



**A Review of the Relationships Among Sleep,
Sleep Deprivation, and Exercise**

By

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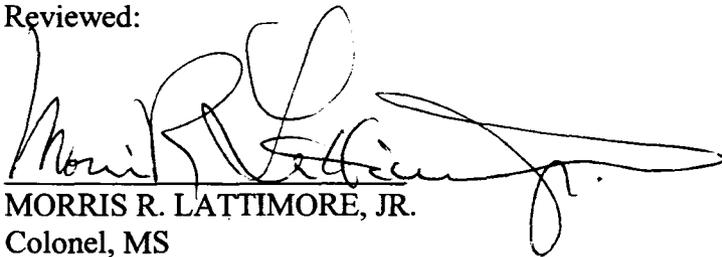
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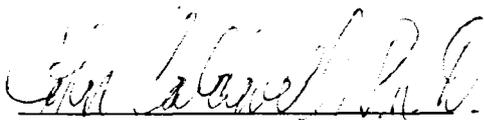
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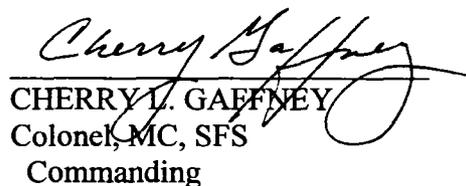


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19. ABSTRACT (Continue on reverse if necessary and identify by block number) This review looked at some of the problems associated with conducting sleep and exercise studies. The impact of factors such as age, gender, fitness level of subjects, and duration and intensity of exercise have been examined. In general, the beneficial effects of exercise on sleep are most pronounced if the exercise is aerobic, conducted in the late afternoon, and of a moderate duration. Disruptive effects are seen when exercise is too close to bedtime or of extremely long durations. With regards to sleep loss and performance, declines in physical and motor performance appear to be influenced more by changes in psychological factors such as mood and perceived exertion than by changes in physiological factors such as blood pressure and heart rate. Literature examining the interaction of sleep deprivation/restriction and exercise on cognitive, physiological, and psychological performance was also investigated. In the majority of studies examining the effects of exercise in sleep deprived subjects, exercise is typically used as a stressor. Articles examining the positive or alerting effects of exercise in sleep deprived/restricted subjects are much less common. Recent evidence does, however, suggest that measures such as self-rated alertness and vigilance performance in sleep (Cont.)												
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deprived subjects can be improved by exercise. Further research is needed to more fully examine the feasibility of using exercise as a countermeasure to help lessen or prevent the performance decrements typically observed in fatigued people.

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Introduction

This paper sprang from what we thought would be a simple search of the exercise literature. We were interested in non-pharmacological interventions which might be of use in preventing or delaying performance decrements associated with sleep deprivation. As everyone knows that exercise makes you feel energetic and alert, we felt sure that it would have been used as a countermeasure for sleep loss induced performance declines. In our search, we found that people had expressed the opinion that exercise could make you feel more energetic and alert. However, we also found that little research had actually been done to test this hypothesis. We did find that some very distinct categories, each with their own set of problems, existed in the sleep and exercise literature. This paper examines some of the difficulties inherent in conducting sleep and exercise studies and tries to present a rationale for extending the use of exercise beyond that of its typical use as an additional stressor in sleep deprivation studies.

Three major divisions in sleep and exercise literature exist. Two of these areas, the effects of exercise/work performance on sleep and the effects of sleep on exercise/work performance, have been well documented but are still topics of much debate. Factors such as age and gender, intensity and duration of exercise, time of day effects, proximity of exercise to sleep time, type of exercise, fitness level of subjects, and duration of sleep or sleep deprivation all cloud the issues. A third area, the effects of exercise on arousal/cognitive performance in sleep deprived/restricted subjects, is no less important but is less well documented. While studies on the effects of exercise in sleep deprived/restricted subjects have been conducted, the typical study examines the effects of exercise on subsequent recovery sleep architecture or physical performance. Studies examining the effects of exercise on cognitive or vigilance performance in sleep deprived (SD) subjects are much less common.

Effects of Exercise/Work Performance on Sleep

According to the existing review papers, sleep electroencephalographic (EEG) patterns are most often used to objectively examine the effects of exercise on sleep. The most common theories of exercise and sleep, the restorative theory and energy conservation theory, predict that the total duration of sleep and in particular the amount of slow wave sleep (SWS) (Stages 3 & 4) will increase following exercise. Increases in SWS which are seen following periods of sleep deprivation and intense exercise have been suggested as part of the restorative and energy conservation process (Adams and Oswald, 1983; Berger and Phillips, 1988; 1990). As energy expenditure increases, presumably as a function of exercise duration and intensity, changes in sleep patterns such as shorter sleep latencies, longer sleep durations, and increases in SWS should mirror the energy output. In a subset of subjects, particularly in younger physically fit individuals, these predictions seems to hold true (Horne, 1981). However, in others such as unfit subjects (regardless of age) and older fit subjects, exercise does not appear to facilitate SWS (Browman and Tepas, 1976; Desjardins et al., 1974; Griffin and Trinder, 1978; Trinder et al.,

1982). Thus, to date, no comprehensive theory has been put forward which can account for the variable changes in sleep which are produced by exercise.

The effect of exercise on subsequent sleep quality and quantity has been the subject of debate for over two decades. Numerous research and review papers on this topic have been published (Horne, 1981; Shapiro, 1981; Shapiro and Driver, 1988; Torsvall, 1981; Trinder et al., 1988), to include a recent meta-analytic review (Kubitz et al., 1996). The review papers generally concur that exercise can produce changes (an increase) in SWS. Horne (1981) and Torsvall (1981) in two independent literature reviews concluded that exercise reliably increased SWS in physically fit individuals. Reviews by Shapiro (1981) and Shapiro and Driver (1988) also concluded that exercise increased SWS and extended their findings to include exercise induced increases in sleep duration and decreases in sleep onset latency. This is not to say that there are no conflicting points of view. Horne (1981) points out that most studies which show large increases in SWS following exercise have been conducted in places with warm or hot climates. These changes are not observed when subjects are cooled during the exercise periods (Horne and Moore, 1985). It has also been demonstrated that increases in core body temperature produced by passive body heating can increase SWS and decrease sleep onset latency (Horne and Moore, 1985; Horne and Reid, 1985; Horne and Shackell, 1987; Horne and Staff, 1983). Thus, changes in sleep patterns may stem from increased core body temperature produced by exercise. Additionally, Trinder et al. (1988) have reexamined much of the literature contained in earlier narrative reviews. These authors concluded that some of the earlier reviews had overstated the positive evidence and that the existing evidence is ambiguous at best. They further argue that little evidence supports the contention that exercise, acute or chronic, can induce increases in sleep duration or SWS.

Acute vs Chronic Exercise

Despite the different results observed in the exercise/sleep research, many studies do report similar results when using acute or chronic exercise as independent variables. Those studies examining exercise vs no exercise conditions are typically defined as acute while research using athletic (fit) vs non-athletic (unfit) subjects are considered chronic. A recent meta-analysis examining the effects of acute exercise on sleep was conducted by Youngstedt et al. (1997). These researchers reported that acute exercise influenced SWS (19 studies found decreases and 30 found increases), reduced the amount of rapid eye movement sleep (REM), delayed the onset of REM sleep, and increased total sleep time. REM sleep is categorized by a low voltage, mixed EEG pattern accompanied by episodic rapid eye movements and very low muscle tone as reflected by electromyogram (EMG) (Rechtschaffen & Kales, 1968). A second exercise and sleep meta-analysis was done by Kubitz et al. (1996), using 32 acute and 12 chronic exercise studies. These authors concluded that both chronic and acute exercise produced a reliable effect on sleep. Increases in SWS and total sleep time and decreases in sleep onset latency and REM sleep were observed in both types of examinations. While these conclusions conflict with others (Trinder et al., 1988) these authors point out that past failures to find an effect of exercise on sleep in acute or chronic studies may be due to compromised statistical power, as sample and

effect sizes in this research field are typically small. Kubitz et al. (1996) additionally point out that failure to find an effect of acute exercise in high fit individuals but observing increases in SWS in low fit individuals, may be due to a ceiling effect. If high fitness individuals have already achieved sleep patterns associated with chronic exercise, they have less room for improvement than low fit individuals.

Intensity of Exercise

The literature becomes murkier when looking at factors such as duration of exercise, intensity of exercise, the time of day exercise is conducted, age, and gender. Many different durations, from a few minutes to many hours, and intensities of exercise, from 20% to 100% VO_2 max, appear throughout the research (see Horne, 1981, Table 1; and Kubitz et al., 1996, Table V). In many cases, studies do not independently examine exercise intensity and duration, varying both within the same study. For example, Paxton et al. (1982) examined the effect of four different intensities of exercise (0%, 50%, 70%, 100% VO_2 max) over 5 days. Sleep measures were assessed on the evenings of exercise sessions 1, 3, and 5. While exercise had no effect on any sleep variable, the duration of exercise at the different intensities was not comparable. The duration of exercise for the 50% group was 45 min, the 70% group exercised for 1 hr, while the 100% group worked until exhaustion. Thus, it is difficult to conclude if the intensity or the duration of exercise was insufficient to produce changes in sleep patterns. In contrast to the results obtained by Paxton et al. (1982), Shapiro et al. (1975) found corresponding increases in SWS and decreases in REM sleep with increasing intensities of exercise (0%, 50%, 75%). The observed differences may, however, have been due to subject fitness levels. Shapiro et al. used extremely fit subjects while Paxton et al. used unfit subjects. Research has shown that increases in SWS and decreases in REM sleep following exercise are more consistently observed in fit subjects.

Duration of Exercise

While a few studies have examined the effects of various exercise intensities on sleep patterns, the effects of different durations of exercise have been more closely examined. Exercise bouts lasting less than 60 mins appear to have little effect on subsequent sleep patterns (Browman and Tepas, 1976; Walker et al., 1978). More lengthy exercise bouts, 1-4 hrs, reliably produce increases in SWS (Bunnell et al., 1983a; Horne and Porter, 1975). The exercise induced changes may be reflected as an overall increase in total SWS, an increase seen only during the first sleep cycle, or an increase in one stage of SWS (Bonnet, 1980; Browman, 1980). It does appear that exercise beyond a certain threshold (approximately 4.5 hrs) disrupts sleep patterns (Driver and Taylor, 1996; Montgomery et al., 1985). Driver et al. (1994) found that sleep patterns following an ultra-triathlon (up to 11.5 hrs of exercise) showed increased wakefulness and delayed and decreased REM sleep. Similar findings have been reported in subjects exercising to exhaustion (Bunnell et al., 1983a, b). Based on these and other findings, it appears that duration of exercise produces an effect on sleep patterns resembling that of a dose response curve. Short durations of exercise produce little or no changes in sleep patterns. Moderate lengths of exercise (less than

4.5 hrs) increase the amount of SWS and REM sleep latency. Long, exhausting bouts of exercise interfere with both SWS and REM sleep. This pattern may not, however, be independent of physical conditioning. Driver et al. (1994) have found that sleep patterns of trained athletes were not affected by runs as long as 15 and 42.2 km. As few untrained athletes could complete the rigorous exercise of marathons or triathlons, only highly trained athletes are used as subjects in such protocols. Thus, this confound with fitness level and duration of exercise may be difficult to resolve.

Timing of Exercise

As with duration of exercise, the time of day when exercise occurs also appears to produce different effects on sleep. Morning exercise does not appear to have an impact on evening sleep patterns (Driver and Taylor, 1996; Horne and Porter, 1976). As high levels of work/exercise in the morning do not produce changes in SWS or other sleep measures, it appears that the ensuing wakefulness provides sufficient time for recovery. In contrast, afternoon exercise can affect both REM sleep and SWS. Intense, exhaustive (80-100% VO_{2max}) or prolonged (150 mins) afternoon exercise has been shown to increase total SWS and delay the onset of the first REM sleep period (Bunnell et al., 1983a; b; Horne and Staff, 1983; Kupfer et al., 1985). As afternoon exercise produces changes in sleep patterns similar to those seen with recovery sleep in SD subjects, it has been suggested that increased time in SWS and longer latencies to REM sleep are associated with body restitution (Driver and Taylor, 1996; Horne and Porter, 1975; Oswald, 1980; Shapiro and Driver, 1988). Evening exercise has been reported to have deteriorative effects on sleep which are clear and consistent. Following evening exercise, measures of systemic arousal such as heart rate, respiration, peripheral pulse volume, and temperature are elevated through Stages 1 & 2 of sleep (Desjardins et al., 1974; Hauri, 1969). Sleep latency and perceived wakefulness are increased following evening exercise. Additionally, engaging in exercise shortly before bedtime (0-2 hrs) does not appear to produce the enhancements in restorative SWS as seen with afternoon exercise (Browman and Tepas, 1976; Desjardins et al., 1974).

Type of Exercise

Among the many other factors involved in exercise/sleep studies, the type of exercise used can impact the obtained results. Anaerobic exercise does not appear to influence sleep patterns to the same degree as aerobic exercise. Browman (1980) assessed the effects of non-aerobic static muscular activity (contraction of a hand dynamometer) on sleep. Subjects engaged in 80 mins of activity, at 40% of maximal levels, which ended 2 hrs prior to sleep. A number of sleep variables were influenced by this type of exercise. Sleep latency decreased, SWS increased, and a reduction in movement time was seen. However, the differences observed in SWS and movement time did not persist past the first REM sleep period and were not large enough to impact whole night sleep patterns. Trinder et al. (1985) examined the possibility that preexisting differences attributable to chronic exercise regimes might account for different variations in sleep patterns obtained in exercise/sleep studies. Many studies do use physically fit athletes as test subjects and few describe the various routines in which the athletes regularly engage. To assess

this possibility, these researchers examined sleep patterns in aerobic, power (weight lifters), and mixed athlete groups. Aerobically trained runners had higher levels of SWS and other nonREM sleep and they slept longer than athletes who's primary exercise was weight lifting. Sleep variables of the mixed group, who combined both exercise techniques, fell in between the other two athletic groups. Thus, the type of exercise used in studies and the type of exercise in which fit subjects routinely engage to maintain fitness may both influence the outcome of exercise/sleep studies.

Gender and Exercise

With the growing popularity of women's athletics and the opening of many military fields to women, gender differences must now be considered when conducting exercise and sleep research. Studies examining the effects of exercise on sleep have been conducted using female subjects, however, few studies examined gender differences prior to the early 1980's. Bunnell et al. (1983a) found that exhaustive submaximal exercise produced an increase in Stage 4 and total SWS. These increases were greatest during the first non-REM sleep period, and considerably higher in women than men. Browman (1980) found that 80 mins of static exercise (sustained muscle activity) 2 hrs prior to sleep reduced sleep latency in both men and women. However, the reduction was influenced by gender, with females exhibiting a 58% decrease in time to sleep compared to a 33% decrease in males. In contrast to earlier studies, Montgomery et al. (1988) found that SWS decreased in young females following exercise but remained the same in men, while the amount of total REM sleep showed an opposite effect, with a decrease in men and no change in women. While these authors concluded that exercise disrupted sleep patterns, no time of day, duration, or intensity of exercise information was provided. Additionally, no description of the daily activities of subjects during the experiment was provided. However, regardless of the shortcomings and direction of results (+ or -) observed in this study, the effects of exercise on sleep were impacted by gender.

From the few studies available, it is apparent that exercise affects sleep differently in men and women and should be more closely examined whenever possible. It should be noted however, that all studies examining gender differences had unequal fitness or exercise levels for men and women. In the Bunnell et al. (1983a) study, the average VO_2 max in female subjects was 39.7 while it was 54.9 in males. The groups were much more closely matched in the study by Montgomery et al. (1988) with females averaging a VO_2 max of 51.9 and males averaging 59.1. The average submaximal values at the start of sustained muscle activity testing conducted by Browman (1980) in females was 7.0 ± 1.5 kg while it was 19.2 ± 4.0 kg in men. The differences in fitness levels and exercise requirements for male and females may be masking true gender differences or compounding observed ones.

Age and Exercise

As with gender, the effects of exercise on sleep in different age groups have not been well documented. The majority of exercise sleep studies have been conducted on 20-25 year old male

subjects. In the few cases that older subjects have been examined, the results have been conflicting. Two previous studies involving older subjects did not find increases in SWS following exercise (Montgomery et al., 1988; Trinder et al., 1982). Montgomery et al. (1988) found no change in SWS following a 42.2 km marathon in older (41 yr) distance runners despite a decrease in SWS in younger runners. Decreases in the duration of REM sleep and the overall amount of REM sleep as a percent of total sleep time were observed in both age groups suggesting a disruption of total sleep patterns probably associated with the intensive level of exercise. Similar to Montgomery et al. (1988), Trinder et al. (1982) did not find increases in SWS following exercise in older fit subjects, however, the mean age of the older athletes was only 31.8 (the mean age of younger subjects was 22). In addition, no set exercise protocol was implemented. Subjects were told to follow their normal exercise routine at a level sufficient to produce fatigue but not exhaustion. Thus, it would be difficult to quantify exercise levels in the different groups.

In a study involving two groups (fit or sedentary) of older men (≥ 60 years), acute aerobic exercise did not interact with fitness level to produce changes in SWS (Edinger et al., 1993). The groups did however display differences in sleep patterns that were attributable to fitness level alone. Older fit men displayed earlier sleep onset and greater sleep efficiency. This group also exhibited significantly more slow waves during sleep and tended to spend more time in SWS than the sedentary group, although not a significant effect. Vitiello et al. (1992) found increases in SWS in a group of older men who engaged in regular exercise for a period of 6 months. As SWS and other measures of sleep quality significantly decline with age, it appears that exercise may help prevent or lessen the sleep disturbances which are typically seen in older people. Stevenson and Topp (1990) found improvements in subjective measures of sleep in older men and women who engaged in regular exercise for 9 months. Attention and concentration measures also improved in these subjects. While the literature on the interaction of age and exercise has not been thoroughly examined, in older populations it may be necessary to use chronic rather than acute research designs to more fully examine the effects of exercise on sleep.

Summary of the Effects of Exercise on Sleep

While several patterns can be seen in the effects of exercise on sleep, recent reviews have not produced adequate syntheses of the existing literature. A recent review found that exercise had the biggest impact on sleep in older or low fit females, who engage in longer durations of aerobic exercise earlier in the day (Kubitz et al., 1996). Unfortunately the terms older, longer, and earlier were not clarified. Another recent paper concluded that early morning exercise, regardless of duration or intensity did not appear to influence sleep, while mild to moderate exercise in the late afternoon reliably improved sleep. In contrast, it was found that exercise conducted for long durations at high intensities close to bedtime, was likely to disturb sleep (Driver and Taylor, 1996). These authors also failed to clarify or quantify terms such as mild, moderate, high, or long. The fact that numerous experimental paradigms are used, and that current review papers tend to use qualitative descriptions rather than quantitative descriptions, leaves numerous unanswered questions about the effects of exercise on subsequent sleep pattern.

Effects of Sleep Deprivation/Restriction on Exercise/Work Performance

Our average amount of sleep has declined 20% over the last century while work obligations have increased (The National Sleep Foundation, 1995). Work habits have also changed with the introduction of rotating shifts, extended work days, and compressed work schedules. Added social responsibilities, changing work schedules, and the ability to easily traverse time zones, can act independently or in combination to produce partial sleep loss or periods of total sleep deprivation in many workers. Because this problem has become more common, research has begun to focus on the impact of sleep loss on performance. While more profuse than the literature on exercise and sleep, the effects of quality and quantity of sleep on various work/exercise thresholds are equally as unclear. Nearly all studies on the effects of sleep disturbances on performance are conducted using different experimental protocols (Shephard, 1984; VanHelder et al., 1989).

Length of Sleep Deprivation on Exercise Performance

Similar to studies which examine the effects of exercise on sleep, those investigating the effects of sleep on work/exercise performance are often contradictory and incomparable (Martin and Gaddis, 1981; Opstad et al., 1980; Plyley et al., 1987; VanHelder et al., 1989). One major factor which accounts for the discordant results in this field of study is the varying amount sleep deprivation. Sleep deprivation periods typically range from 24 to 120 hrs (VanHelder et al., 1989). Additionally, many studies examine the effects of partial rather than total deprivation, by employing naps or minimizing evening sleep durations throughout the study. In general though, studies examining the effects of sleep deprivation find that the longer the period without sleep the greater the performance declines (Bonnet, 1994). However, the level at which physical performance is affected is often related to the type of measure used, the intensity and duration of exercise/work, as well as the gender and age of subjects.

Sleep Deprivation and Intensity of Exercise/Work

Much like the literature examining the effects of exercise on sleep, factors such as intensity of exercise, duration of exercise, age, and gender also muddy the waters when the effects of sleep deprivation on exercise/work performance are assessed. Several experiments have assessed physiological and psychological responses to different intensities of exercise in sleep deprived subjects. It has been demonstrated that exercise conducted at three different intensities (25%, 50% and 75% of VO_{2max}), each for the same period of time, produces few changes in physiological variables at any intensity of exercise when measured pre- and 30 hrs postdeprivation (Martin and Gaddis, 1981). Sleep loss did however produce significant increases in ratings of perceived exertion (RPE) from control (nondeprivation) levels. The increase in ratings was not independent of exercise intensity. Light intensity exercise in sleep deprived subjects produced a small nonsignificant increase in ratings from control levels. Both moderate (50%) and heavy (75%) exercise significantly increased RPE from control levels, with heavy exercise producing the largest increase from predeprivation measures.

In terms of actual performance, a moderate length of sleep deprivation (30-36 hrs) has been shown to reduce heavy exercise performance (prolonged treadmill walking at 80% $\text{VO}_{2\text{max}}$) by an average of 11% while longer periods (50 hrs) produce approx 20% decrease (Martin, 1981). This decrease occurred despite unchanged heart rate and metabolic rate and doubling of monetary incentives during the sleep deprivation period. These decreases were, however, accompanied by increases in perceived exertion. These studies are typical examples of those examining the effects of sleep deprivation on different intensities of exercise performance. Sleep deprivation produces few physiological changes associated with the declines in exercise/work performance but the declines in performance at different intensities of work/exercise are associated with psychological variables (i.e., reduced motivation, interest, etc.).

Sleep Deprivation and Duration of Exercise/Work

As with intensity of exercise, sleep deprivation interacts with duration of exercise to influence performance measures. The elevation in perceived exertion seen with increased exercise duration in nonsleep deprived subjects is well documented. Edwards et al. (1972) demonstrated that as intermittent exercise periods were progressively increased from 15 to 120 sec, perceived exertion also rose progressively. A few studies have examined a range of exercise/work durations in sleep deprived subjects. In three different studies, Myles (1985) compared the influence of short (30 sec) or long (15-50 mins) exercise durations on perceived exertion in sleep deprived subjects. Ten, 30 sec bouts of exercise were performed at five different exercise intensities in subjects deprived of sleep for 54 hrs. RPE was unaffected by the 30 sec bouts of exercise. In a second study, subjects exercising for 50 mins every 3 hrs exhibited significant increases in RPE throughout a 60 hr period of sleep deprivation. To reduce the chance of confound from prior fatigue produced by repeated 50-min bouts of exercise, in a third experiment Myles had subjects exercise for eight 15-min bouts prior to 30 sec and 50-min assessments. It was concluded that prior fatigue had little or no impact on RPE in sleep deprived subjects exercising for short (30 sec) bouts but did interact with SD to increase RPE in those exercising for longer durations. Thus, while RPE increases with duration of exercise, sleep deprivation appears to compound these increases (Myles, 1985; Soule and Goldman, 1973). As with intensity of exercise, increases in duration of exercise appear to impact most on psychological measures such as RPE. Studies may employ exercise bouts as brief as 30 seconds (Myles, 1985) or as long as several hours (Martin, 1981; Symons et al., 1988).

Sleep Deprivation, Exercise and Physical Performance

The typical limit of human performance when working without sleep is reported to be about 3 days for tasks which involve both a physical and mental component (Haslam, 1982). When task type is examined separately, sleep deprived subjects can maintain physical workloads for longer periods of time than they can maintain mental workloads (Haslam, 1981). Pilcher and Huffcutt (1996) suggest that performance measures involving motor tasks, as opposed to cognitive or mood effects, were the least affected by sleep deprivation. This held true regardless of the

duration of sleep deprivation (short, long or partial) when compared with cognitive or mood assessments. Other studies have found that periods of sleep deprivation as long as 60 hours produce few if any changes in isometric and isokinetic muscular strength or endurance, simple reaction time, and most cardiovascular and respiratory responses to exercise (Martin, 1981; 1985; Mougín et al., 1991; Symons et al., 1988). Some studies have shown slight decreases in the tolerance to prolonged exercise (9.7% at 24 hrs, 11% at 36 hrs and 20% at 50 hrs) however, subjects in these studies were required to remain relatively passive during the sleep deprivation periods (Holland, 1967; Martin, 1981; Martin and Chen, 1984). Yeager et al. (1987) found that moderate intermittent exercise (30 min every hour at 30% treadmill VO_{2max}) during 20-hr periods of continuous mental work increased VO_{2max} on subsequent exercise tests in comparison to non exercise controls. Takeuchi et al. (1985) found that a decrease in vertical jump height, a measure of anaerobic leg power, seen following 64 hrs sleep deprivation in nonexercise control subjects was prevented in subjects who engaged in intermittent exercise (1 hr every 3 hrs, at 28% treadmill VO_{2max}) during the SD period. Thus, although decrements in physical performance are the least problematic in terms of the effects of SD, they do occur. However, decrements on some physical performance measures are prevented by having subjects engage in moderate, intermittent exercise during periods of sleep deprivation.

Sleep Deprivation, Exercise and Cognitive Performance

Many of the largest performance declines are seen when experiments employ cognitive or vigilance based tasks. Cognitive based performance in sleep deprived subjects declines nearly twice as much as performance based on motor tasks (Pilcher and Huffcutt, 1996). Sleep loss also hastens the onset and increases the frequency of cognitive performance decrements, especially on demanding vigilance tasks. Cognitive tasks involving learning, memory, auditory and visual vigilance, arithmetic calculations, logical reasoning and decision making have all been shown to suffer following sleep loss (Babkoff et al., 1985; Caldwell et al., 1997, Englund et al., 1985; Haslam and Abraham, 1987). Additionally, it has been reported that physical exertion can produce performance decrements on cognitive tasks which mirror those caused by total sleep loss. Bonnet (1980), marched subjects approximately 20 miles in a 16-hr period in order to approximate the energy expenditure of 40 hrs of relatively inactive sleep deprivation. At the end of the exercise period, performance on a multitude of tasks including vigilance, choice reaction time, short term memory and symbol substitution tests were similar to the decrements typically reported following 40 hrs of sleep deprivation. Similar decrements on short term memory tasks were reported in subjects participating in a 48-hr continuous operation/exercise study (Englund et al., 1985). However, these authors reported that decrements in cognitive performance were attributable to sleep loss and were not accentuated by exercise. Visual vigilance, however, degraded sooner in subjects who did not exercise during the continuous work scenario than in subjects who did exercise. Thus, it appears that exercise at 30% VO_{2max} may delay sleep loss induced declines on some cognitive tasks. The opposite results in vigilance performance in these studies may be due to the extreme differences in exercise conditions (20 mile march vs 30 min/hr exercise at 30% treadmill VO_{2max}). The degree to which cognitive performance is impaired depends on the duration of sleep loss, the amount of exercise/work or an interaction of both these

factors. Also, the degree to which these impairments can be detected is influenced by a number of methodological factors including duration, difficulty, novelty, and complexity of task; knowledge of results and subject's interest in the task may also impact on cognitive performance in sleep deprived subjects (Wilkinson, 1961; 1964; Elsmore et al., 1995).

Sleep Deprivation, Exercise and Psychological Effects

Interestingly, psychological factors such as perceived exertion, perceived fatigue, and mood may have more impact on physical responses following sleep deprivation/restriction than physiological factors such as heart rate, respiration, blood lactic acid, norepinephrine, epinephrine, and dopamine concentrations (Martin, 1985). Pilcher and Huffcutt (1996) concluded that the most severe declines produced by sleep deprivation were seen in measures of mood. Subjective measures such as mood and RPE can be influenced by many factors. For example, Pyley et al. (1987) had subjects exercise at 28% VO_2max while Martin and Gaddis (1981) had subjects exercise at nearly the same level of exertion (25% VO_2max). Pyley et al. collected ratings after 30 mins of a 60-min exercise bout while Martin and Gaddis collected ratings after 7 mins of exercise in a 24-min exercise bout. Ratings in subjects who had exercised for 30 mins prior, began to increase after 15 hrs of sleep deprivation while those who did ratings at 7 mins did not exhibit increases in RPE throughout the 30-hr test. Neither group of subjects showed increases in exercise heart rates as a result of sleep deprivation. Conversely, some studies have shown changes in RPE simply as a function of anticipated SD. Subjects participating in a 5-day Army Ranger Course, which involved intense military tactical training with little opportunity for sleep, began to show mood deterioration prior to the start of any organized activities or sleep loss (Opstad et al., 1978). Increases in negative mood as indicated by ratings on the Profile of Mood States (POMS) were seen. The authors concluded that anxious anticipation of the strenuous course may have been the significant factor producing this result. Thus, subjective measures such as perceived fatigue ratings and mood appear to be more easily influenced by psychological factors than physiological factors.

Sleep Deprivation, Exercise and Gender

Although there are a few studies which examined the effects of exercise in both males and females who were sleep deprived, none have examined gender as a factor. Myles (1985) ran female subjects in one of three experiments. As all three studies used different exercise protocols, no examination of gender differences was conducted. While Martin (1981) ran both males and females in the same study, gender differences were not analyzed or presented. Similarly, Horne and Pettitt (1984) and Martin and Gaddis (1981) used both male and female subjects in their sleep deprivation and exercise experiments but did not examine gender differences. Gender has been examined as a factor in the response to sleep deprivation but the interaction with exercise has not been assessed. However, it has been shown that, generally, elderly women exhibit more disruption on the POMS during sleep deprivation but show better recovery sleep than elderly men (Reynolds et al., 1986). There is only one report which examines gender differences in young adult sleep deprived subjects. Caldwell and LeDuc (In

Press) has shown that in aviators (mean age 30) subjected to 40 hrs of sleep deprivation, performance decrements were equivalent in both male and female subjects. From the few studies examining gender differences in response to sleep deprivation, it appears that gender may play a role in elderly populations but not to any strong degree in young adults. However, it is currently unknown if exercise and gender interact to influence motor, cognitive, or psychological performance in sleep deprived subjects.

Sleep Deprivation, Exercise and Age

Similar to gender, the effects of age on performance in sleep deprived subjects has not been thoroughly examined, but a few studies do exist. Researchers have found that slow wave sleep and long periods of uninterrupted sleep declines with age (Miles and Dement, 1980). Several recent reports have demonstrated that recovery sleep following sleep deprivation in elderly subjects is similar to that seen in young adults. On the first night of recovery after sleep deprivation, young adults exhibit typical increases in SWS (Berger and Oswald, 1962; Bonnet, 1994; Sakamoto et al., 1984) and increased REM sleep latency (Bonnet, 1994). Carskaden and Dement (1985) found that older subjects (61-77 yrs) showed similar increases in deep sleep (Stage 4) on sleep recovery nights. Additionally, Bonnet and Rosa (1987) have shown that sleep deprivation produced increases in Stage 3 sleep on recovery sleep nights in a second elderly population (55-71 yrs). However, Webb and Levy (1982) found more deterioration on auditory vigilance and reaction time tests in older subjects (40-49 yrs) than in younger ones (18-22 yrs) undergoing sleep deprivation. Thus, it may be that performance based measures are influenced more by age than physiological measures. This view is supported by the findings of Webb et al. (1981) which show no deterioration in cardiovascular, respiratory or muscle system measures in older subjects (40-49 yrs) sleep deprived for two days when compared to younger subjects (18-22 yrs). While a scant amount of literature is available on the interaction of age and sleep deprivation on cognitive performance and basic physiological measures, the interaction with exercise/work has yet to be examined.

Summary of the Effects of Sleep Deprivation on Performance

Although sleep deprivation is generally considered stressful, findings from sleep deprivation studies which examine physiological changes do not support this idea (Horne and Pettitt, 1984; VanHelder et al., 1989). The main effects of sleep deprivation are evidenced as declines in mental performance. Physiological measures such as VO_2 max, heart rate, blood pressure, and respiration do not show consistent changes related to deprivation. Physical performance decrements during sleep deprivation are more closely linked to psychological rather than physical fatigue. As discussed above, decreases in physical performance produced by increasing the duration or the intensity of exercise in sleep deprived subjects are accompanied by increases in perceived exertion but not heart rate or other physiological assessments. Thus, when conducting sleep deprivation studies, psychological and motivational factors should not be ignored as they can easily influence subject performance. Additionally, as the influences of

gender and age on sleep deprived exercise/work performance are unclear at the present time, these issues should be more closely examined.

Effects of Exercise on Sleep Deprived Vigilance Performance

While research on the effects of exercise on sleep and the effects of sleep on exercise/work performance has contributed much to our knowledge, one area is still largely underrepresented in the literature. Few systematic studies have examined whether or not exercise may have positive effects on cognitive performance or arousal levels in sleep deprived/restricted subjects. The most commonly held view of exercise is that it provides a short-term increase in arousal levels in sleep deprived subjects. This opinion is expressed in early literature (1950's & 1960's) but little research has been done to actually test this hypothesis (Horne and Foster, 1995). In the majority of studies, exercise has been used as an additional stressor when examining physical performance declines in SD subjects. While many workers will never be affected by long periods of sleep restriction/deprivation, sleep loss can be a problem in continuous military operations and in long haul or extended civilian or military aviation missions. Thus, the potential utility of using exercise to sustain performance should be considered.

Sleep Deprivation and Arousal

In general, tasks that require sustained concentration and vigilance such as monitoring radar screens and control panels are the most susceptible to the influences of sleep deprivation. While time on task alone can produce decreases in hits and increases in false alarms on vigilance tasks, sleep deprivation increases these decrements (Wilkinson, 1960; 1969). Performance on short duration vigilance tasks is less susceptible to decrements but is by no means immune from the effects of sleep loss. Tasks that place heavy demands on working memory or that call for sustained attention, even for short durations are affected by sleep deprivation (Alluisi et al., 1977; Williams et al., 1959). Sleep deprivation produces periods of slow performance and periods of nonperformance or lapses. During a lapse, subjects go to sleep for a moment or two and performance terminates. As the duration of sleep loss increases, the lapses increase in frequency and duration. Williams et al. (1959) found that performance on a 10-min monotonous vigilance test which is typically performed without difficulty, began to degrade within 7 mins after one night of sleep loss. On this same task, after 2 nights without sleep, the degradation began after 2 mins.

According to Kjellberg (1977a; b; c), the lapses seen in subjects who have been sleep deprived are due to lowered states of arousal. EEG recordings of sleep deprived subjects when awake show decreases in the rhythm and amplitude of alpha waves like those observed in normal subjects falling asleep (Johnson et al., 1965; Wilkinson, 1965). On performance measures, failure to respond to a stimulus is often associated with reductions in alpha activity (Williams et al., 1959). Hockey (1970a; b) has shown that sleep deprivation produces slower reaction times on tracking tasks and that subjects become more easily distracted and have difficulty on

sustained attention tasks such as card sorting. Studies which examine arousers such as noise on sleep deprivation performance typically find that decrements in performance are to some degree ameliorated. Wilkinson (1963) has reported that 100 db of white noise reduced the error rate produced by 32 hrs of SD on a serial reaction task. Similarly, 75 mins of pink noise, delivered at 75 db improved speed of response at 0500, the lowest point of the circadian dip, on a spatial memory test in subjects subjected to partial sleep deprivation (Tassi et al., 1993).

Sleep Deprivation and Exercise

While exercise is considered an arousing activity, little is known about the effects of exercise on alertness in SD subjects. To date, most studies employ what appear to be excessive amounts of exercise (Angus et al., 1985; Englund et al., 1985; Plyley et al., 1987; Ryman et al., 1985). The most commonly used schedules of exercise are bouts of 30 continuous mins/hr or 1 continuous hr/3 hrs, throughout the duration of sleep deprivation. Englund et al. (1985) looked at 30% VO_2 max treadmill exercise every 30 mins throughout a 48-hr deprivation period. Despite the rather intense exercise schedules, exercise neither attenuated nor accentuated decrements in cognitive performance produced by sleep loss, but decrements in visual vigilance were delayed by intermittent exercise. Angus et al. (1985) had subjects walk on a treadmill at 25-30% VO_2 max for 1 continuous hour every 3 hrs throughout a 60-hr period of sleep deprivation. With the exception of a slight increase in the number of gaps on serial reaction time by the exercise group, no cognitive or physiological differences were observed between exercise and no exercise conditions. Plyley et al. (1987) reported that the physiological effects of sleep deprivation (a slight decrease in VO_2 max) and the psychological effects (an increase in RPE) were not influenced by exercise. As with other research, these studies were using exercise as an additional stressor and not as a mechanism to enhance arousal. However, it is interesting to note that in spite of the strenuous exercise schedules used in the above mentioned studies, cognitive and physiological performance decrements in sleep deprived subjects were not compounded by exercise. On the contrary, in the case of Englund et al. (1985), vigilance decrements may have been delayed by as much as 8 hrs when compared to nonexercising controls.

Exercise and Arousal

Despite the extreme levels and durations of exercise typically used, there are some hints throughout the literature that exercise may be used in a practice manner, outside of the laboratory, as an effective method to increase alertness/arousal during periods of sleep deprivation. It has been shown that short bouts of submaximal exercise can improve cognitive performance in nonsleep deprived subjects (Davey, 1972; 1973). Davey (1973) examined the function of various amounts of exercise on a continuous attention task. Exercise had an inverted U-shaped effect on performance. Low intensity exercise had little or no effect, moderate submaximal exercise enhanced performance, and exhaustive exercise produced decrements in performance. One recent study has shown that EEG alpha activity decreases to below baseline levels when subjects actively engage in 15-min bouts of moderate stationary cycle exercise (Kubitz and Mott, 1996). These and other studies provide supporting evidence that moderate

levels of exercise can affect cognitive performance by raising arousal levels. Unfortunately, few studies have been done which examine exercise induced arousal on cognitive performance in sleep deprived subjects.

Sleep Deprivation, Exercise and Arousal

The only study to date which directly examined the arousing effects of short bouts of submaximal exercise in sleep deprived/restricted subjects was conducted by Horne and Foster (1995). These researchers examined the effects of 10 mins of exercise, at four different levels 0%, 20%, 40%, and 70 % VO_2max , on performance of sleep restricted people. Subjects were restricted to 4 hrs of sleep and subsequently tested between 1400-1600. These authors used the Wilkinson Auditory Vigilance Test (purported to be extremely sensitive to sleepiness/alertness). The 30-min test was given prior to exercise and readministered following 10 mins of exercise and 5 mins rest. Exercise at all levels (20, 40, & 70%) produced some improvement in vigilance performance. The only significant change, however, was seen in subjects who exercised at the highest level (70%). Post exercise vigilance measures were significantly better in the high exercise group. Self-rated alertness was improved in all exercise groups but the effects were short lived, lasting only 10-15 min in the low (20%) and middle conditions (40%). In the high exercise condition (70%), this effect was extended to 30 mins. As self-rated measures of sleepiness and exertion are more highly correlated with performance than physiological measures (Angus et al., 1985; Martin, 1981; Plyley et al., 1987), it may be possible to capitalize on the alerting effects of short bouts of submaximal exercise in sleep deprived workers.

Summary of the Effects of Exercise on Sleep Deprived Vigilance Performance

Sleep deprivation has repeatedly been shown to increase simple reaction time, decrease auditory and visual vigilance, and increase sleepiness and irritability. While the literature examining the alerting effects of exercise in sleep deprived subjects is sparse, a few studies show that exercise can produce improvements or can reduce and delay the onset of decrements in auditory and visual vigilance tasks when compared to no exercise, sleep deprived controls. The alerting effects do, however, seem to be very short lived. Despite the short time frame found for improvements, this practice of short, fairly vigorous bouts of exercise may help to prevent decrements in tasks requiring sustained attention. Additionally, short bouts of submaximal exercise may help alleviate the sleep inertia produced by both short or long episodes of sleep. While exercise undoubtedly will not enhance performance on a long term basis to the extent that stimulants do, it may provide a short term intervention which can be used during times when arousal is lowest (e.g. during periods of continuous wakefulness or shift work during the hours of 0500-0800, when arousal is lowest due to natural circadian patterns).

Discussion

A review of the literature indicates that the relationships among sleep, sleepiness, and exercise remain unclear despite the existence of several studies examining the effects of exercise on sleep, the effects of sleep (or sleep loss) on physical performance, and the usefulness of exercise for sustaining the performance of sleep deprived subjects. Unfortunately, there are a variety of confounding variables that obscure attempts to create a meaningful synthesis of the existing literature. Among these are the facts that different intensities, types, and durations of exercise have been examined; widely divergent subject samples have been tested; and very different types of performance metrics have been employed. It is, for instance, difficult to compare the effects of exhaustive, continuous exercise in one study to moderate, intermittent exercise in another; to equate the results from highly fit subjects to those of unfit (or less fit) subjects; and to make global conclusions about exercise effects when one study examines cognitive data, another assesses physiological effects, and another evaluates psychological variables.

The results of several recent meta analytic reviews have been helpful in synthesizing the available knowledge of exercise-related effects; however, many of the individual studies summarized in these reviews have not provided adequate information about design, treatment, or statistical procedures. The review by Kubitz et al. (1996) located 73 studies relevant to their topic. After screening, only 38 studies met the full criteria for the meta analysis. Thus, only 43.8% of the studies which examined the effects of acute or chronic exercise on sleep were included. Similarly, Youngstedt et al. (1997), using a meta analytic approach to examine the effects of acute exercise on sleep, found 48 studies and excluded 10 of these (26.3%) because of inadequate information. Better reporting of individual research methods, employing more systematic approaches to exercise and sleep research, and the continued use meta analyses may help clarify many of the inconsistencies currently found in the literature. At present, although definitive conclusions are not easily drawn, generalizations can be made regarding the relationships between sleep (or sleep loss) and performance.

Considering the effects of exercise on sleep, it appears that physical exercise produces a general increase in slow-wave sleep especially if it is aerobic (versus anaerobic) activity of higher intensity (75% VO₂max) and of longer duration (1-4 hrs), although very long exercise durations (greater than 4.5 hrs) are associated with sleep disruptions. Morning exercise seems to have little impact on a subsequent night's sleep, but intense afternoon exercise increases slow-wave sleep and delays the onset of REM sleep, and evening exercise has a disruptive effect. Some studies suggest there are gender and age-related differences in responses to physical exercise, but definitive conclusions are not possible given the differing fitness levels between the groups as well as the presence of other confounding variables.

With regard to the effects of sleep loss on physical performance, there appears to be a consensus that motor (or physical) tasks are the least affected by inadequate sleep. Sleep deprivation generally does not increase the amount of physiological exertion required to perform

physical activity regardless of whether the exercise is low, moderate, or high intensity. However, there is a definite relationship between perceived physiological exertion and the amount of sleep loss, and it has been suggested that lengthy and intense exercise periods are more likely than short ones to reveal differences between sleep deprived and nonsleep deprived subjects. This may be at least partially attributable to the deterioration in psychological mood that occurs as a result of inadequate sleep. Of course, sleep deprivation is known to cause significant decrements in cognitive performance, but it has been observed that intermittent exercise during periods of sustained wakefulness may actually attenuate these decrements. There may be differences between males and females in older subjects, but apparently not in younger ones. Also, while older participants appear to be more affected by sleep deprivation than younger subjects (in terms of vigilance and reaction-time tasks), there are no concurrent physiological changes, and the overall performance effects are far from definitive.

In terms of the usefulness of physical exercise for sustaining the performance of sleep-deprived volunteers, it seems that at best, there may be short-term benefits. Studies in which very high exercise intensities were used revealed no differences in cognitive performance, physiological indices, or psychological status of exercising versus nonexercising sleep-deprived subjects. However, one recent investigation suggests that self-rated alertness may be improved by a wide variety of exercise intensities, and that auditory vigilance is increased in sleep-deprived volunteers who exercise at 70% VO₂max. Further exploration of these effects may substantiate the fact that specific types of exercise, performed at prescribed intervals, can be useful in sustaining the performance of sleep-deprived subjects.

If intermittent exercise is in fact found to be a feasible countermeasure for sleep deprivation in some situations, this will be of significant interest to modern society. With the popularity of rotating shifts, compressed work hours, and flex-time schedules to accommodate our increase in travel time and social responsibilities, we are becoming a society of sleep deprived workers. It is well known that sleep deprivation increases simple reaction time, sleepiness, and irritability while decreasing our auditory and visual vigilance capabilities. Extensive data suggest that sleepiness and fatigue may play a significant role in accidents involving people who work or drive under such conditions (Dinges, 1989b; 1995; Leger, 1994).

It may be possible to alleviate some of the fatigue-related problems with stimulants such as caffeine and amphetamines since both have repeatedly been shown to ameliorate many of the physiological and performance decrements produced by sleep loss (Clubley et al., 1979; Caldwell et al., 1995; Lieberman et al., 1987; Walsh et al., 1990); however, the use of these drugs may not always be practical. Acute use of caffeinated products has repeatedly been shown to decrease sleepiness and increase alertness; however, tolerance to these effects is often seen in chronic users (Curatolo and Robertson, 1983; Muehlbach and Walsh, 1995). As many people drink caffeinated beverages on a regular basis, using caffeine to promote alertness during periods of fatigue may not be effective. Stimulants such as Dexedrine can produce serious adverse reactions such as palpitations, tachycardia, and elevated blood pressure. Additionally, many stimulants can be toxic at doses only slightly higher than the recommended dose, and tolerance

develops quickly with repeated use (Hoffman and Lefkowitz, 1990; Jaffe, 1990). For these reasons, long term stimulant use does not seem to be a realistic intervention for night shift workers or personnel involved in long periods of sustained operations. Thus, it is important to find nonpharmacological interventions which can be used in cases where stimulants are contraindicated.

Strategic naps are known to increase the alertness and performance of sleep deprived subjects (Bonnet, 1991; Bonnet et al., 1995; Caldwell et al., 1997; Nicholson et al., 1985), and this may be a more palatable countermeasure for fatigue in some settings. In fact, a recent study has shown that napping may be an effective strategy for sustaining military performance during periods of sustained operations (Caldwell et al., 1997). However, there are many problems associated with the implementation of napping. The first is that napping is considered by many Americans to be a sign of laziness or lack of dedication, and this may discourage compliance. The second is that the timing, length, and placement of naps in the circadian phase all must be carefully considered if strategic napping is to be an effective approach (Bonnet, 1990; 1991; Dinges, 1986; 1989a; 1992; Lumley et al., 1986). The third is that there must be a suitable interval from the time of awakening from a nap until work performance is to begin in order to avoid sleep inertia which may interfere with performance (Dinges, 1989a). Thus, napping can be time-consuming since allowances must be made both for the nap itself and recovery from the nap.

Intermittent bouts of exercise may offer a feasible, nonpharmacological alternative for the maintenance of performance and alertness in sleep deprived personnel. Although exercise has typically been used as an additional stressor in sleep deprivation studies, recent study (Horne and Foster, 1995) has demonstrated the arousing effects of short bouts of exercise in sleep deprived/restricted subjects. Self-rated alertness was improved in all exercise groups and post exercise vigilance was significantly better in the high exercise group. Short, vigorous bouts of exercise may prove to be a palatable, useful, and easily-implemented method for ameliorating cognitive performance decrements associated with sleep loss. In cases where subjects are required to perform sustained attention tasks such as monitoring radar screens or routine tasks such as assembly line work, short exercise periods could easily be incorporated into work schedules. Unlike pharmacological interventions, extensive medical oversight or the acquisition of controlled substances is not required. The issues of drug tolerance and abuse potential are not problematic with exercise since it is a behavioral intervention. Exercise can be conducted in almost any environment and does not necessarily require modifications to the work setting (such as the creation of quiet, dark, relaxing places needed for napping strategies). Additionally, little or no recovery period is required following brief periods of exercise as is the case after a nap. In short, if the benefits of short bouts of exercise for improving alertness in sleep deprived/restricted people are proven, a new countermeasure with few drawbacks can be made available. However, further work remains and testing to be conducted before the value of exercise interventions are fully understood.

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