemented, the command decisions must take into account not only the capability of equipment but the *ability* of men to perform effectively for prolonged periods under field conditions.

Marks (1969), in a discussion of human factors and continuous operations, offered a definition of unit endurance:

> The length of time (hours, days, weeks) a unit can perform its primary mission effectively before it must be relieved, plus the length of time it must rest before it is operationally ready for commitment again. (p. 132)

Marks adds that the same definition may be applied to the individual soldier performing a particular task. The endurance definition may be stated as a question which the military commander must answer if he is to optimize the use of limited resources: how long can a man maintain effective performance before he must be relieved (before his performance degrades to an unacceptable level), and how long a recovery period does he need before he is again ready to perform effectively? The answers to this question must take into account several factors: the conditions of task performance, the task being performed, the characteristics of the performer, the conditions of rest, the physiological "cost" of maintaining effective performance, and the cumulative effect of successive periods of performance.

The main purpose of this review was to find out what is known about the recovery of men from the effects of exposure to certain adverse conditions. Is there information in the literature that will enable the prediction of the course of recovery in men after exposure to the adverse conditions likely to be encountered in continuous or sustained field operations? Is there information that will enable the prediction of operational performance following given recovery periods? If not, what needs to be known about recovery functions in men to determine if the concept of continuous operations is feasible? These were the questions that guided the literature review reported here.

PROBLEM STATEMENT

There is an extensive literature about the effects of exposure to adverse conditions, or various stressors, for relatively short periods of time on man's performance, behavior, and physiology. There is a smaller literature about the effects on man of exposure to adverse conditions for relatively long periods of time. There is very little literature on the recovery of man from the effects of either short or long periods of exposure to adverse conditions. There is nearly no literature on the possible *cumulative* effects of repeated exposures to adverse conditions. The lack of a significant, *directly* relevant literature on recovery functions required the consideration of *possibly* relevant literature.

The term "recovery" implies that some degradation has occurred. The performance, behavior, or bodily functions of man, and perhaps his motivation to continue, may degrade as a result of prolonged exposure to adverse conditions. The military is primarily interested in man's performance. If a man can perform effectively in the face of adversity then, in terms of military requirements, he is functioning adequately. But a man may maintain effective performance only at considerable cost to other bodily systems, as determined by the expenditure of energy, the depletion of "resources," or by the strain imposed on some physiological system. If the cost is not paid, in rest time to restore a depleted or strained system, there may be catastrophic failure in the system, and the man may be unable to perform effectively, if at all. The military commander must face this possibility in considering whether or not he can still maintain an effective force by requiring men, already exposed for a long period, perhaps near the limits of their endurance, to endure a "few hours more."

Any study of recovery functions must consider the conditions of exposure and their effects on specific bodily systems: Which system has degraded? What is the level of degradation? How long does it take to restore the system to a normal level of functioning? What is the interrelation of bodily systems in maintaining organismic integrity?

Some answers to the first two questions, what has degraded and how much, can perhaps be inferred from the literature on the effects of prolonged exposure to adverse conditions. Studies in the following areas are relevant:

1. Sleep deprivation.
2. Work/rest schedules.
3. Prolonged physical work.
4. Circadian rhythm disruption and temporal displacement.
5. Environmental stress brought on by:
    a. Temperature and humidity.
    b. Altitude and weather.
    c. Confinement and isolation.
    d. Vibration and noise.
    e. Nutritional and water or electrolyte deficiencies.
6. Situational stress such as:
    a. Threat of injury or death.
    b. Command responsibility.

No attempt has been made here to review in detail the literature in all the above areas. Much of that has already been done by other investigators. Rather, an attempt has been made to identify the types of performance and physiological processes that degrade under different conditions and to determine the levels of degradation.

Perhaps a unifying, though oversimplified, concept to relate studies from various areas would be one of "fatigue." If a man works for a long period of time, even under benign conditions, he becomes "physically" fatigued; if he performs a non-physically demanding rote task or monitors a display on which signals appear infrequently, he may become "mentally" fatigued. In both cases, a usually reversible deterioration in performance or in a physiological system occurs which can only be restored by rest. If the man performs under conditions other than benign, the onset of fatigue may be hastened. The presence of environmental and situational stressors, unusual work/rest schedules, or disruptions in circadian rhythms may be thought of as affecting both the rate and ultimate level of fatigue in performance and physiological systems, or the rate and level of their degradation. The rate of recovery of a degraded system function will likely be a function of the rate and level of degradation, though not likely a simple linear function. The intensity and duration of exposure to adverse conditions and the corresponding "fatigue" of systems must be considered in a determination of recovery functions.

The observation of physiological systems in determining both the effects of exposure to adverse conditions and the course of recovery from them is critical. We have already noted that performance may be maintained at some cost to the integrity of various physiological systems. Physiology may be altered to "compensate" for the presence of adverse or threatening stimuli. Teichner (1968), in a discussion of behavioral and physiological reactions to stress, states the case well:

> Stressor-stress reaction associations are difficult to demonstrate, however, without specific consideration of the compensatory action of the regulating systems. For example, the rectal temperatures of men exposed to air temperatures of 100°F may show

> little or no increase. A naive investigator observing only rectal temperature might be tempted to conclude that 100°F is not a stressor. In fact, at this temperature, he could find an increased sweat rate, a raised skin temperature, an increased peripheral blood flow, and a decreased metabolic rate, all of which represent compensatory activities of the thermoregulatory system. Rectal temperature is a *controlled* event; compensatory responses are *controlling* events. It is the controlling event which first exceeds normal limits of variation given a stressor. When the controlled variable exceeds its normal range of fluctuation, the compensatory processes are failing in control, but this may not happen short of severe exposure to the stressor. In other words, one level of stress reaction is present when the compensatory events exceed their normal limits; a more intense level is present when the controlled events exceed their normal limits. For this reason, it cannot be emphasized too strongly that the investigation of stress phenomena must put emphasis on measurement of the activities of controlling or compensatory processes for, except under relatively severe conditions, the variables which they control change very little. (p. 272)

Teichner's distinction between *controlled* and *controlling* events is especially pertinent. Performances are certainly controlled events. One would expect that performance would usually be less susceptible to adverse conditions than compensatory physiological responses and also recover most rapidly if degradation does occur. The rapidity of performance recovery has been shown in one of the few studies of the effects of battlefield conditions. During the Korean War, Pace *et al.* (1956) studied the psychological and physiological reactions of two groups of soldiers following an 18-hour intense attack period and a 5-day sustained defensive period. There was no difference between the two groups and an unexposed control group on any of several tests of psychological processes. If performance had degraded during the exposure periods, it had recovered rapidly. However, marked differences between the groups were noted in the recovery rate of several physiological responses (described in a later section).

Performance on many tasks, notably monitoring and short-term memory tasks, will degrade under adverse conditions. Performance on other tasks, notably task paced or heavy physical labor tasks, will degrade simply from continued performance, or task fatigue. Performance on all tasks will degrade if the conditions of performance are severe enough or the period of performance is prolonged enough. But performance is still a controlled process. When performance is degraded, some changes must have occurred in controlling processes. The immediate controlling processes for performance mainly occur in the central nervous system (CNS). But the functioning of the CNS surely depends upon controlling processes in still other physiological systems, such as the cardiovascular, endocrine, and other systems responsible for whole-body metabolism. Changes in the controlling processes of these systems have not only occurred when performance degradation is observed, but have probably occurred long before. Compensatory mechanisms have been set in motion to maintain performance; performance degradation probably signifies a breakdown in the compensatory capacity of some physiological system.

If changes in the controlling physiological processes occur before changes in performance, then knowledge of these processes and the conditions that affect them may be used to predict performance degradation and to determine the recovery needs for the systems. The main emphasis in this review has been to bring together what is known about physiological system responses to adverse conditions and the recovery of normal system functioning.

In most studies of the effects on men of adverse conditions, recovery functions have not been observed even when marked changes in performance or physiology have occurred. The investigators' main interest has been in the effects of diverse conditions. Because these studies, in most cases, have been "one-shot" affairs, the recovery of men from any effects that may have occurred have not been of much concern. Men do recover, and it is not likely they would again be exposed to the adverse conditions. In most studies of sleep deprivation, though, recovery functions have been observed. But these studies also have been, typically, "one-shot": men have been observed under wakefulness conditions from one to several days and under normal sleep conditions for a few days following the deprivation period. In no cases have men been observed on the repeated deprivation/recovery cycles that might be of interest in determining the feasibility of continuous operations.

The literature on the possible cumulative effects of repeated exposures to adverse conditions is practically nonexistent. The problem and its relevance to military operations has long been recognized. For example, in an early review of performance under stress, Harris *et al.* (1956) made the following comment:

> The effect upon performance of successive stress exposures, therefore, needs study. For example, how many successive exposures can an individual or a group tolerate and still maintain effective performance? And, what is the optimum rest period between successive exposures? (p. 52)

The importance of determining the cumulative effects of repeated exposure periods in evaluating the concept of continuous operations, or, for that matter, sustained operations, cannot be overemphasized. That there are cumulative effects seems certain. The anecdotal literature is full of examples suggesting that stress effects in men "build-up" as a result of frequent exposures. The psychiatric casualties of our several wars bear testimony that in some men, at least, the effects of repeated exposures to adverse conditions build to a breaking point (e.g., Grinker and Spiegel, 1945). Often the breakdown has occurred suddenly, with no prior signs in the man's performance or behavior. Often the cumulative effects seem irreversible, leaving a lasting impression on the man.

When recovery does occur, the time period is likely to be very long, and the man may not be able to return to the precipitating situation again. Less severe cumulative effects have been observed in other situations. Men working long hours without adequate rest have shown what is called "cumulative fatigue" (e.g., Cantrell *et al.*, 1970). The men feel tired all the time, and the feeling may be reflected in their performance and in their motivation to perform. In a study of successive prolonged flights of 20-35 hours, Hale *et al.* (1968) showed that crew members who had two days rest between flights were in a chronic state of stress, as defined by physiological measurements, throughout the period of the successive missions (described in more detail later).

The major questions in evaluating the concept of continuous operations--how long can man perform and how long must he rest--cannot be answered without considering the cumulative effects of successive performance/rest cycles. Suppose an implementation of continuous operations were to keep men in the field for 24 hours and permit them 24 hours rest for an indefinite number of cycles. A man may be able to perform under this regime for some time without apparent loss of performance effectiveness. But he may be incurring a small cost on each successive cycle to maintain effective performance; his physiological systems may function outside normal ranges to compensate for the unusual regime. If the rest periods are not sufficient to restore normal functioning, the effects of the performance periods may cumulate. Eventually, the cost may become so great that compensatory mechanisms fail and performance effectiveness cannot be maintained. And if this occurs, the recovery period required to restore the man to normal functioning may be very long. The "advantage" that this particular continuous operation had may have been illusory, in that the result may be a "depleted" force that cannot be committed soon again.

The concept of continuous operations implies more than one schedule of performance and recovery. There is the overall schedule, as in the preceding example, where men are in the field for a period of performance and withdrawn for a recovery period. And there is the schedule in the field, where men have work periods and rest periods. The evidence from the literature, and common sense suggests it is unlikely that men can perform continually on any task for as long as 24 hours and maintain performance effectiveness, and particularly on those tasks that require heavy work or vigilance performance. Let us call the first schedule the performance/recovery schedule; and the second, the work/rest schedule.

How man endures a field performance period and how much of a recovery period he needs surely depends on his work/rest schedule in the field and, of course, on the conditions of his rest. It is not always possible to have fixed work/rest schedules in the field, but there will necessarily be rest periods if men are to continue functioning over long periods of time. When it is possible to have fixed work/rest schedules, these should be set to meet the requirements of not only the performance periods in the field but the overall performance/recovery schedules as well.

The considerations expressed above have provided the guidelines for the literature review reported here. It is necessarily a highly selective review, with the emphasis on those studies in which recovery functions have been observed and on those judged to be the most relevant to continuous operations.

PERFORMANCE DEGRADATION AND RECOVERY

In most studies of the effects on performance of prolonged exposure to adverse conditions, performance has been observed on abstract or synthetic laboratory tasks. Few studies have observed performance on operational tasks. Even when studies have been conducted under field conditions, operational performance may not be observed. In the Hale *et al.* (1968) study of prolonged flight stress, aircrew performance during the flights was not observed, providing no evidence for a possible degradation in performance corresponding to the degradation of physiological systems. In the Pace *et al.* (1956) study of battlefield conditions, operational performance was not observed, but rather performance on abstract psychological tests. There is no taxonomy of the performance required in military tasks that might be used to relate the results of studies of performance or abstract or synthetic tasks to military operations. Even if there were such a taxonomy, the different conditions of performance likely preclude any generalizations from the laboratory to the operational task. The application of the results of laboratory studies to operational military situations should be done with caution.

Two successive studies of the effects on performance of sustained operations by the same group of investigators illustrate the difficulty of generalizing from the laboratory to the field. In the first study (Drucker *et al.*, 1969), tank crewmen performed a simulated driving task and a filmed target detection task under laboratory conditions over a 48-hour period. Some groups of crewmen were given 15-minute breaks every 1.5 hours and a 1-hour meal break every 6 hours, a total of about 12 hours' rest. A control group of crewmen had a similar work and break schedule but had a 5-hour sleep period on each of the 2 days, a total of about 21 hours' rest and sleep. The results showed that sleep-deprived crewmen performed significantly poorer on the driving task than the control group. Sleep-deprived performance was also poorer in the target detection task, though not significantly so. The performance decrements were more pronounced at night for the sleep-deprived group, particularly on the second night. But it was pointed out that it was difficult to keep crewmen awake on the second night.

In the second study (Haggard, 1969), experimental tank crewmen performed a 48-hour continuous field exercise, with no provisions for rest or sleep. Control crewmen performed the exercise on a 12/24 work/rest schedule. Performance tests were developed for the study on gunnery, surveillance, communications, driving, and maintenance, and were administered at 12-hour intervals to the crewmen. The results of the field test did not confirm the results of the simulation test. There were some differences between the experimental and control groups on the driving and surveillance tasks, but there were no performance decrements that could be attributed to fatigue as a result of the continuous exercise. The author concluded "...it would appear that the usual laboratory situation requiring continuous performance of a single task does not sufficiently duplicate the job situation where many tasks must be performed, any one of which occurs only periodically. Thus, we might well question the continuing use of standard tasks in present laboratory situations to predict job performance in real life situations." (pp. 8-9)

In a third study by different investigators (Banks *et al.*, 1970), soldiers were tested intermittently during 44 hours of "continuous" operations and on a recovery day following 24 hours' rest. Performance tasks included target detection with night vision devices, live rifle fire, and grenade tossing. There was no difference in performance on any of the tests between the first and second day of the operation (the "recovery" day data were not analyzed). The authors concluded "When properly motivated, soldiers can perform at a stable level with no loss in efficiency on important combat-related tasks during a 44-hour period of continuous military operations" (p. 7).

These three studies provide little information that may be used to evaluate the concept of continuous operations--partly because of the lack of control of sleeping in experimental subjects, partly because of testing procedures used, but mainly because they were single-exposure studies.

Studies of the effects on performance of sleep deprivation have usually included observations during a recovery period. The typical result has been that if performance decrements occur during the deprivation period, they recover to predeprivation levels after one or two days of normal sleep and rest. For example, Williams *et al.* (1959) in two studies of the effects of sleep loss for 74 and 98 hours found that mean visual reaction time became progressively longer over the deprivation period but recovery was complete on the first day after a normal sleep. These studies also illustrate another common finding of sleep deprivation studies: on an addition task, the number of items attempted decreased over the deprivation period (and increased on the first recovery day) but the percentage correct was unchanged. Sleep loss seems to affect the amount of work performed on subject-paced tasks but not necessarily the accuracy of performance. By contrast, the same studies showed that the accuracy of performance on experimenter-paced visual vigilance tasks was progressively impaired over the deprivation period, but again restored on the first recovery day.

Wilkinson (1964), in a series of studies of the effects of up to 60 hours of sleep deprivation, identified the characteristics of tasks sensitive to sleep loss. He observed performances on a serial choice reaction task, a card-sorting task, a rote learning task (a serial list of numbers), and on two complex decision-making tasks, among others. The results showed performance impairment on the choice reaction and vigilance tasks, no impairment on the rote learning task, and some improvement on the decision-making tasks. Wilkinson concluded that tasks are sensitive to sleep deprivation if they are complex or "lacking in interest, incentive, or reward." He also concluded that decision-making processes were resistant to the effects of sleep deprivation, if incentive to perform were high. His decision tasks were game-like, though; performance on them are likely unrelated to operational decision performance.

There have been many reviews of the effects of sleep deprivation on performance (e.g., Naitoh and Townsend, 1970). The consistent findings have been that performance becomes more variable as deprivation continues and that if deprivation is continued long enough, obviously, performance on any task will degrade. Our difficulty in generalizing from the results of laboratory studies of sleep deprivation is that task performances have typically been observed for relatively short periods at different times of deprivation, rather than continuously.

Sleep deprivation studies have generally ignored certain variations in men. Usually the subjects are "young, healthy males." This is also true of most prolonged stress studies. For example, there have been practically no studies of the relationship between age and the effects of sleep deprivation or of exposure to adverse conditions. There is a general recognition that older men tire more quickly than young men, are less able to endure severe stresses, and recuperate more slowly. There is some evidence to support these notions in studies of work fatigue (e.g., Cantrell *et al.*, 1968; Anonymous, 1969).

Fröberg *et al.* (1970a, b), in a study of the effects on performance and physiology of 75 hours of sleep deprivation, observed a group of junior officers and corporals (mean age 29), and a group of senior officers (mean age 56). Performance was observed on an electronic firing range task. The young group performed the task continually over the 75-hour period, except for 15-minute breaks about every 3 hours. The older group alternately performed the firing task and a "number of intellectual tasks" for about 3 hours each, with 15-minute breaks between continuous performance sessions. The performance measures on the firing tasks were the total number of shots fired during the 3-hour period and the number of hits. The results in the firing task showed that the younger group fired many more shots than the older group during corresponding periods on the range. The number of shots fired by the younger group decreased significantly over the deprivation period; the number of shots by the older group remained relatively constant. The number of hits by the younger group decreased significantly from 47% to 26%; the older group decreased slightly, from 28% to 23%. The two groups were very close in accuracy of firing on the third day of sleep deprivation. It seems as though the older men paced themselves over the deprivation period; they worked at about the same rate and maintained about the same level of performance. The younger men were initially much harder workers and better performers, but could not maintain either performance level.

Measurements of two physiological variables whose values usually increase during stress tended to confirm the pacing notion. The measures were the plasma protein bound iodine concentration (PBI, an index of thyroid hormone concentration) and the erythrocyte sedimentation rate (ESR). At the start of the deprivation period, the older men were less fit, probably because of aging, than the younger men, as shown by the PBI and ESR measures. After 75 hours of deprivation, the older men's PBI and ESR had increased by 19% and 38%, respectively; the younger men's increased by 30% and 168%, respectively. The final average PBI and ESR levels of the two groups were very close. If the task had been experimenter paced rather than subject paced, the results likely would have been different.

The older men might not have been able to conserve their resources by pacing their energy expenditure. No recovery-period observations were made in this study.

There has been little work on the effects of chronic or partial sleep loss, a condition which seems more likely than prolonged total sleep loss in continuous operations. Webb and Agnew (1965) restricted subjects to three hours' sleep a day over an eight-day period. They found that performance on an experimenter-paced addition task and on auditory and visual vigilance tasks began to deteriorate on nights 7 and 8. But the decrements observed were "neither uniform nor fully consistent." They did observe marked differences in the percentages of the various stages of sleep between a full-night sleep period and the three-hour period: the percentage of Stage 1 (REM) sleep decreased significantly for the three-hour period; Stage 2 sleep decreased somewhat; Stage 3 sleep was unchanged; and the percentage of Stage 4 sleep increased significantly. Perhaps these results indicate a cost of reduced sleep that may eventually seriously affect performance. One night's full sleep restored all measures to base-line values.

There have been a number of studies of the effects on performance of work/rest schedules maintained for relatively long periods of time. In a series of studies reported by Alluisi (1963) and Chiles (1968), relatively continuous performance during work periods was observed on several different work schedules. Subjects performed the following tasks on a synthetic task console: auditory vigilance (non-occurrence of a beeping tone), visual vigilance (warning-lights and probability monitoring of a dial display), arithmetic computation, code-lock solving (a team task), and target identification. Pulse rate and axillary temperature were observed in some studies.

The results of a study of performance on four equal ratio schedules, 2/2, 4/4, 6/6, and 8/8, over a 96-hour period, showed no significant differences in performance by the schedules.

"Adequate" performance was maintained on each schedule. Subjects expressed a preference for the 2/2 and 4/4 schedules, possibly because the work periods were shorter.

A study of 4/2 and 6/2 schedules over 96 hours also showed no difference in performance between the schedules. But interviews with subjects "suggested that severe decrements in performance would probably have resulted from prolongation of the 6/2 schedule beyond the 96 hours." Subjects on the 6/2 schedule averaged less than 4 hours' sleep a night; those on the 4/2 schedule, 5½ or more hours a night. The authors concluded "four hours of sleep are considered to be inadequate over prolonged periods of time."

Air Force subjects were studied under confinement conditions on 4/2 schedules over 15-day periods. In one study (designated OPN-360), subjects showed marked diurnal variation in the performance of all tasks, peak performance in the early evening hours and poorer performance in the early morning hours, and corresponding diurnal variation in the pulse rate and axillary temperature measures. In another study (designated Hope II), subjects showed diurnal variation only on the arithmetic task, but also showed variation on the physiological measures. The age range of subjects of the OPN-360 study was 26 to 43 years; of the Hope II study, 19 to 22 years. The authors suggested that the differences observed in performance, however, were due to the higher motivation level of the Hope II subjects.

Air Force subjects also were observed on a 4/4 schedule over 30 days of confinement (designated Hope III). Significant diurnal variations were observed on all performance tasks, except the probability-monitoring and warning-lights tasks. Significant diurnal variation was observed on the physiological measures. The authors attributed the difference observed between the Hope II and Hope III subjects in diurnal variations of performance partly to different instructions given the two groups regarding the avoidance of diurnal effects.

The Hope III subjects performed significantly better than the Hope II subjects on all tasks, except the arithmetic task. The performance of the Hope III subjects showed no decrement over a 30-day period; performance of the Hope II subjects did show decrements over the 15-day period. The authors concluded that the 4/2 schedule was more demanding on the "performance reserves" of the subjects: "The extra four hours of performance per day is achieved at a price."

Chiles (1963) further studied the possible effect on performance reserves by introducing a total sleep deprivation period of 44 hours on the 6th and 7th days to subjects performing on 4/2 and 4/4 schedules over a 12-day period. The results showed that performances on the probability monitoring and arithmetic tasks were more severely decremented for the 4/2 subjects than for the 4/4 subjects. The authors concluded that this was evidence for the depletion of performance reserves in the 4/2 subjects.

Hartman and Cantrell (1967) evaluated the performance reserve concept in a study of the effects of three days of total sleep deprivation introduced on days 8, 9, and 10 to subjects performing on 16/8, 4/4, and 4/2 schedules over a 12-day period. Performance was observed on a variety of tasks, including vigilance, arithmetic, tracking, reaction time, and complex coordination tasks. The results showed that performance on the 16/8 schedule deteriorated less during sleep deprivation than performance on the 4/4 or 4/2 schedules, and recovered more rapidly. Recovery was slowest for the 4/2 subjects. The authors concluded that the 16/8 schedule was less demanding on performance reserves or, as they called it, "physical reserves."

In all the sleep deprivation and work/rest schedule studies, the performance conditions have been relatively benign. Most studies have confined men for the observation periods, but the working environments have not been severe. The performance tasks generally have been sedentary; no great expenditure of energy was required to perform them. When rest periods were given, as in the schedule studies, men generally have been removed from the work area to an equipped rest area. All this makes it difficult to determine from the results of these laboratory studies what might be expected in field studies. Field conditions are usually not benign; rest often must be taken in the field under harsh condition; many operational tasks may require hard physical labor; and other stressors may be present, such as noise, vibration, or threat.

The stress literature shows that performance on many tasks deteriorates when men are exposed to adverse conditions for even short periods of time and even more when exposed for prolonged periods. The tasks most likely to be affected by environmental or threat stress are vigilance tasks, perceptual tasks (where subjects are required to interpret the significance of stimuli and respond appropriately), and cognitive tasks involving short-term memory; the tasks least affected are motor tasks, particularly well-learned ones (e.g., Harris *et al.*, 1956). Studies of the effects of fatigue on performance have shown similar results. For example, Grandjean (1968) identified the symptoms of fatigue as a decrease in attention, slowed and impaired perception, impairment of thinking, decrease of motivation, and decrease of performance for physical and mental activities.

When conditions become severe enough or prolonged enough, performance on nearly any task will deteriorate. A significant problem in evaluating the concept of continuous operations is to determine what happens to the performance of *operational* tasks, often well-learned, performed under various field conditions on given work/rest and performance/recovery schedules.

THE BIOLOGICAL EFFECTS OF SLEEP DEPRIVATION

Introduction

The biological effects of sleep deprivation are poorly understood, as is the biological requirement for sleep itself. Yet it is obvious that some physiological dysfunction must occur during sleep deprivation. Men progressively behave in a more lethargic, erratic, and irrational manner, suggesting progressively deteriorating cerebral function. Also, the fact that animals die after prolonged sleep deprivation seems indisputable proof that some physiological dysfunction has occurred. For acute exposures to sleep deprivation, the evidence suggests that the final catastrophic failure lies in the central nervous system (CNS). Yet some peripheral signs of the impending failures of the other systems have been noted in sleep-deprived men. Moreover, some of those signs are less easily reversed by rest than are signs of cerebral dysfunction. Therefore, the limiting factor in chronic sleep deprivation might be the result of a peripheral system failure, rather than failure of the CNS.

Much of what is known today concerning the biological changes that occur in sleep-deprived men is reviewed in this section. The review concentrates upon the results of studies published since 1945 which used more than a single human subject.

Physical Working Capacity

Performance Under Maximal and Submaximal Work Loads. The classical methods for ascertaining maximal aerobic working capacity and submaximal working efficiency are described in detail in the next section of this paper (PROLONGED PHYSICAL WORK). Briefly, maximum aerobic working capacity is determined from the rate of whole-body oxygen consumption ($\dot{V}_{O_2}$) reached at a power output which is the greatest that can be sustained for several minutes. Submaximal working efficiency has been determined from the physiological cost, as measured by $\dot{V}_{O_2}$ or heart rate (HR), of work requiring a power output that is less than maximum.

Vogel and Gleser (personal communication) completed a study in 1970 at the U. S. Army Institute of Environmental Medicine which was aimed at showing the effects of sleep deprivation on maximal aerobic working capacity and submaximal working efficiency. They tested three subjects on a bicycle ergometer and noted 3.2%, 6.0%, and 3.8% reductions in their respective values of $\dot{V}_{O_2max}$ after 72 hours of sleep deprivation. The investigators also studied the subjects as they worked for a presumably short period under a constant load which was about 85% of their maximum, and under a load which increased to maximum as the subjects worked. The results of both of these tests seemed to indicate that the subjects' submaximal working efficiency improved slightly during their exposure to sleep deprivation. Their average HR declined over repeated periods of work under the submaximal load, and the average ratio of their $\dot{V}_{O_2}$ to HR under an increasing submaximal load was greater after sleep deprivation. Still, the apparent improvement in submaximal working efficiency could have been due to the effect of training rather than that of sleep deprivation. Training has been shown to improve submaximal working efficiency markedly without substantially changing maximum working capacity (P-O. Åstrand and Rodahl, 1970).

Immediate Recovery from Physical Work. An alternative method for assessing physical working capacity has been to define the immediate course of the recovery of certain physiological parameters following a standardized exercise. This technique is employed in the Harvard Step Test where a subject mounts and dismounts from a 20" pedestal in cadence with the beat of a metronome for periods ranging up to five minutes. The subject's HR is recorded following the exercise and an index (S) of HR recovery is calculated according to the formula:

$$S = \frac{100\ V'}{2(HR_{1-1.5} + HR_{2-2.5} + HR_{3-3.5}}$$

where

V' = duration of the test in seconds

$\left.\begin{matrix} HR_{1-1.5} \\ HR_{2-2.5} \\ HR_{3-3.5} \end{matrix}\right\}$ = average HR per minute during the indicated interval

Brodan and Kuhn (1967) employed the Harvard Step Test in a study to evaluate the effects of 120 hours of sleep deprivation on a group of 26 Czech students and soldiers. Their results are shown in Figure 1.

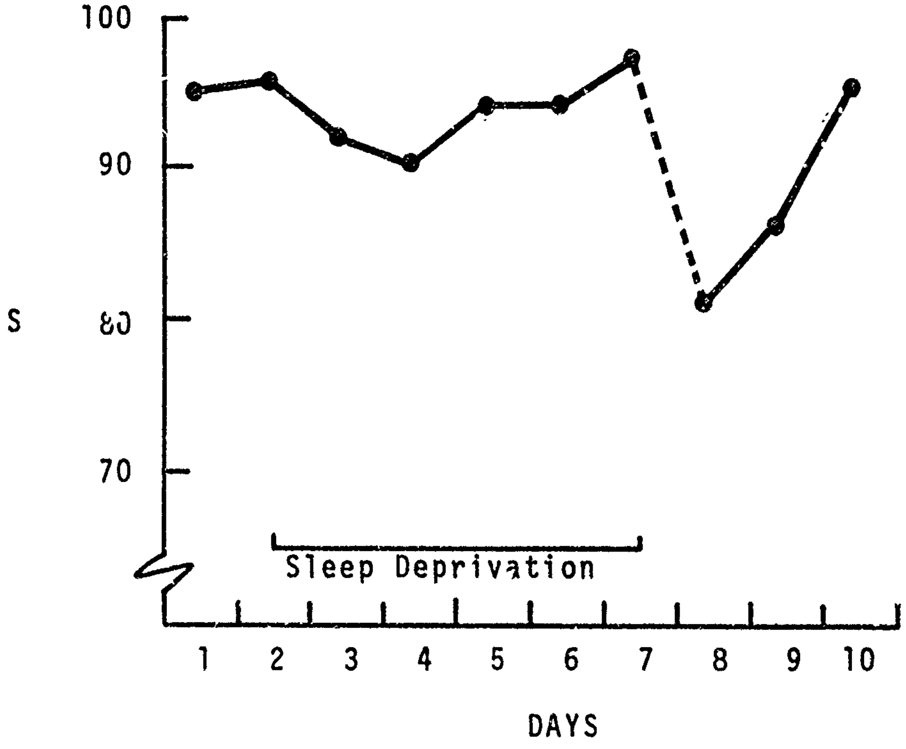

Figure 1. The Harvard Step Test index, S, a measure of physical working capacity, as a function of time, before, during, and after sleep deprivation (from Brodan and Kuhn, 1967).

Those results indicate that the subjects' physical working capacity was slightly reduced during the first two days of sleep deprivation. Their working capacity subsequently returned to pre-deprivation levels during the remaining three days of sleep deprivation. Surprisingly, that capacity was drastically reduced after 18-20 hours of sleep on the first recovery day. Full recovery was not seen until the third recovery day.

Brodan and Kuhn also reported testing some of their subjects on a bicycle ergometer under an unspecified submaximal work load. Little change in the subjects' physiological working status was noted during the period of sleep deprivation. However, on the first recovery day, there was an unusual rise in the pyruvic acid concentration in the subjects' plasma, suggesting a partial inhibition of carbohydrate metabolism (described in detail, pp. 36-37). At the same time, there was a corresponding rise in the subjects' HR's under the work load. Recovery from that condition matched the recovery of physical working capacity as measured by the Harvard Step Test.

System Functions

Thermoregulation. A progressive decline in body temperature has been frequently observed in subjects experiencing sleep deprivation (Kleitman, 1963; Wilkinson, 1965). This could either reflect a general decline in the level of CNS arousal or a more selective deterioration in the hypothalamic regulation of the body temperature. Fiorica *et al.* (1968) set out to determine the correct alternative. In their study, six subjects were exposed to moderate cold (10C) for one hour on each of four consecutive days without sleep. The results obtained from them were compared to results from a similar group who were similarly exposed to cold but were allowed to sleep normally. As judged from the drop in rectal temperature, both groups lost an equivalent amount of heat during every cold exposure. Moreover, the cold-induced increase in metabolic rate was similar for both groups during every exposure. However, the sleep-deprived subjects' average rectal temperature fell progressively whereas that of the control subjects rose progressively, over the successive cold exposures. By the fourth day, the groups' average rectal temperatures were about 0.5C apart throughout the cold exposure. That difference was highly significant and suggested that the groups had acclimatized differentially to the cold stress. Fiorica *et al.* were unable to explain how this might have occurred and indeed the paucity of information on human acclimitization to cold would frustrate any present attempt to provide an explanation. It must be said, however, that the effect of sleep deprivation on thermoregulation, if any, remains a matter for conjecture.

Blood Formation. In several early studies, immature dogs were walked continuously (or practically so) until they collapsed, and in many cases died, after 2-7 days (e.g., Kleitman, 1963). Autopsies performed on those animals showed a marked reduction in circulating red cell concentrations which suggested that sleep deprivation with continous physical activity somehow impairs erythropoiesis, resulting in anemia. Attempts to show the same result in sleep-deprived, though physically inactive, men have generally failed (Kleitman, 1963).

Recent results obtained by Kuhn *et al.* (1967) have reopened the question of whether, under certain circumstances, sleep deprivation will impair erythropoiesis. Their six subjects were deprived of sleep for 120 hours. Daily blood samples were obtained from them before, during, and for six days following the period of sleep deprivation. These were assayed for plasma iron concentrations, and the results are shown in Figure 2.

Those results show a drastic (> 50%) drop in the plasma iron concentration during the sleep deprivation period.

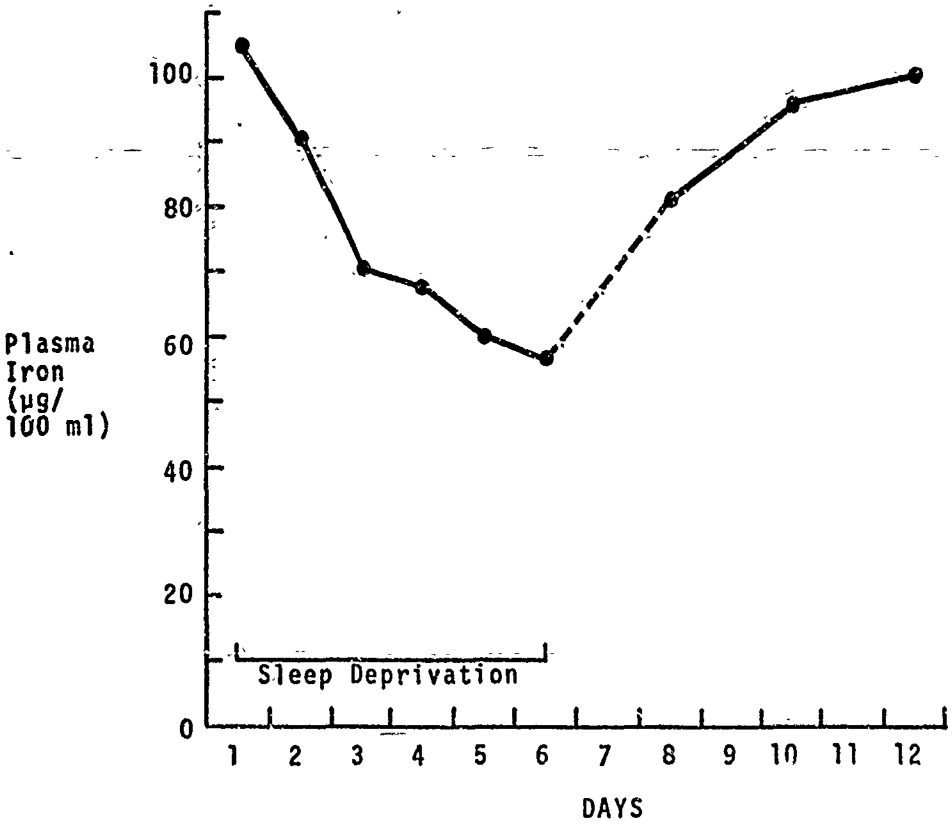

Figure 2. Plasma iron as a function of time before, during, and after sleep deprivation (from Kuhn *et al.*, 1967).

Moreover, the recovery of plasma iron to its normal concentration was slow, requiring more than six days for completion.

Kuhn *et al.* also examined their subjects' intestinal absorption and renal excretion rates for iron, the half-life of injected $^{59}F_e$ in the blood, the $^{59}F_e$ utilization rate in erythropoiesis, and various hematological indices of the adequacy of erythropoiesis. The results showed that iron absorption and excretion were unaffected, as was the half-life of injected $^{59}F_e$. Plasma iron binding capacity was reduced, though to a much smaller degree (about 9%) than was the plasma iron concentration. At the time when the plasma iron level was lowest, there was a striking increase in the rate of iron utilization in erythropoiesis (greater than 100% in all instances). There was, however, no evidence of any erythropoietic failure for supplying the circulation with an adequate number of mature red cells.

Fröberg *et al.* (1970a) partially confirmed those results by noting an average 52% drop in the serum iron concentration of 31 young soldiers after performing on an electronic firing range for 75 hours.

Among other things, erythropoiesis depends upon the reclamation of iron from aged or damaged red cells by the splenic-hepatic reticuloendothelial system, and upon the return of iron from there to the erythropoietic tissue in the bone marrow via reversible binding to a plasma protein, transferrin. A failure at any point in the reclamation process can deprive the immature red cells of iron for synthesizing sufficient hemoglobin to meet the body's needs for oxygen and carbon dioxide transport. A pathological state of hypochromic anemia would then ensue, leading, if unchecked, to severe debilitation or even death.

The above results indicate that the iron reclamation system is severely strained by sleep deprivation. Iron removed from the circulation by the reticuloendothelial system is not then bound to transferrin and returned to the bone marrow as before. In the bone marrow, the immature erythrocytes are apparently able to compensate for the reduced iron supply by increased utilization. Thus the rate of erythropoiesis is not significantly reduced. At least this appears to be true for adult, otherwise unstressed, individuals. In immature individuals, whose need for iron is greater due to an ever-increasing blood volume, the reduction in plasma iron could conceivably lead to anemia. Perhaps this process was responsible for the severe anemia observed in sleep-deprived puppies. Likewise, anemia might result in sleep-deprived men who are simultaneously subjected to a stress that usually evokes a compensatory increase in erythropoiesis. For instance, there is a need for increased erythropoiesis during heavy physical labor to balance the increased rate of red cell destruction.

In hypoxia and hemorrhage there is a similar need to ensure adequate oxygen delivery in the face of the reduced oxygen carrying capacity of the blood. Therefore, one might expect the sleep-deprived individual to be less able to tolerate the stresses of physical work, hypoxia, and hemorrhage.

The blood's white cell (leucocyte) concentration is also altered during sleep deprivation. After about 24-48 hours, the total leucocyte concentration increases progressively, due mainly to a marked rise in the neutrophile fraction (Kleitman, 1963; Kuhn *et al.*, 1969). Since the neutrophiles represent a line of defense against invading microorganisms, this reaction may be thought of as a beneficial adaptation to the stress of sleep deprivation.

Hypothalamo-Sympathoadrenomedullary. The reaction to sleep deprivation of the system which regulates peripheral sympathetic tone and circulating concentrations of the catecholamine hormones, adrenaline and noradrenaline, remains somewhat obscure. Studies depending upon measurements of the urinary excretion rate of the catecholamine metabolite, vanillylmandelic acid (VMA), for showing sympathetic tone have yielded conflicting results. One has shown an increase in VMA excretion during 5 days of sleep deprivation (Kuhn *et al.*, 1969); another has found no consistent trend over 8½ days (Rubin *et al.*, 1969).

Fiorica *et al.* (1968) used a chemical assay which does not differentiate between adrenaline and noradrenaline and failed to find any systematic trend in catecholamine excretion by six subjects over four days of sleep deprivation. On the other hand, Fröberg *et al.* (1970b) employed an assay which does differentiate between catecholamine concentrations and found that the noradrenaline excretion rate rose slowly but steadily in 63 subjects who were deprived of sleep for 75 hours. The subjects' adrenaline excretion rate followed a marked circadian rhythm but did not increase over successive days of sleep deprivation.

Perhaps the most interesting study of the hypothalamo-sympathoadrenomedullary reaction to prolonged wakefulness was undertaken by Hasselman *et al.* (1960). They employed four subjects who worked on a bicycle ergometer under different experimental conditions on four separate occasions. On each occasion, the subject worked for four hours, was deprived of sleep for a single night, and worked for another four-hour period. Work load and ambient temperature were varied systematically between conditions, so that each subject performed under all possible combinations of two work loads (40 and 80 watts) and two ambient temperatures (22C and 37C [two subjects], or 32C and 40C [two subjects]).

After sleep deprivation, working adrenaline and noradrenaline excretion rates were always elevated with respect to corresponding control values. Under both work loads and at the lower ambient temperatures, the excretion rates for adrenaline and noradrenaline were elevated by about 300% and 200%, respectively. Similar, though less extreme, reactions were observed during work at the high ambient temperatures. These results indicate that the loss of only a single night of sleep produces an elevated, and possibly, compensatory, level of sympathetic tone during physical work. In other words, the sleep deprived individual may be able to perform the same amount of physical work as before, but in doing so, he may have to elevate his sympathetic tone for more rapid utilization of his resources. Apparently, also, the stress produced by exercise is directly related to the period of prior wakefulness.

Hypophyseo-Adrenocortical. Many investigators have sought to show a hypophyseal-adrenal cortical reaction during sleep deprivation. Unfortunately, the composite picture provided by their results is most obscure. Much of the current state of confusion is due to the former inadequacy of procedures for determining plasma levels of cortisol, the primary stress-related product of the adrenal cortex in man. Early investigators had to infer cortisol secretion rates from more or less confounded measurements of the excreted metabolities of that hormone, such as the 17-ketosteroids (17-KS) or the 17-hydroxycorticosteroids (17-OHCS).

Tyler *et al.* (1946) stated that 100 hours of wakefulness had no effect on subjects' excretion of 17-KS. Yet Wilkinson (1965) reworked their data to show a significant fall in the subjects' 17-KS excretion rate on their second, third, and fourth days of wakefulness. Murawski and Crabbé (1960) also found that the normal early morning peak in 17-OHCS excretion failed to occur in 18 subjects deprived of a single night's sleep. However, Frank *et al.* (1966) failed to confirm that finding after measuring plasma cortisol levels in three men after a night without sleep. Bliss *et al.* (1959) also found no change in 17-KS or 17-OHCS excretion during 72 hours of wakefulness. Similarly, Kollar *et al.* (1966) were unable to find consistent trends in the patterns of 17-OHCS excretion by six subjects deprived of sleep for 120 hours. Rubin *et al.* (1969) measured both plasma and urine levels of 17-OHCS and found a depression followed after 90 hours by an elevation in adrenal cortical activity in four men deprived of sleep for 205 hours. Unlike in the other studies, they also measured the course of recovery of plasma and urinary 17-OHCS after completion of the period of wakefulness. They found recovery was complete within a day.

In contrast to the above, both Mandell *et al.* (1964) and Kuhn *et al.* (1969) found marked elevations in the 17-OHCS excretion rates of separate groups of subjects during the first two days of a five-day vigil.

Cardiovascular. Little is known about the effects of sleep deprivation on man's cardiovascular system. Resting mean heart rate and arterial blood pressure have been relatively constant during vigils extending to 200 hours (e.g., Wilkinson, 1965). Resting ballistocardiogram measurements, which provide a rough estimate of cardiac output (i.e., blood volume pumped per minute, $\dot{Q}$), have likewise shown no change over 123 hours of sleep deprivation (Ax and Luby, 1961). Peripheral blood flow, as inferred from recordings of the finger pulse pressure, has also been found unchanged over the same period (Williams *et al.*, 1962; Ax and Luby, 1961). Unfortunately, none of those cardiovascular parameters has been studied in working, sleep-deprived subjects, and no firm conclusions seem warranted from the results obtained from resting individuals.

Yet, Fröberg *et al.* (1970) have given a warning that the heart might be seriously affected by sleep deprivation. Those investigators noted electrocardiogram (ECG) signs of myocardial fatigue or ischemia (notably ST-T depressions) in recordings from about 25% of 63 soldiers who had participated in the 75-hour firing range task. All of those ECG abnormalities eventually disappeared after the subjects were allowed to sleep and rest for "several days."

Central Nervous System. More study has been devoted to the effects of sleep deprivation on the central nervous system than on any other physiological system. Tyler *et al.* (1947) were among the first to demonstrate a progressive slowing and a reduction in the abundance of the dominant alpha rhythm (8-13 Hz) in electroencephalogram (EEG) recordings from sleep-deprived subjects. Armington and Mitnick (1959) confirmed those findings and showed that the reduction in resting alpha abundance was essentially linear over 72 hours of sleep deprivation. Recovery of alpha abundance was rapid: it was 90% complete in 24 hours and 95% complete in 48 hours following termination of the sleep deprivation period. Malmo and Surivillo (1960) reported essentially the same finding but, in contrast to Armington and Mitnick, they interpreted the reduction in alpha abundance as indicating an increase in psychophysiological arousal. However, subsequent work by Williams *et al.* (1962) in which changes across the entire EEG band were more closely examined with respect to concurrent behavioral responsiveness in an auditory monitoring task has shown rather conclusively that Armington and Mitnick's interpretation was correct. In their study, EEG recordings from seven soldiers who were deprived of sleep for 64 hours revealed that the decline in alpha abundance occurred along with an increase in theta (4-7 Hz) activity. A preponderance of theta activity often indicates a reduced level of arousal. This seemed to be the case in the study by Williams, *et al.* (1962): the subjects' failures to detect signals almost invariably occurred when their EEG's were comprised of frequencies in the theta range. Recoveries of normal EEG frequency spectra and reaction times to signals were not fully complete before the third recovery day; i.e., after two nine-hour periods of sleep. Moreover, during the first two periods of recovery sleep, the subjects' EEG's revealed that they spent a disproportionate amount of time in deep (slow-wave) sleep. On those nights, they were extremely resistant to awakening as judged by an increase in the time it took them to respond electroencephographically and behaviorally to an intermittent auditory stimulus (Williams *et al.*, 1964).

Naitoh *et al.* (1969) reported an extensive analysis of EEG recordings from four subjects who were kept awake for 205 hours. The investigators found that the alpha abundance generally declined for 120 hours in a linear manner (disregarding the usual circadian periodicity of the alpha rhythm). Simultaneously, there was an increase in both theta and delta (2-3 Hz) activity relative to the total EEG output. After 120 hours, there was no further decline in alpha abundance, and even a partial recovery of alpha in one subject. The investigators also measured the subjects' oral temperatures, plasma levels of 17-OHCS, pursuit tracking performance, and feelings of fatigue and "effort" required to stay awake. Higher alpha abundance was significantly correlated with lower 17-OHCS, smaller tracking error, less fatigue, and less "effort." More "effort" was correlated significantly with higher temperature, higher 17-OHCS, greater tracking error, and lower alpha abundance. After two nights of recovery sleep (12 hours and 8 hours) all variables had returned to pre-deprivation levels, except the alpha abundance of one subject.

Naitoh *et al.* (1971) have also examined the effect of sleep deprivation on yet another EEG parameter, the surface negative slow potential, or cortical negative variation (CNV). The CNV had been shown to occur in suddenly heightened attention and to be related in degree to the speed and adequacy of a response to anticipated stimuli. The results of Naitoh *et al.* showed that CNV's given in anticipation of responding to visual stimulus diminished in amplitude after one night without sleep and were abolished entirely by another night of wakefulness. No performance decrement was observed, possibly as a result of the general insensitivity of simple reaction time to sleep deprivation. CNV recovery was found to be complete after two nights of recovery sleep.

Pathological EEG signs have been observed in sleep deprived subjects. Rodin *et al.* (1962) kept 16 apparently normal subjects awake for 120 hours and observed high-voltage paroxysmal (epileptic-like) activity in recordings from five subjects, particularly during the period of 24-48 hours of sleep deprivation. The same subjects had abnormally low thresholds for the convulsive action of the drug, megimide, so the authors concluded that even short periods of sleep deprivation produce a degree of cerebral instability which may result in epileptic-like manifestations in predisposed individuals. Related to this may be the finding that fatigue and/or sleep deprivation appeared to be the major precipitating factor for first seizures of numerous naval and aircrew personnel who were provisionally diagnosed as epileptics (Johnson, 1969; Bennet, 1963).

The functional integrity of autonomic control centers, located in the hypothalamus and medulla, can be inferred from peripheral measurements of homeostatic processes controlled by those centers or of autonomic mobilization of processes which prepare the organism for meeting the challenge of some stress. As mentioned above, the autonomic nervous system seems perfectly capable of regulating resting cardiovascular processes during all stages of sleep deprivation. Moreover, the autonomic regulation of homeostatic hypophyseal functions seems unimpaired by sleep deprivation. For example, antidiuretic hormone release by the neurohypophysis is apparently normal during prolonged wakefulness as judged from essentially normal circadian patterns of urine flow (Fröberg *et al.*, 1970b). Also, adrenocortotropic hormone release by the adrenohypophysis is apparently sufficient to ensure adequate glucocorticoid (primarily cortisol) release by the adrenal cortex, although the circadian pattern of adrenal cortisol activity may be somewhat disrupted as described above. Autonomic regulation of the blood glucose level is little impaired during periods of wakefulness of up to 100 hours (e.g., Wilkinson, 1965), except perhaps to attenuate the circadian periodicity of that parameter (Slater *et al.*, 1967). It is true that body temperature declines in sleep-deprived individuals in a manner suggesting some failure in the autonomic control of thermoregulatory processes (Kleitman, 1963; Wilkinson, 1965). However, the previously described work by Fiorica (1968) demonstrated that no drastic change in the thermoregulatory response to cold stress results during prolonged wakefulness. Attempts to determine whether there are autonomic reactions to other stresses have led to somewhat ambiguous results. For instance, Ax and Luby (1961) administered a standard pain stimulus to five men who maintained a 123-hour vigil. They noted progressive blunting of reactions mediated by the autonomic nervous system. In particular, the pain-evoked rise in blood pressure and increase in palmar skin conductance were attenuated during that period of wakefulness. Ax and Luby interpreted this as showing "profound fatigue of central sympathetic centers." Their observations were supported by those of Johnson (1965) and of Naitoh *et al.* (1969) who found a late decline in autonomic responsiveness to external stimuli of all types during prolonged periods (200 hour plus) of wakefulness. Yet all of those results can as easily be explained as resulting from a decline in the general level of activity within the midbrain reticular activating system. Thus there appears to be no conclusive evidence for a deterioration in autonomic control functions during sleep deprivation. In any case, all reports indicate that recovery of normal autonomic responsitivity is complete after two nights of recovery sleep.

The results of neurological examinations have revealed some cerebral dysfunction during sleep deprivation. Kollar *et al.* (1968) found mild lateral nystagmus, an increase in hand tremor, speech slurring, and mild ptosis (eyelid drooping) beginning after the third day of an 8½ day exposure to sleeplessness. Sassin (1970) reported results from nine sailors who had been kept awake for 60 hours which showed a marked loss (20%-40%) in neck flexion strength and a general increase in hand tremor. Three subjects experienced lateral nystagmus, and four experienced clumsiness and lack of serial coordination in fine adjustive hand movements. None showed any impairment of visual acuity or general muscular strength, although four showed increased sensitivity to pain (thereby confirming an earlier observation by Kleitman [1963]). All signs of impaired cerebral function were again gone after two nights of recovery sleep.

Metabolism

Whole Body. In early studies, the basal metabolic rate (BMR), as inferred from $\dot{V}_{O_2}$ and $\dot{V}_{CO_2}$ in the usual indirect manner, was found unchanged during sleep deprivation (e.g., Kleitman, 1963). Recent data of Fiorica *et al.* (1968) showed a surprising 7% increase in the average resting $\dot{V}_{O_2}$ of six subjects from the control value to values measured in the second and third days of sleep deprivation. Those changes were found not to be statistically significant by the experimenters. However, this may have been due to their use of an inappropriate statistical test which assumed that measures obtained from the same subjects on successive days were independent (normally one would expect those measurements to be highly correlated). If there is an increase in $\dot{V}_{O_2}$ without a corresponding change in BMR during sleep deprivation, it may mean that there is a shift from carbohydrate to fat as the major substrate for metabolism. This shift has already been suggested from other evidence which is described as follows.

Carbohydrate. Luby *et al.* (1960, 1962) studied intermediary carbohydrate metabolism and energy transfer systems in erythrocytes obtained from subjects deprived of sleep for as long as 212 hours. The erythrocyte is an atypical cell possessing no mechanism for obtaining energy from the tricarboxylic acid cycle. Nonetheless, the investigators were able to show that the erythrocyte's ability to produce the basic high-energy transfer compound, adenosine triphosphate (ATP) via the oxidation of glucose in less efficient alternate pathways first increased remarkably, then declined as sleep deprivation continued. Maximum ATP production occurred for one subject after four days in the first experiment and after an average of two days for 12 subjects in the later experiment. Luby *et al.* interpreted those findings as showing initial intracellular mobilization to supply the heightened energy requirement imposed by the stress of sleep deprivation and eventual exhaustion of the mechanisms responsible for the increased production of ATP.

Kuhn *et al.* (1969) examined whole-body carbohydrate metabolism in several ways. First, they administered the glucose tolerance test to 26 subjects before and after they had been deprived of sleep for 3-4 days. The fall in the blood glucose level observed after glucose ingestion was much slower following sleep deprivation than before; i.e., imposed wakefulness had produced a "glucose tolerance curve" similar to that seen in borderline diabetes. Eleven of those subjects' plasma levels of pyruvic acid were also measured on each successive day of sleep deprivation and for three days afterward. Those levels reached a peak that was 130% greater than the pre-deprivation control value by the fourth day. Recovery to control values was essentially complete following 72 hours of rest. Kuhn *et al.* further reported that there was a "marked increase" in the subjects' urinary thiamine (Vitamin B_1) excretion.

Thiamine is necessary for the conversion of pyruvic acid, a glucose metabolite, into acetyl coenzyme A which can in turn unite with oxaloacetic acid to form citric acid. The latter metabolite typically enters the tricarboxylic acid cycle which yields the major portion of the high-energy compounds required for metabolism in such organs as the brain. Thiamine deficiency is thus capable of blocking a major pathway of carbohydrate metabolism beyond pyruvic acid. If the subjects of Kuhn *et al.* were suffering from mild thiamine deficiency as the result of excessive thiamine loss during sleep deprivation, it would explain why their plasma pyruvic acid levels were elevated and why their rates of glucose utilization were retarded.

Fat. In another experiment reported in the same paper, Kuhn *et al.* measured various plasma lipid levels in the subjects at rest before, during, and after 72 hours of wakefulness. The mean, non-esterified or "free" fatty acid (FFA) level progressively increased to a peak that was 180% greater than the control value during the wakeful period. Recovery was complete within the following 72 hours. Esterified fatty acids and cholesterol levels did not increase.

Only FFA of all the plasma lipid fractions is responsive to direct neural and endocrine regulation during stress. Moreover, FFA is the primary lipid substrate for metabolism in those tissues which derive a major portion of energy from fat. When FFA is mobilized but unused during stress, there is often a secondary rise in the plasma levels of other lipid fractions, including cholesterol. Kuhn *et al.* observed a rise in the plasma level of FFA but not cholesterol during sleep deprivation. This suggests that FFA was mobilized and used by certain tissues. Coupled with their data on carbohydrate metabolism, their findings indicate that tissues, such as the skeletal musculature, which can metabolize both carbohydrate and FFA, tend to derive more energy from the latter as sleep deprivation continues. Furthermore, this change may come about as the result of a gradual failure in carbohydrate metabolism as described above. Tissues, such as those in the CNS, which metabolize only carbohydrates, would of course be unable to compensate for failing metabolism by shifting to FFA as an alternative energy source. The CNS could, however, compensate for some reduction of activity within the tricarboxylic acid cycle by increasing activity within the same glycolytic pathways available to the erythrocyte.

Protein. Several teams of investigators have tried and failed to find any general and systematic change in protein metabolism during sleep deprivation (e.g., Kleitman, 1963; Kuhn *et al.*, 1969). However, Scrimshaw *et al.* (1966) were able to find evidence for imbalance between protein anabolism and catabolism in six subjects who were deprived of sleep for 48 hours. During their first day of wakefulness, the subjects' total nitrogen excretion was less than normal. This condition reversed itself on the second deprivation day and total nitrogen excretion remained abnormally high during the first recovery day. There was again apparent retention of nitrogen on two subsequent recovery days and the subjects on two subsequent recovery days and the subjects finally appeared to regain nitrogen balance on the fourth recovery day.

Scrimshaw *et al.* were able to estimate that an average 12% increase from the basal dietary protein requirement would have been necessary to balance the apparent increase in protein anabolism occurring during the second day of sleep deprivation. Though the authors were largely unimpressed with the magnitude of the average increase in protein requirement, they hastened to point out that some individuals showed a more pronounced loss of nitrogen. The extreme subject of the six, for example, would have required more than a 20% increase in protein intake to achieve nitrogen balance.

Discussion of the Biological Effects of Sleep Deprivation

The foregoing should make it clear that current knowledge of the physiology of sleep deprivation is often confused and fragmentary. The biological literature lends itself poorly to the prediction of the consequences of sustained and continuous operations. Nonetheless, some potential problem areas are indicated in the literature.

Physical working capacity, as measured in tests of relatively short duration, is little changed over periods of sleep deprivation of up to five days. However, the ability to perform physical work is apparently retained at some cost. After sleep deprivation is over, a state of reduced physical working capacity persists, to a diminishing degree, for several days. There are some data to suggest that this may be due to an impaired capability for fully utilizing glucose as an energy source.

Body temperature declines during sleep deprivation but it is unclear if this indicates any loss in thermoregulatory capability.

Iron reclamation by the splenic and hepatic reticuloendothelial system is severely and rapidly impaired by lack of sleep. Studies on humans have not found that this results in the pathological condition of hypochromic anemia. However, there is evidence that the erythropoietic system is operating under a high degree of strain to compensate for the reduced availability of iron during sleep deprivation. Any additional strain on the erythropoietic system as imposed by such stresses as physical work, hypoxia, or hemorrhage might result in an inadequate production of mature red cells, and in anemia.

The recovery of the reticuloendothelial system is very slow following sleep deprivation. The effect of 48-72 hours of sleep loss on plasma iron would probably be apparent, in diminishing degree, for as long as a week afterward.

Adrenal functions are affected subtly by sleep deprivation. Little consistent change in adrenal medullary secretion occurs, but the sympathoadrenomedullary response in physical work is exaggerated after the loss of only a single night of sleep. During sleep deprivation, the adrenal cortical pattern of cortisol release fails to conform to its usual circadian rhythm--the evidence favors the view that the early-morning rise in cortisol secretion is reduced progressively--beginning after the first night of sleep loss.

Abnormal and possibly pathologic ECG patterns have been observed in healthy individuals after 75 hours without sleep. These changes suggest some myocardial dysfunction which is only slowly reversed by rest after prolonged wakefulness.

Judging from electroencephalographic and neurological evidence, the CNS is the first system to show clear impairment during sleep deprivation and the first system to recover following cessation of that stress. The most obvious cause of that impairment seems to be a decline in the activity of subcortical centers responsbile for the general level of psychophysiological arousal. That decline seems generally linear over time, at least during the first 120 hours of wakefulness.

Recovery of normal arousal levels seems complete after one or two nights of recovery sleep.

Pathological signs of epileptic-like cortical activity have been observed in predisposed but otherwise healthy individuals. Thus, it seems that the waning of subcortical control over the cortical level of arousal may accentuate incipient unstable and seizure-related activity within the cortex in certain individuals.

Most individuals show metabolic signs of stress during moderate periods of sleep deprivation. There is evidence of some blocking of carbohydrate metabolism at the point where pyruvic acid enters the tricarboxylic acid cycle. Less secure evidence suggests that this may be due to an induced thiamine deficiency. The rate of fat catabolism increases during sleep deprivation, possibly to supply some of the energy lost by the blocking of carbohydrate catabolism in tissues that can utilize either substrate. In tissues, such as those in the brain, which can only utilize carbohydrates as an energy source, there may be a compensatory increase in the activity of unaffected, though less efficient, metabolic pathways. This has not been observed but may be inferred from studies of erythrocyte metabolism during sleep deprivation. Protein metabolism is relatively unaffected by sleep deprivation. Still, some sleep-deprived individuals show a negative nitrogen balance which indicates a net reduction in the body's protein reserve.

Unfortunately, it is very difficult to generalize strongly from the above findings to the situations which are anticipated in sustained and continuous operations. This is mainly due to the fact that subjects in practically all reported studies on sleep deprivation have engaged in essentially sedentary activities throughout their periods of wakefulness. The energy expenditures required for those activities have presumably been uniformly low. Soldiers engaged in sustained or continuous field operations will not as a rule be sedentary. They will be required to perform physical and "mental" work on an intermittent or continuous basis over long periods. Thus the stress imposed on all physiological systems, save perhaps the CNS, will be far greater than the stress experienced by typical laboratory subjects in sleep deprivation experiments. For example, Goldman (1965) has shown that the average rifleman bearing a normal 20 kg load expends energy at a rate of about 3.8 kcal/min while merely marching at 5.5-6.5 km/hr over dry and level ground. More heavily loaded individuals such as radiotelephone operators, mortarmen, and machine gunners expend energy at considerably higher rates while marching; i.e., up to 10 kcal/min. Even riflemen expend energy at high rates (about 7 kcal/min) while engaging in other activities such as a fire fight. Yet it may be estimated on the basis of much related data (P-O. Åstrand and Rodahl, 1970) that the sedentary subject of sleep deprivation experiments does not expend energy at rates much greater than about 2 kcal/min. Thus, by the end of 24 hours of continuous activity, the marching and fighting soldier would expend about 5,400 and 10,000 kcal, respectively, while the sedentary subject would expend only about 2,880 kcal.

Applied physiologists have long held that the maximum allowable 24-hour energy expenditure for workers engaged in heavy labor on a daily 8-9 hour basis should not exceed about 4,800 kcal (Lehmann, 1958; Müller, 1962; Burger, 1964). Rates of energy expenditure in excess of that value are thought to be associated with feelings of chronic fatigue and increased susceptibility to physiologic dysfunctions of many kinds. Thus, while subjects of sleep deprivation experiments have not exceeded the "maximal allowable" rate of energy expenditure, soldiers engaged in sustained operations will routinely. Consequently, many of the physiological problems observed in subjects during prolonged wakefulness should be exaggerated in soldiers deprived of sleep for similar periods. In addition, it may be anticipated that additional, presently unforeseeable, problems will occur in the latter group as they endure the combination of many stresses, including sleep deprivation.

PROLONGED PHYSICAL WORK

Very few investigations have been performed to determine how men are affected by performing physical work on either an intermittent or continuous basis for periods in excess of eight hours. What follows is a thorough review of those few directly relevant studies on prolonged work with the inclusion of pertinent data from some studies in which subjects worked for shorter periods.

Human Capability for Performing Physical Work Over Prolonged Periods Under Different Loads

It is well known that oxygen consumption, $\dot{V}_{O_2}$, increases as a linear function of increasing work load to the point where the cardiorespiratory system becomes incapable of providing additional oxygen to the working skeletal muscles. The measurement of the maximum rate of oxygen consumption, $\dot{V}_{O_2max}$, is taken as an index of an individual's maximum aerobic working capacity. Typically, $\dot{V}_{O_2max}$ is determined in brief (< 30-minute) tests requiring the individual to work on a treadmill or a bicycle ergometer under a steadily increasing load until he can no longer continue. After noting a subject's terminal work load, investigators often subsequently study the same subject as he works under a load which causes his $\dot{V}_{O_2}$ to stabilize at some particular percentage of $\dot{V}_{O_2max}$. He is then said to be performing at that percentage of his maximum capacity, or submaximally.

It is generally accepted that no individual can perform near his maximum capacity for more than several minutes. Naturally, individuals can perform physical work for increasingly longer periods at progressively lower work loads. On the basis of admittedly scanty data, P-O. Åstrand and Rodahl (1970) have attempted to relate the time it takes for average healthy men to become exhausted while performing continuous (or nearly so) physical work under different relative loads. Their estimates are shown in Figure 3.

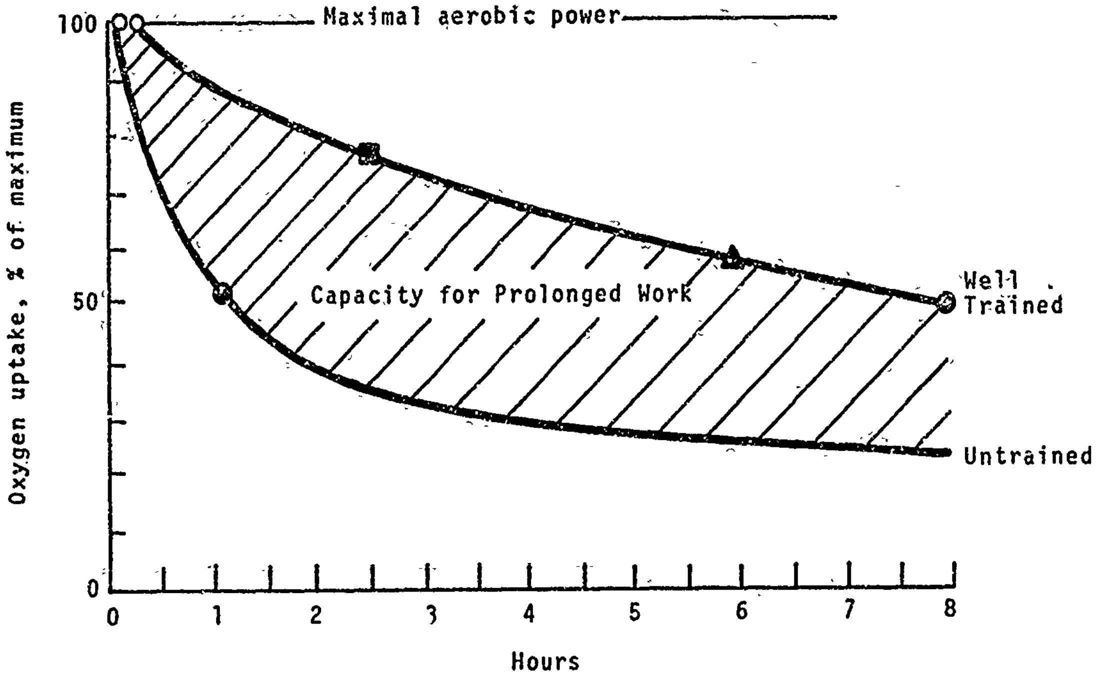

Figure 3. A graphic illustration based on a few observations showing approximately the percentage of a subject's maximal aerobic power he can tax during work of different duration, and how this is affected by his state of training (from P-O. Åstrand and Rodahl, 1970).

It may be seen that well-trained athletes can perform for longer periods under the same work load than can healthy but untrained men of approximately the same age. According to P-O. Åstrand and Rodahl, the well-trained, better-conditioned individuals can be expected to work continuously at 50% of their maxima for a period of eight hours, whereas untrained individuals cannot be expected to work at much more than 25% of their maxima over the same period.

Generally speaking, P-O. Åstrand and Rodahl's estimations of the times men can be expected to work under different work loads have been supported by observations of the energy expenditures of various occupational groups. For the average healthy young male (body weight of 70 kg), with a normal diet and a $\dot{V}_{O_2\max}$ of 3.5L, the rate of energy expenditure associated with physical work at 50% and 25% of relative maximum is approximately 9 and 5 kcal/min, respectively. In studies of the energy expenditures of various occupational groups, it has been shown that the average eight-hour working day rate of energy expenditure rarely exceeds 6 kcal/min, even in occupations involving manual labor (e.g., Durnin, 1965). Occasionally, however, many individuals in lumbering, mining, and building occupations have been shown to sustain bursts of activity associated with rates of energy expenditure which are up to twice that value (Lundgren, 1946; Lehmann, 1950; I. Åstrand, 1967). Consequently, it may be said that well-trained men engaged in occupations that require intermittent or continuous heavy physical labor typically work at between 30% and 40% of their maximum capacity, with occasional periods of working at one-half of their maximum capacity, or more, without incurring the need for unusually long periods of recuperation.

Limiting Factors for Prolonged Work

After the above, it is appropriate to ask why individuals become unable to continue performing physical work under different relative work loads. It is generally accepted that the factor limiting work under near maximal loads is an insufficient blood flow for providing oxygen to the working muscles and removing accumulated CO_2, lactic acid, and heat from them (P-O. Åstrand and Rodahl, 1970). It is far less clear what those factors might be for prolonged work under different submaximal loads. Yet for complete understanding of the process of recovery from prolonged physical work, it seems essential to know what biological or psychological changes lead invariably to the cessation of work and how those changes are reversed during rest.

Work Under Relative Loads Exceeding 50% Maximum. It now appears as if a decline in the availability of suitable energy sources at the working skeletal musculature, and possibly at the CNS, determines the limit for work performed under relatively heavy, though submaximal, loads. The musculature has several alternative energy sources. At rest, approximately 90% of the energy expended by the muscles is derived from fat catabolism. To accomplish this, free fatty acids (FFA) are first mobilized, along with glycerol, from triglyceride stores in the adipose tissue. FFA is bound to protein in the plasma and then removed and utilized as an energy source by the muscles. The proportion of the muscles' total energy expenditure based on fat catabolism diminishes as the work load increases. This occurs as the muscles draw more and more upon their own depot glycogen as a source of energy. Thus the muscles' total energy expenditure is derived in approximately equal proportions from fat and carbohydrate catabolism in men working at 50% of their respective maxima. Under near-maximum work loads, glycogen supplies practically all of the energy expended by the musculature (e.g., P-O. Åstrand and Rodahl, 1970).

The muscles' glycogen concentration is affected by many factors, including diet, adaptation to physical work, and exercise. However, over a relatively short period, the muscle glycogen depot is maintained by a regulated balance between rates of glycogen synthesis and breakdown. The two processes are largely independent and concurrent. In gross terms, the rate of synthesis is determined by the availability of glucose from the circulation, and the rate of breakdown is determined by the requirement for energy to perform physical work.

The blood glucose concentration is maintained by a homeostatic feedback loop involving the liver and certain CNS centers and is regulated by the actions of several neural and endocrine mechanisms. This process and that responsible for the maintenance of the muscles' glycogen depot are far too complex to discuss in any more detail here (a thorough review of those processes is available in practically any advanced biochemistry or physiology text). Yet the limitations of those processes for supporting prolonged physical work are known to a great extent (P-O. Åstrand and Rodahl, 1970). Suffice to say that general muscle exhaustion will ensue if any of the following occur:

1. Depletion of the muscle glycogen depot.
2. Depletion of the liver glycogen depot, leading to a substantial decline in the circulating glucose concentration.
3. Failure of neuroendocrine mechanisms responsible for EFA mobilization.
4. Loss of the capability on the part of the skeletal musculature for utilizing available fat or carbohydrate substrates.

It should be mentioned in this context that any substantial reduction in the blood glucose level would also impair CNS function. This is because the CNS has very limited glycogen stores and depends almost exclusively upon circulating glucose as an energy source. Blood glucose concentrations below about 60mg/100ml are associated with symptoms of hypoglycemia, such as nausea, dizziness, confusion, partial or complete blackout.

Hultman *et al.* (1967) have extensively studied the relationship between exercise, submaximal working capacity, and muscle glycogen. They worked subjects to exhaustion by intermittent work on a bicycle ergometer at an average of about 77% of their respective maxima. Muscle tissue samples were obtained before and after work and later assayed for glycogen content. The initial muscle glycogen content was positively related to the eventual working time, and almost complete depletion of muscle glycogen was observed in every case aft exhaustion had occurred. With the possible exception of the blood gluco . concentration (which was below 60mg/100ml after exhaustion in some individuals), none of the other physiological parameters measured (heart rate, blood pressure, blood volume, and plasma and muscle electrolyte concentrations) underwent a sufficient change to explain the cessation of working ability. Total recovery of an individual's muscle glycogen was typically complete in one day following exercise, if his diet was not deficient in carbohydrates. On exclusively fat and protein diets, recovery of both muscle glycogen and physical working capacity was much retarded.

Pruett (1971) reviewed a series of investigations in which she studied circulating levels of glucose and FFA, among other factors, in men working on a treadmill or bicycle ergometer under work loads between 20% and 90% of their relative maxima for a period of six hours or until exhaustion, whichever came first. During prolonged work, FFA increased in direct relation to the work load, except under near maximal loads, when the accumulation of lactic acid apparently inhibited FFA mobilization. Glucose varied insignificantly when the work load was less than 50% of maximum. However, glucose declined in a progressively more rapid manner as the work load increased from 50% to 70% of maximum. In those cases, exhaustion always occurred when the blood glucose concentration fell to about 60mg/100ml. This was accompanied by pronounced CNS symptoms of hypoglycemia. At work loads greater than 80% of maximum, exhaustion was not related to the blood glucose level.

Pruett interpreted those data as showing different limiting factors for work performed under different work loads. Under work loads greater than about 70% of maximum, the limiting factor appeared to be the depletion of muscle glycogen depots. However, at work loads between 50% and 70%, the limiting factor could have been the same and/or an exhaustion of the hepatic glycogen causing the circulating concentration of glucose to fall below the level required for the maintenance of normal CNS function.

Although the work described previously strongly implicates the depletion of glycogen reserves as the limiting factor for severe, prolonged physical work, it should be emphasized that other authorities have proposed alternative limiting factors. For example, different investigators (Ekelund and Holmgren, 1964; Saltin and Stenberg, 1964) have measured cardiac function in men working to exhaustion on an ergometer at above 75% of their respective maxima for periods of 60-90 minutes. It was their common observation that, while $\dot{Q}$ (cardiac output, the volume of blood pumped per minute) and $\dot{V}_{O_2 max}$ remained relatively constant, HR increased substantially. Because $\dot{Q}$ is the product of HR and the average stroke volume (SV, the volume of blood pumped per beat), this means that SV must have declined substantially. In other words, during prolonged, severe exercise, the heart manages to deliver a constant blood flow to maintain a constant $\dot{V}_{O_2}$, in spite of its declining SV, by increasing HR. Yet, according to the above authors, the progressive increase in HR hastens myocardial fatigue and leads to eventual exhaustion with an inability to continue work.

Each group of investigators offered different explanations for their common finding. Ekelund and Holmgren believed that the decline in SV resulted from inadequate venous return to the heart due to a change in the distribution of the central blood volume. Saltin and Stenberg felt that some factor, possibly intracellular dehydration, progressively reduced the myocardial contractability during the work. Intracellular dehydration appeared a strong possibility in their study since the subjects lost water in perspiration and respiration which was equivalent to 3%-5% of their total body weights, while showing no significant reduction in plasma volume.

Work Under Loads of 50% Maximum or Less. I. Åstrand (1960) measured a number of physiological parameters in well-conditioned subjects working on a bicycle ergometer at 50% of maximum for nearly seven hours. Her most important finding was that the subjects' heart rates and rectal temperatures gradually increased, in a manner suggesting progressive dehydration. She did not determine whether complete recovery had occurred by the day following the work but ventured the opinion that 7-8 hours of work at 50% of maximum should be the upper limit for prolonged work performed on a daily basis.

Michael *et al.* (1961) were unable to confirm some of I. Åstrand's results: none of their subjects were able to work on an ergometer at 50% of their respective maxima for periods exceeding three hours. The same subjects were able to work at 25% on the ergometer, and at work loads up to about 44% on a treadmill, for an eight-hour period. However, only *one* subject was able to work on the treadmill at 44% of maximum for eight hours. He complained of excessive fatigue while showing substantially elevated HR (140 bpm) and rectal temperature (38.1C) at the end of work. He also reported residual fatigue and a strong disinclination for any physical work on the following day. All subjects were able to complete eight hours of treadmill work at about 35% of their respective maxima. Under that load, HR remained below 120 bpm, and rectal temperature below 38C. The subjects were not unusually fatigued by this experience and reported complete recovery within 12 hours.

Olsson (1970) reported two studies in which the same seven subjects bicycled in a 293 km road race for 17 hours (working time ≃ 15 hours) or worked on an ergometer for 14 hours, both at about 50% of their respective maxima. Olsson's primary goal was to determine the effects of prolonged work on body fluid balance. During the tests, he forced the subjects to drink all the water they could without vomiting. Still, he observed that they progressively lost water through perspiration and respiration (by 22%, in the extreme case). Much of the lost water had previously been bound to glycogen and had played no part in maintaining plasma volume. Yet, in spite of their apparent utilization of that water reserve, the subjects showed a net loss in extracellular water, since their plasma volumes were substantially reduced. According to Olsson, this progressive dehydration was almost surely responsible for an increase in the subjects' HR during the ergometer study, and was probably responsible for a decline in performance (cycling speed) in the road study. Olsson also measured about a 90% fall in muscle glycogen content over the work in both studies, and emphasized the importance of the loss of glycogen as a depletion of both energy and water reserves. Olsson mentioned nothing about the course of his subjects' recoveries from the work.

Young and his co-workers (1966, 1967; Shapira *et al.*, 1967) conducted a series of tests on 47 well-conditioned men between the ages of 23 and 42 years in which each man fasted and worked at about 33% of his maximum for 24 hours or as long as he was able. Foremost among their findings was that only a small proportion (about 11%) of those subjects were able to complete the 24-hour walking task. The first voluntary termination was after nine hours of walking and the average walking time was 16.7 hours. The most frequently given reason for terminating the walks was the onset of "generalized fatigue." The investigators were, however, unable to measure the biological basis for "generalized fatigue." They were, by direct measurement, able to show that blood glucose never approached hypoglycemic levels. They also determined from measurements of the subjects' respiratory quotient (RQ) that about one-third of the subjects' energy requirement was consistently met from carbohydrate stores. This seemed to preclude exhaustion of glycogen stores as the limiting factor for this work. The investigators also assumed that dehydration was not a limiting factor, because they forced the subjects to drink enough water at intervals during the work to ensure, theoretically, normal body hydration. They did not, however, attempt to determine whether that assumption was valid. Some ECG anomalies were noted in recordings made from the walking subjects but, with one exception, these were not judged to be sufficient cause for terminating the test.

The authors stated, from apparently very casual observations, that recovery following the work was uneventful and complete within 24 hours.

Ayoub (personal communications) at Texas Tech University has done similar studies. He has measured HR, $\dot{V}_{O_2}$, and body temperatures in men working for periods up to 24 hours on a treadmill at 30% and 50% of their respective maxima. In general, his preliminary results support much of what has been described above. The subjects were generally able to walk for 24 hours at 30%, but with progressively increasing HR's and high (> 38C) rectal temperatures, perhaps indicative of progressive dehydration. However, the subjects were unable to work at 50% for the same period. The subjects' reasons for quitting under the heavier work load were not reported.

Discussion of the Biological Effects of Prolonged Physical Work

It has never been demonstrated in the laboratory that men are capable of performing continuous physical work at some realistic level (between 30% and 50% of $\dot{V}_{O_2max}$) for time periods which may be encountered in continuous and sustained operations. Thus, nothing definite can be said regarding the recovery period that will be required in the event that men do someday perform in that manner. But the literature on prolonged physical work does allow some tentative generalizations.

Work under very light loads will probably be limited by the need for sleep. Work under moderate to heavy loads, such as those experienced by riflemen carrying full packs and marching at 6.5 km/hr (4.0 mph) might well be limited by other factors. The most likely now appears to be progressive dehydration.

More should be said about the potential problem of dehydration. It is well known that the mechanism of thirst is not sufficient for maintaining fluid balance in exercising men, particularly in hot (> 28C) environments. After losing water due to perspiration and increased respiration, men do not immediately replace the lost fluid by drinking when unlimited water is available. Rather, the water is replaced gradually over hours or days, even though this slow return to fluid balance may leave the individual behaviorally and physiologically debilitated during the interim. This phenomenon has been widely recognized and has been called "voluntary dehydration" (Adolf *et al.*, 1947), or more correctly, "involuntary hypohydration" (Greenleaf, 1966).

The body water loss during prolonged submaximal work may be substantial: water deficits up to 8% of initial body weight have been reported (Strydom and Holdsworth, 1968). The physiological effects of hypohydration are varied and may be severe. After as little as a 1%-2% water loss, there is clear indication of increased circulatory strain; i.e., with a diminished plasma volume, the heart must beat more frequently to maintain a constant $\dot{Q}$ (Saltin, 1964). A progressive water deficit also leads to declining capability of the thermoregulatory system for maintaining body temperature. The sweat rate falls, leading to rising body temperature and further decline in sweat rate (Strydom and Holdsworth, 1968; Ekblom *et al.*, 1970; Greenleaf and Castle, 1971). If left unchecked, progressive dehydration would certainly lead to circulatory insufficiency, heat exhaustion, or both.

Psychologically, hypohydration increases subjective feelings of fatigue (Greenleaf and Sargent, 1965; Strydom and Holdsworth, 1968). Naturally enough, this decreases motivation for performing physical work. A remarkable example of how extreme that reaction can be may be taken from Strydom *et al.* (1966). Those investigators studied the reactions of

60 soldiers carrying 24 kg and marching at 6.5 km/hr on a 29 km hike. Throughout the march, the ambient temperature and humidity were moderate. Half of the group was allowed one liter of water while the other half was permitted to drink *ad lib.* (the latter, in fact, drank an average of 2.7L during the march).

Seven of the water-restricted soldiers and one from the *ad lib.* group fell out or collapsed in exhaustion. Those from the water-restricted group who completed the march endured an average 4.8% (of body weight) water loss, and a 1.7C increase in body temperature. Those from the *ad lib.* group who were successful endured an average 3.9% water loss and a 1.2C increase in body temperature. Thus, both groups became hypohydrated and suffered from hyperthermia, although to different degrees. More striking were the effects of hypohydration on the men's morale. According to the authors:

> At the start, and even up to about the third hour of marching, there was little to distinguish between the two groups with respect to general appearance and behavior. Thereafter a distinct difference in reaction and appearance occurred. Whereas the morale of the *ad lib.* group remained high throughout, that of the restricted group was markedly poor; they became morose, aggressive, and disobedient towards their superiors and showed obvious signs of fatigue. A subject from [the restricted] group defied all orders and attempted to snatch water from a subject in the other group. One of the unsuccessful subjects complained bitterly to the officer-in-charge when refused additional water and then summarily refused to walk further. He was given extra water, allowed to ride on the truck and then became most apologetic about his behavior.
>
> The response to discipline among the group decreased markedly towards the latter part of the march. The members of [the restricted] group were mainly responsible for this decline. On being reprimanded for not keeping up the pace, they talked back and were difficult to control. To some extent, this behavior also influenced men in the [*ad lib.*] group, but in general these men were still easy to handle and kept their positions in order of marching until the end.

The authors could not deny the possibility that the low morale in the water-restricted group partly resulted from feelings that they had been unfairly selected for an exceptionally stressful experience. Nonetheless, the striking and unusual degree of insubordination shown by the men to their officers strongly suggested that hypohydration had the effect of dramatically reducing the men's tolerance for frustration while increasing their feelings of fatigue.

Recovery from hypohydration is relatively slow. Restoration of fluid balance after severe (6%-8%) hypohydration requires 2-3 days for completion (Lemaire, as described by Greenleaf and Sargent, 1965).

The problem of involuntary hypohydration may be precluded in sustained and continuous operations by determining water and electrolyte balance at frequent intervals and by forcing replacement of lost water and salt. In view of the likelihood and seriousness of the problem, this measure seems mandatory.

Another problem in continuous and sustained operations might be depletion of the body's energy stores. No one knows whether the human is capable of storing and effectively utilizing appropriate energy sources when required to expend energy at rates that can be anticipated during a sustained operation (see the preceding chapter). The studies by Young and his co-workers described above have shown that men working under a moderate (33% $\dot{V}_{O_2max}$) load for 24 hours can convert fat to glucose rapidly enough to ensure normal CNS function. However, it is not known whether those individuals maintained enough of a carbohydrate reserve to meet an additional demand for energy. Could they, for example, have sustained a two-fold increase in energy expenditure required in an emergency situation after their 24-hour march? Questions like this should be answered before men are committed in life-or-death situations during continuous or sustained operations.

OTHER RELEVANT STRESSES

In addition to the consequences of sleep deprivation and prolonged physical work, it is likely that men in sustained and continuous operations will suffer from the disruption of certain of their biological rhythms, from the threat of injury and/or death, and from environmental stressors such as heat or cold. The extensive literature on the effects of stress will not be reviewed in detail here. However, it seems certain that the presence of other stressors during prolonged periods of activity will affect the rate of degradation of men's performance and physiological status, and the period of recovery needed to restore the men to normal functioning.

Disruption of Circadian Rhythms

There exists little doubt that human behavioral efficiency normally follows a circadian rhythm. This has been repeatedly demonstrated for subjects performing both abstract laboratory tasks (e.g., Kleitman, 1963; Alluisi and Chiles, 1967) and more realistic complex tasks such as "flying" an F-104 simulator (Klein, 1970). Behavioral efficiency was usually found to be highest at 1200-1800 hours, and lowest at 0300-0600 hours. Moreover, the cycle of behavioral efficiency seems to be in phase with the circadian rhythm of psychophysiological arousal as judged from body temperature and autonomic tone (Klein, 1970; Fröberg *et al.*, 1970b; Kleitman, 1963).

Disruption of the normal circadian rhythm by temporal displacement or by the assumption of unusual work/rest cycles has been shown to initially result in sleep disturbances and impaired performance efficiency (Benson, 1970; Klein *et al.*, 1970; Siegel *et al.*, 1969). Adaptation to local time after a temporal displacement eventually occurs after a period determined by both the amount and direction of the time change (e.g., Siegel *et al.*, 1969). Adaptation to some unusual work/rest cycles is apparently quite possible, although there are great individual differences in this respect. U. S. Navy personnel have long performed acceptably while operating according to four-on/four-off (surface Navy), or six-on/twelve-off (submarine), duty cycles. Likewise, men confined within a simulated space capsule maintained a constant acceptable level of performance on a battery of tasks for 30 days while operating on a four-on/four-off schedule (Chiles *et al.*, 1968). Similarly, individuals have been found able to adjust their activity and arousal rhythms to adjust to both 21-hour and 27-hour "days" (Lewis and Loban, 1957).

However, with the exception of a single individual who apparently adapted to what amounted to a 60-hour "day" (48 hours on/12-14 hours off) (Oswald, 1963), there have been no reported cases of adaptation to "days" longer than 27 hours. On the contrary, Kleitman (1963) described two individuals who, for one month, *attempted* to adapt to a 48-hour "day" (40 hours on/8 hours off). They consistently reported marked sleepiness with low motivation and capability for performing work during the first night of their 48-hour "day." Kleitman concluded that men may be unable to resynchronize their basic circadian rhythm of arousal to conform to "days" of exceptionally long duration.

Hale *et al.* (1968) studied fatigue in C-130 and C-135 aircrew members as they engaged in prolonged and repeated flying missions. On one type of mission, the fliers worked continuously for 20-35 hours and were then allowed to rest for about 24 hours before undertaking another flight. From measurements of urinary excretion rates of adrenaline and noradrenaline, Hale *et al.* were able to demonstrate that fliers were in a chronic state of stress throughout the mission. On another type of mission, when the aircrewmen were allowed

10 days of rest between similar periods of work, the fliers were apparently able to recover between flights. Operational performance was not measured, so it is impossible to say whether the men's efficiency was impaired by their arduous duty cycles. However, it is clear that, at best, the men were able to maintain acceptable levels of performance while operating according to 44-hour to 69-hour "days" only at considerable physiological cost.

Physiological dysfunctions that might occur in men performing according to unusually long work/rest cycles are matters for conjecture. This is mainly because no one understands the nature of, or necessity for, circadian periodicity in biological functioning. Nonetheless, there are a few research findings which indicate that certain biological rhythms may be essential for the maintenance of homeostasis and behavioral efficiency. For example, data obtained by Frank *et al.* (1966) suggest that the early morning rise in the circulating cortisol concentration may be responsible for the later increase in the CNS level of arousal. The data showed a periodic relationship with a six-hour, or 90° phase, difference between plasma cortisol and the total EEG power output. The authors interpreted their data, in the light of other research findings, as showing that the rise in circulating cortisol may, after a presently inexplicable delay, facilitate synoptic transmissions in the midbrain reticular activating system and, thus, increase the general level of CNS arousal.

As noted earlier, a general damping of the circadian rhythm for circulating cortisol has been observed in sleep-deprived subjects (Murawski and Crabbé, 1960). Similarly, in the study by Hale *et al.* described above, airmen operating in accordance with arduous duty cycles excreted subnormal amounts of cortisol metabolites (i.e., the 17-OHCS's). Thus there is some support for the notion that disruption of circadian rhythm of circulating cortisol may lead to impaired CNS function and behavioral deficiencies in men adhering to unusually long work/rest duty cycles.

There is also circadian periodicity for sensitivity to various disease states and tolerance for various environmental stressors. For example, asthmatic attacks, acute myocardial insufficiency, and infarcts are commonest at the nadir of psychophysiological arousal; i.e., at about 0400 hours (Martinez-O'Ferral, 1968). Hypoxia tolerance, on the other hand, is greatest at that time (Klein *et al.*, 1968). There is also evidence from research on animals that susceptibility to infection follows a circadian rhythm (Halberg, 1962). Again, it is not known whether susceptibility to disease and tolerance for stress would be affected by a disruption of circadian rhythms that might occur in men engaged in around-the-clock operations. Yet these remain as distinct possibilities which cannot be ignored.

Threat of Injury and/or Death in Combat

A major component of stress endured by soldiers in combat has arisen from the imminent threat of injury or death. Unfortunately, little is known about the specific effects of that stress. Prior to World War II, there was very limited and ill-conceived recognition of the problems arising from exposure to threat in combat. Studies performed during World War II concentrated on largely anecdotal observations by field commanders and on the incidence of psychiatric casualties following different exposures to combat in various campaigns (e.g., Cannon *et al.*, 1964). Thus those early studies are of limited utility for defining the effects of stress experienced by infantrymen who do not become psychiatric casualties in combat. Moreover, they provide very little information for estimating the periods of recovery that must be provided to ensure a return to full combat efficiency after various exposures to that stress.

During the Korean War, a major investigation was undertaken by a University of California group who attempted to show how groups of infantrymen are affected by engaging in intense offensive and defensive operations (Pace *et al.*, 1956; Elmadjian, 1955). Two infantry companies were studied: one engaged in an 18-hour attack of regimental size and sustained 61% casualties; the other held a defensive position and sustained 17% casualties while withstanding three enemy counterattacks over a five-day period. At the end of their ordeals, both companies appeared near the limit of their endurance, showing marked signs of physical exhaustion and mental depression.

Twelve hours after being withdrawn from combat, both groups showed biochemical and physiological signs of having endured considerable stress. The attacking group in particular showed signs of substantially increased protein catabolism. Both groups showed a marked increase in glucose excretion, and both groups showed a lack of sympathetic reactivity to an injection of the depressor drug, mecholyl. The groups differed with respect to excretion of the 17-ketosteroids (metabolites, primarily, of the anabolic steroid hormones; e.g., testosterone); the excretory rate for the attacking group was elevated, whereas that for the defending group was depressed. Injections of adrenocorticotrophic hormone (ACTH) apparently produced a nearly normal increase in cortisol secretion by the adrenal cortex in the attacking group. However, the same treatment produced almost no effect on members of the defending group.

From all biochemical and physiological signs, the recovery of the attacking group was complete after five days, whereas recovery was not complete for the defensive group until more than 10 days had elapsed since the men had engaged in combat.

Other information from the Korean War confirms the apparent requirement for an extensive recovery period following exposure to combat. Van de Water (1954) reported that soldiers removed from the combat area after fighting intermittently for from 2 to 4 weeks were chronically hypohydrated and showed a stress-induced paucity of white blood cells. Remission of those signs was complete in from 5 to 12 days, depending upon the individual and prior exposure to combat.

In the Vietnam War, a few attempts have been made to show the effects of combat stress on certain endocrine and metabolic processes. Bourne *et al.* (1968) found, for example, members of a Special Forces A team holding an isolated outpost under threat of an imminent attack experienced stress in degrees related to their respective awareness of the total tactical situation and their responsibility for the team's effectiveness and well-being. Judging from 17-OHCS excretion rates, the officers and a radioman apparently experienced more stress than the other enlisted men. There was also some evidence suggesting that secretions of the catabolic and anabolic steroids were reciprocally related in those individuals under stress; the higher the 17-OHCS excretion rate, the lower was the testosterone excretion rate (Rose *et al.*, 1969).

Naval aviators engaging in combat operations over North Vietnam were also studied (Austin *et al.*, 1967). In particular, various plasma lipid fractions were measured and it was shown that certain circulating lipid (i.e., phosphatidyl glycerol, phosphatidic acid, and phosphatidyl ethanolamine) levels were chronically elevated. Moreover, the alteration in lipid metabolism implied by those changes was most persistent: the recovery of normal lipid metabolism occurred slowly for weeks after removal from the combat area.

To summarize, even the scanty information presently available strongly suggests that exposure to combat produces a state of stress which is in many ways more severe and persistent than those produced in the laboratory studies described above. Work completed during the Korean War has shown that infantrymen, exposed for less than a day of intense combat, lose nitrogen in a manner suggesting a marked increase in protein catabolism. Soldiers exposed to less intense combat for longer periods were found to become hypohydrated and showed hematological changes suggesting some impairment of the body's defenses against infection. Whether their exposure was long or short, infantrymen apparently developed diminished adrenocortical and sympathoadrenomedullary responsiveness as a result of combat experience. That is, their ability to rise physiologically to meet new challenges appeared diminished. Recoveries from these states of stress were slow, requiring at least five days, and usually longer.

More recent data have shown that the effects of combat stress may be greater in infantrymen who, by means of rank or specialty, possess greater awareness or responsibility in the stressful situation. Furthermore, the finding of slowly reversible alterations of lipid metabolism in naval aviators flying combat missions clearly demonstrates the potency of threat as a stressor in combat. Those men were properly nourished and their rest between missions was at least sufficient to ensure a high level of performance efficiency. They were not subject to heavy physical work or extreme environmental conditions. Yet their physiological homeostasis was disturbed in a manner that might eventually lead to the failure of a susceptible physiological system.

Environmental Stressors

Men engaging in sustained or continuous operations will rarely perform their missions under optimal environmental conditions. It is predictable that they will often be required to endure thermal stress. If those missions are conducted at altitude, they will operate under hypoxic stress. Armored personnel will have to endure additional stress resulting from confinement, noise, and vibration. Given the high caloric requirement of troops, and the difficulty of fulfilling that requirement during sustained and continuous operations, it is even possible that those personnel will suffer a nutritional deficit. All of these factors have been repeatedly shown to impair physical and mental working capacity and to increase susceptibility to diseases of many types. Excellent reviews of the separate effects of each stressor exist (e.g., Dill *et al.*, 1964; Edholm and Bacharach, 1965; Poulton, 1971) and no attempt can be made to duplicate those works here. However, any attempt to generalize from the information provided in this review should be tempered with the knowledge that the information was compiled largely from studies in which the isolated effects of a stressor, such as sleep deprivation or physical work, was studied under otherwise benign circumstances. Under realistic field conditions, it can be expected that the degradation in both the men's performance and physiological status will occur much more rapidly and recovery will be slower as a consequence of the combination and interaction of the effects of numerous stressors.

CONCLUSIONS

What has been learned from the literature survey about recovery functions in man that may be applied in evaluating the concepts of sustained and continuous operations? There have been no directly relevant studies of continuous operations; that is, where men have performed operational tasks under field conditions on given work/rest and performance/recovery schedules for extended periods of time. The literature does not provide the data necessary to implement the continuous operations concept, but perhaps it does provide guidelines for the design of studies to collect the required data. The factors that must be considered in the design of such studies are discussed below.

Operational Tasks

The evidence is strong that one cannot generalize from performance in laboratory tasks to performance on real tasks. Military tasks are often complex and often well learned. Complex tasks are more likely to be sensitive to the effects of adverse conditions; well-learned tasks more likely to be resistant. The military tasks most likely to suffer performance decrements under adverse conditions are monitoring tasks, perceptual tasks that require interpretations of events and appropriate responses, and, probably, complex decision tasks that call on short-term memory stores. If valid inferences are to be drawn about performance in continuous operations, means must be developed to measure operational task performance.

Field Conditions

Laboratory conditions in which some significant variables are present, like sleep deprivation, and many others are absent, like environmental stressors, provide little basis for determining the effects of adverse conditions on performance or physiological responses. There are, undoubtedly, always present some combination of stressors in the field. One important field stressor in the military situation is the amount of physical work done by soldiers in marching, carrying loads, fighting, and so on. The effects of this stressor, together with those of environmental stressors, will certainly interact to determine the capability of men to endure given work/rest and performance/recovery schedules. And the course of recovery will certainly depend on the nature and intensity of the field stressors.

Cumulative Effects

There will likely be cumulative effects of any work/rest or performance/recovery schedule where the rest periods are not adequate to fully restore all functions. No one knows if it is necessary to completely return all physiological systems to a normal range of functioning before again exposing men to adverse conditions. But if systems are not adequately restored, the consequences may be a sudden failure in a system that could immobilize a man. The important questions to be answered concern the effects of repeated exposure periods on performance and physiological status. Does the cost of maintaining effective performance build to a breaking point? And what recovery schedules are necessary to prevent a cumulation of effects?

Characteristics of Men

The common finding of all studies of the effects of adverse conditions is that men differ in their ability to perform or function effectively under the conditions and, probably, if it were known, to recover from their efforts. Responses will likely vary as a function of such variables as physical fitness, experience with the adverse conditions, the level of training on tasks, the level of performance skill, motivation, and personality factors. One variable that has received scant attention in the literature is age. If the Volunteer Army is implemented, one consequence would likely be an increase in the mean age of soldiers. It seems important to determine the effects of the many adverse variables likely to be encountered in continuous operations in both young and older men. "Young, healthy males" make good, "safe" subjects for studies of adverse conditions, but limit the generalization of results. Another important variable in the military situation is the command responsibility of men. A commander is subject to many pressures that junior men are not: he is responsible for other men, he must make critical decisions affecting them, the situation, and himself, and he is usually more aware of threat and the possible immediate consequences of bad decisions. The commander and his performance should also be observed in continuous operations situations.

Circadian Rhythms

Performance and physiological system response have been shown to vary at different times of the day. If men are kept awake and required to perform when ordinarily they would be sleeping, their performance may suffer. This possibility is obviously important in an around-the-clock continuous operation. It may also be important if men are transported suddenly to a significantly different time zone and required to perform immediately. This is not an unlikely event in modern warfare with the dependence on air transport for quick response to threatening situations. The effects of circadian periodicitv and the course of adaptation to temporal displacements needs study in operational situations.

Physiological Systems

Changes in the status of physiological systems certainly occur before changes in performance are observed, as the systems react to compensate for the onslaught of aversive stimuli. It seems likely that measures of physiological systems responses will provide the significant criteria to determine the effects of adverse conditions and the course of recovery from them. The literature has provided many suggestions about physiological systems and measures of their functions that might be applied in studies of continuous operations. The following potential physiological failures seem most important to consider:

1. Degraded physical working capacity.
2. Inadequate iron reclamation leading to hypochromic anemia.
3. Myocardial "fatigue."
4. Paroxymal cerebral cortical activity.
5. Impaired carbohydrate metabolism.
6. Thiamine deficiency due to increased urinary excretion.
7. Involuntary hypohydration.
8. Glycogen exhaustion and, possibly, hypoglycemia.
9. Alterations in practically all system functions that may arise from disrupted circadian periodicity.
10. Increased susceptibility to infection and decreased tolerance to stressors.
11. Imbalanced protein metabolism leading to exhaustion of protein reserves and, possibly, structural damage.
12. Adrenal cortical or medullary exhaustion.

This is a forbidding list of possible systemic effects of adverse stimulation, but an evaluation of continuous operations demands that they be considered. All except the last two dysfunctions have been observed in the laboratory (imbalanced protein metabolism and adrenal exhaustion were observed in the Korean battlefield study). The field conditions of continuous operations will surely be more severe than those of the laboratory.

Recommendations for Physiological Research

This review has left us with little doubt that soldiers engaging in sustained and continuous operations will experience some physiological dysfunctions. Exactly what these will include and the importance of each is difficult to determine from the literature. So also is the recovery period which will be required to resolve all dysfunctions. This is mainly because studies of men engaged in prolonged activities similar to those anticipated for sustained and continuous operations have yet to be conducted.

The evidence compiled to date indicates that several system functions are particularly susceptible to the stresses imposed by prolonged wakefulness and physical activity; and likely susceptible to stresses imposed by combat and extreme environmental conditions.

It is recommended that the existence and importance of each of the identified physiological failures be ascertained before men are committed in sustained and continuous operations. This should be accomplished in extensive and complementary laboratory and field investigations. Some laboratory studies are required by the necessity for highly controlled and sometimes invasive (e.g., venipuncture) physiological measurement procedures. But significant laboratory findings should be validated by the results of more realistic field studies. Regardless of the research setting, certain principles should guide the design and conduct of studies to ensure that results are indeed applicable to sustained and continuous operations.

1. The performance/recovery cycle should be a realistic approximation of that anticipated for sustained and continuous operations. The performance period should be prolonged, probably 48 hours or longer. Various recovery periods should be investigated to determine both the course of recovery and the time required to ensure effective recovery from the efforts of the performance period.

2. Studies should encompass at least two, and preferably more, performance/recovery cycles. Since we are ignorant of the exact number and nature of significant system dysfunctions that will occur during the performance period, any judgment of the time required for whole-body recovery might be seriously in error if based solely upon measurements of the recoveries of currently identified dysfunctions which develop during a single performance period. The selected recovery period might be too short if unmeasured, though significant and slowly reversible, dysfunctions occur; and too long, if the significance of observed system dysfunctions is exaggerated. It seems that the reasonable way to determine the adequacy of a given recovery period is to measure critical whole-body and system functions during periods of performance prior to and following recovery.

3. The work/rest schedules within performance periods should be varied. The extent to which systems will be depleted or exhausted and, in turn, the time required to restore them, will surely be a function of the amount and spacing of rest during the performance period.

4. The activities of subjects during the performance period should realistically simulate those activities soldiers engage in during military operations, at least with respect to *total energy expenditures.*

5. Every attempt should be made to relate any physiological changes observed to changes in task performance, in subjective feelings, in motivation to continue working, and in various interpersonal or social variables, such as communications between members of the subject group.

6. The effects of superimposed environmental stressors, such as inadequate nutrition, temperature extremes, or low oxygen levels, on subjects during both work and rest periods should be determined. Superimposed stress seems very likely to hasten exhaustion during work and retard recovery during rest; and, therefore, must be considered when setting realistic performance/recovery and work/rest schedules.

Literature reviews directed toward answering practical problems often end with a statement of critical information which is lacking. This one is no exception. Physiological data are needed to answer such basic questions as:

1. Does prolonged wakefulness and physical activity inhibit the usual nocturnal rise in the circulating concentrations of agents, such as the growth hormone and insulin, which have a restorative effect on energy depots within the body?

2. Does the cardiovascular system lose any capacity for coping with increased circulatory demands? For example, can the heart continue to increase its output by a constant amount in response to intermittent applications of a constant work load during prolonged wakefulness? And can the heart and vascular system continue to maintain an adequate blood pressure during exercise and postural change?

3. What are the reactions of the musculoskeletal, renal, hepatic, gastrointestinal, and infection combating systems to prolonged wakefulness and physical activity?

4. What are the reactions of endocrine systems other than the adrenal cortex and medulla?

5. Do men acclimatize to prolonged and repeated performance/recovery cycles? If so, how long does it take for acclimatization to occur, and how long does acclimatization persist after resumption of the normal 24-hour diurnal rhythm?

6. Are there pharmacological means for increasing the performance capabilities of men during periods of prolonged wakefulness and physical activity, or for decreasing the time necessary for recovery in the subsequent rest periods?

Many similar questions could be posed. It is not reasonable to recommend immediate research for answering each one. However, the point is that much more information will have to be acquired before anyone can say whether the present concepts of sustained and continuous operations are *physiologically* feasible.

The Concept of Continuous Operations

In our discussion of the literature, we have treated the concept of continuous operations as if it were a meaningful one; that is, what one has to do is to figure out how *best* to implement the concept from knowledge of the capacities of men. The notion of maintaining an around-the-clock effective fighting force for long periods of time is a compelling one. But the notion that this can be achieved by getting more out of men is probably fallacious. We have noted that men can and will perform effectively for extended periods when forced by circumstances to do so. If the extended performances were *planned*, though, rather than dictated by circumstances, men may be unable, or *unwilling*, to function effectively for very long periods--particularly if performance/recovery cycles persisted indefinitely.

It is obvious that men must be given rest periods if they are to function effectively during performance periods. It is useful to look at some consequences for force effectiveness of different combinations of performance/recovery and work/rest schedules. Table 1 shows the percentage of the total forces a commander has at his disposal that are in the field and "up" at a given time for representative schedule combinations.

The ratios shown for the performance/recovery schedules could be in terms of hours, days, or even weeks: for example, 5-day-performance-period/2-day-recovery-period or 48-hour-performance/12-hour recovery or 3-week/1-week. The ratios for the work/rest schedule are in terms of hours. If a 1/1 performance/recovery schedule is maintained, the force in the field represents 50% of the forces available to the commander; if the field forces are on a 3/1 work/rest schedule, the "effective" force at a given time is 38% of the total forces. Under the "best" schedule conditions illustrated in the table, 4/1 and 4/1, force effectiveness is 64%.

TABLE 1

FORCE "EFFECTIVENESS" BY PERFORMANCE/RECOVERY AND WORK/REST SCHEDULES

Performance/ Recovery Schedule	In Field	Work/Rest Schedule 1/1	2/1	3/1	4/1
	%	%	%	%	%
1/1	50	25	33	38	40
2/1	67	33	45	50	53
5/2	71	36	47	53	57
3/1	75	38	50	56	60
7/2	78	39	52	59	62
4/1	80	40	53	60	64

This kind of measure of force effectiveness obviously does not make sense. Two assumptions were made in constructing and interpreting the table, neither of which is true. One is that men can be substituted for one another on a one-to-one basis; the other is that during a performance period a man is "effective." The first assumption ignores both variability in men and in the many different tasks performed by soldiers in the field. A rifleman and a radio operator likely are not interchangeable; a rifleman and a commander certainly are not. The second assumption ignores variability in the performance of men over time and the demands of different tasks, among other things. The point of presenting this illustration, then, is not to argue for its validity, but rather to suggest that the concept of continuous operations be further analyzed from a logistics viewpoint. We think that the concept has been accepted uncritically, and that an analysis based on present operational data likely will prove it to be untenable.

Final Remarks

We think that the implementation of the concept of continuous operations is not feasible, if "continuous operations" implies pushing men to the limits of their capabilities. Men likely will not perform or function effectively for very long periods unless there are good reasons for doing so. A planned attempt to get the most out of men will not be viewed as a good reason. If the purpose is to take advantage of night-fighting equipment, perhaps a better concept would be to select and train day and night fighting units. Men do adapt to changed time schedules, witness shift workers, and some men perform better at night than other men. Perhaps the concept also should be to maximize, rather than minimize, rest and recovery periods; the result would surely be a more effective fighting force.

The concept of sustained operations is a different matter. Circumstances will dictate sustained operations but, in some cases, they may be planned. Whether planned or fortuitous, the commander must know how well his men can perform over long periods and how long they must be rested to restore depleted resources. The information the commander needs is not presently available.

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