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Cognitive Processing and Sleep: Implications for Enhancing Job Performance

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The relation between cognitive processing and sleep is examined in three areas: the effect of sleep in producing deficits in memory for events that take place immediately before sleep, the effect of naps on performance following sleep, and the capacity of individuals to process information presented while asleep. A review of the literature and discussion of practical implications lead to the conclusions that sleep does produce a form of amnesia for events taking place immediately before sleep and that sleep inertia can produce detrimental effects on subsequent performance, particularly if individuals have been sleep deprived. Nevertheless, naps have been found to improve subsequent performance during critical work periods if time for recovery from sleep inertia is provided. In the area of cognitive processing during sleep, considerable evidence exists for some forms of cognitive processing. However, elaborated processing of semantic information during sleep has rarely been demonstrated in the absence of signs of arousal, even when one examines implicit, in addition to explicit, tests of memory.

In many work activities of modern life, continuous, around-the-clock operation is necessary. We expect individuals to accommodate their sleep, somehow, to work schedules. Problems due to irregular schedules and shiftwork—such as fatigue at work, industrial accidents, and sleep disturbances—have been well documented (e.g., Folkhard & Monk, 1985). These problems highlight the importance of sleep for optimal cognitive processing and effective job performance. In this article, we examine the relationship between cognitive processing and sleep. On the one hand, there may be detrimental effects of sleep on cognitive performance, both preceding and following sleep. On the other hand, there has been renewed interest in the possibility that cognitive processing during sleep could be used to enhance

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next-day performance (e.g., Swets & Bjork, 1990). There is much about cognition and sleep that we do not discuss. In particular, we do not attempt to discuss why we dream. In this article, we focus on the processing of external stimuli.

MEMORY FOR ACTIVITIES PRECEDING SLEEP ONSET

It has been stated often that Americans are chronically sleep deprived (e.g., Webb & Agnew, 1975). Simply having too many social and work demands can lead to getting an insufficient quantity of sleep at night. Additionally, sleep disorders (e.g., sleep apnea and periodic limb movements) can produce so many disruptions of sleep that the individual is deprived of deeper stages of sleep, and the sleep that remains often is experienced as unrestorative.

One of the major effects of sleep deprivation or sleep fragmentation is an increase in daytime sleepiness. Consequently, a sleep-deprived individual may fall asleep for a few minutes even in the midst of an activity. It is well understood that this is a danger for truck drivers or those operating heavy equipment. In addition, however, there may be cognitive effects of sleep that would be detrimental for many jobs. What happens if a navigator on an international flight falls asleep for a few minutes, or a night shift engineer monitoring the dials at a nuclear generator, or a telephone salesperson between calls? When they wake up, will they remember what they were attending to? How does cognition change at the transition from wakefulness to sleep? Does one's memory function normally at this time—or does this brain function shut down as we fall asleep?

In an early attempt to answer the last question, Portnoff, Goodenough, and colleagues (Goodenough, Sapan, Cohen, Portnoff, & Shapiro, 1971; Portnoff, Baekeland, Goodenough, Karacan, & Shapiro, 1966) examined morning recall and recognition for material presented during brief awakenings from sleep. After being awakened to view a stimulus word, the subjects were allowed to return to sleep, either without delay or after performing a brief motor task. In the motor task delay condition, the longer the subjects took to fall back to sleep, the better their memory was for the stimulus word. Follow-up experiments provided evidence that increasing the delay to sleep onset after a stimulus was necessary but not sufficient to increase retrieval rates. The authors suggested that the subject's arousal level during stimulus presentation needed to be higher than a certain minimum level in order for memory to be facilitated.

In a study that examined the direct effect of sleep onset on memory, Guilleminault and Dement (1977) presented verbal material (single words) to two college students as they were falling asleep. The subjects, who were restricted to 2 hr of sleep the prior night to ensure sleepiness, heard one word each minute until they fell asleep. From the time the experimenters determined that the electroencephalograph (EEG) had changed from wake to sleep frequencies, subjects were allowed to accumulate a maximum of either 30 sec or 10 min of sleep. Upon awakening the subjects, the experimenters gave them a recognition test of memory.

The results indicated that when the subjects had slept for no more than 30 sec, they showed no deficit on the memory test for all words heard before sleep occurred. However, if allowed to sleep for 10 min, the subjects displayed a severe deficit (near chance performance) for words heard in the 5 min preceding the onset of sleep. Guilleminault and Dement (1977) interpreted their results as suggesting the closing of a "gate" between short-term or primary memory and long-term or secondary memory after a certain amount of sleep had transpired. This closed gate interrupted the transfer of verbal information into more permanent storage and hence, the information was unavailable at the time of testing. The conclusions have to be considered preliminary, however, because they were based on the results from only two subjects.

Recently, we conducted a study to reexamine and expand on the issue of memory functioning at sleep onset (Wyatt, Bootzin, Anthony, & Stevenson, 1992; Wyatt, Bootzin, Bazant, & Anthony, 1993). In addition to testing more subjects, we examined a variety of memory measures, including free recall, recognition, and explicit and implicit paired-associate learning. During a paired-associate task the subject is presented with a cue (in this instance, the first word of a word pair) and asked to either recall the word paired with it originally (a cued-recall test or explicit task) or to free associate or speak the first word that comes to mind without regard to whether it had been presented before (implicit task). Explicit memory refers to memories that are accessible to conscious thought. Free recall, explicit paired-associate, and recognition tests are common tests of explicit memory. Implicit memory is that which is "encoded during a particular episode [but] is subsequently expressed without conscious or deliberate recollection" (Schacter, 1987a).

In our study, a computer-controlled audio system presented word pairs selected for low to moderate associative strength (e.g., "kittens–cats" and "scissors–sharp"), one pair per minute, until sleep onset. Subsequent to being allowed to obtain either 30 sec or 10 min of sleep, subjects were awakened and given the four memory tests. Twenty subjects were tested, with each subject getting at least one trial of each sleep duration condition (30 sec and 10 min). Preliminary analysis of the results indicates qualitative and quantitative differences from the Guilleminault and Dement (1977) results.

On the free recall test, the subjects in the 10-min sleep condition had significantly poorer memory than those in the 30-sec condition for the word pairs heard in the 3-min period immediately prior to sleep onset (see Figure 1). Sixteen of the 20 subjects could not remember even one of the words

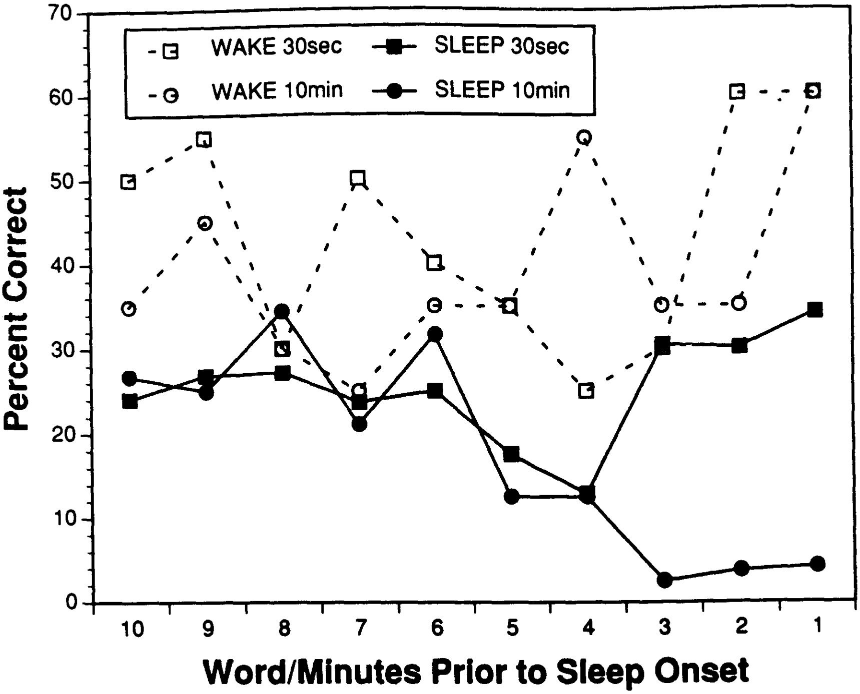

FIGURE 1 Free recall task performance: Percentage of words/pairs correctly recalled at each word/minute prior to sleep onset.

presented during those 3 min. Although memory was substantially better for the 30-sec sleep condition, memory was impaired when compared to awake control subjects.

On the recognition test, a more sensitive test of memory than free recall, the subjects allowed to sleep 10 min had significantly poorer memory only for the word pairs heard 1 min prior to sleep onset. As shown in Figure 2, compared to 84% correct for the last stimulus pair in the wake conditions, subjects allowed to fall asleep were 64% correct in the 30-sec sleep condition and only 25% correct in the 10-min sleep condition. These 3- and 1-min intervals are briefer than the 5-min interval found in Guilleminault and Dement (1977). There were no similar overall deficits observed in the explicit and implicit paired-associate tasks. However, there was an advantage of the 30-sec over the 10-min sleep condition as the word pairs got closer to sleep onset for the explicit task but not in the implicit task. Although the intervals for which the subjects were amnesiac for material presented before sleep were briefer than previously hypothesized, the subjects, nevertheless, showed severe memory deficits.

In interpreting these results, one needs to take into account the relative

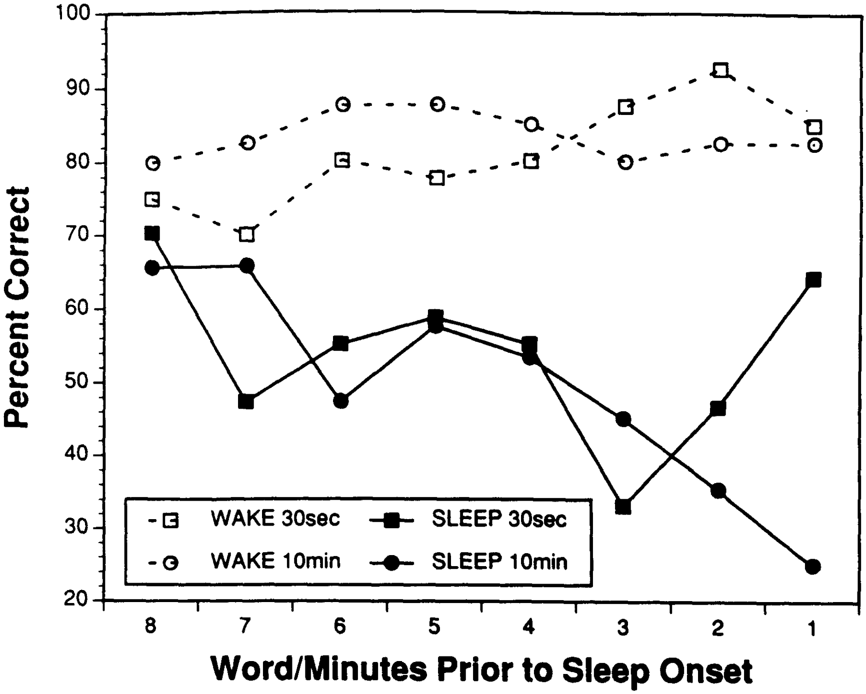

FIGURE 2 Recognition task performance: Percentage of word/pairs correctly recognized at each word/minute prior to sleep onset.

sensitivities of the memory tests. First, the free recall test is a more "difficult" test of memory, as there are no retrieval cues given to the subject; the recognition test is more "sensitive" to weaker memory traces, as subjects are presented with the target items and distracters and asked to choose between them. Thus, one would expect that memories that were encoded deeply and richly would be accessible to a test of free recall. Words that were poorly encoded or otherwise difficult to retrieve might not be accessible on free recall but may be retrieved with a recognition test. Taken together, the results of the free recall and recognition tests in the study suggest at least two possible explanations for the apparent amnesia for verbal material presented prior to sleep onset.

The first explanation posits that a certain amount or a certain depth of sleep interrupts the transfer or consolidation of information from short-term to long-term memory—Guilleminault and Dement's (1977) "closing gate." In the 10-min sleep condition, words presented just prior to sleep onset may not have been processed into long-term memory and are no longer present in short-term store when the subjects are awakened. In the 30-sec sleep condition, words presented just prior to sleep onset also may not have been processed into long-term storage, but the information may still exist in short-term storage, allowing the subjects to recall the word pairs during testing.

A second explanation deals with the issue of encoding strategies and depth of processing, two common terms used in memory research (Cermak, 1979). As subjects get progressively closer to sleep, the frontal lobes of the brain seem to change to sleep EEG frequencies more quickly than the more posterior regions of neocortex (van Sweden, Kemp, Kamphuisen, & Van der Velde, 1990). As the frontal lobes have been shown to be associated with the maintenance of attention (Schacter, 1987b) and the use of strategies (Shimamura, 1989; Warrington & Weiskrantz, 1982), the progressive deactivation of the frontal lobes seen prior to and during the onset of sleep might be associated with less and less deeply encoded memory traces. Thus, subsequent recall for words heard during this period of decreasing arousal and attention would be impaired due to a progressive anterograde amnesia, in contrast to the retrograde amnesia proposed in the first explanation.

Regardless of the cause of the memory deficit observed during the testing sessions, the findings indicate that amnesia occurs for auditory material presented immediately prior to sleep onset. An inability to recall what happened during a 3-min interval can have disastrous consequences in many jobs. The finding that the interval for the recognition task was briefer, only 1 min, suggests that cues may reduce the length of the interval. Deficits in memory might be reduced by systematically employing cues from a variety of sensory domains for that period of time. Another strategy, the use of naps to reduce sleep deprivation, is discussed in the next section.

MEMORY/COGNITION AT SLEEP-TO-WAKE TRANSITIONS

The term *sleep inertia* is used to describe the feeling of sluggishness and mental dullness commonly reported after awakening from a period of sleep. Reports describe difficulty in focusing attention, concentrating, or, as we have seen, remembering what one was doing prior to falling asleep. Sleep inertia has major consequences for jobs in which someone might be awakened from sleep to make an important decision. Can we trust the decisions made by physicians called in the middle of the night or of ships' captains awakened to deal with an emergency? Several studies have attempted to measure and describe this phenomenon and to isolate the factors influencing the duration of postsleep impaired performance.

In a study of young adults (age 18–30 years), Dinges, Orne, and Orne (1985) measured subjects' reaction time, cognitive task performance, and subjective ratings of alertness when awakened from sleep. The subjects were part of a larger study examining performance during extended sleep deprivation, like that associated with "continuous operations" occupations (e.g., medical house staff and military personnel). The postsleep reaction time was found to be related to the stage of sleep from which the subjects were awakened—the deeper the sleep the slower the reaction time ($r = 0.60$). Additionally, Dinges et al. (1985) found that the amount of slow wave sleep (SWS) correlated negatively with performance on the postsleep cognitive task ($r = -0.63$). The authors suggest that the transition from postsleep sluggishness to full alertness, which they refer to as "the waking process," varies in relation to the amount of time since the last SWS period. In other words, subjects awakened directly from SWS had the hardest time reaching full performance levels.

Evidence has been reported suggesting that prior sleep and the accompanying sleep inertia can impair learning and memory processes for up to 20 min after awakening (Stones, 1977; Tilley & Statham, 1989). Similar results were found in a study of memory for a learning task placed during an interruption of a sleeping period (Bonnet, 1983). In this study, subjects were awakened briefly from either light (Stage 2) or deep (Stage 4) non-rapid-eye-movement (NREM) sleep, given a brief learning task, and then allowed to return to sleep either immediately or after a short waiting period. Bonnet found that on trials when subjects were awakened from Stage 4 NREM sleep, they had poorer short-term and long-term memory than when awakened from lighter sleep. Additionally, subjects performed worse when the learning task occurred immediately after awakening, as opposed to after an 8-min delay.

A recent National Aeronautics and Space Administration/Federal Aviation Administration study (Rosekind et al., 1994) examined the effects of a brief, in-flight "rest opportunity" on a number of factors in long-haul, transpacific flight crews. In particular, the researchers were interested in developing a strategy to mitigate some of the effects of sleep loss and circadian disruption that these flight crews face. Particularly noteworthy was the fact that the study took place during actual flights, not in a jet simulator. To date, the following variables have been examined: sleep during the rest period, psychomotor performance, physiological alertness, accumulated sleep debt, and subjective alertness.

The rest opportunity was a 40-min period, during which flight deck crew members, one at a time, were allowed to nap in their cockpit seats. The other two crew members continued to maintain regular flight operations. The rest group (12 subjects) was compared to a no-rest group (9 subjects) that had a 40-min control period when they performed their usual flight duties. Throughout the fight, all crew members' EEG and eye movements (measures crucial to the assessment of sleep or wakefulness) were physiologically monitored with ambulatory recording devices. In addition, a flight deck observer administered a psychomotor vigilance test of reaction time to the flight crew members at multiple times, including prior to and following the nap opportunity.

Overall, the crew members in the rest group were able to sleep on 93% of the rest opportunities. Generally, they fell asleep quickly and slept efficiently. Measurements of the flight crews' performance on a 10-min, visual reaction time test generally indicated that the no-rest group's performance decreased across flight segments, on night as compared to day flights, and within flight segments. Overall, the rest group maintained consistent performance, significantly better than the no-rest group.

The researchers also found evidence of improved physiological alertness in subjects who were allowed to nap (as compared to control subjects) during the last 90 min of flight, including the descent and landing phases. Crew members who were allowed to nap evidenced significantly fewer "microevents," defined as 5-sec or longer periods of slow eye movements or alpha or theta EEG activity. Interestingly, the crews' self-reported alertness after the 40-min period was lower than before the period, regardless of their test condition (nap vs. no nap). In only the first of four flight segments tested did the crew members in the nap condition rate their alertness as being higher after the nap. For the nap subjects, sleep inertia may have affected the alertness ratings following naps. Superimposed on these findings is the observation that the crews in both conditions rated their alertness lower on nighttime flight segments than on daytime ones. The authors suggest that accumulated sleep debt due to the influence of local layover time and circadian variations may have accounted for the differences between the day and night results.

The overall differences between the nap and no-nap crew members support a conclusion that the in-flight naps can improve a flight crew member's performance and alertness during critical phases of long-haul flights. This appears to contradict the earlier discussed findings that performance may be impaired upon awakening, particularly from slow wave sleep. The resolution of the conflict appears to lie in how sleep deprived the individual is. The more sleep deprived the individual is, the more SWS and the longer the effects of sleep inertia. Naps can facilitate performance if there is sufficient time for the person to recover from the effects of sleep inertia.

SLEEP LEARNING

Sleep learning is a term used to describe learning that takes place as a result of the presentation of information during sleep. This can be either the strengthening of previously learned information or the learning of new information during sleep. The terms *learning during sleep, sleep-assisted instruction,* and *hypnopedia* are used synonymously with *sleep learning.* The promise of sleep learning has been that it might enhance performance in a relatively effortless manner. The prototypical example of sleep-learning research has been the learning of a foreign language by playing language tapes during sleep.

There have been numerous reviews of sleep learning over the past 40 years. Included among these, in order of publication, are reviews by Simon and Emmons (1955), Williams (1973), Lehmann and Koukkou (1973), Aarons (1976), Cohen (1980), and Eich (1990) and books edited by Drucker-Colin and McGaugh (1977) and Fishbein (1981). A comparison of the comments and observations these authors have made about sleep-learning experiments reveals some trends and conflicts within the field. Researchers differ on definitions of key terms, numerous basic methodological issues, and interpretations of results.

Perhaps one of the most significant factors accounting for the disparities among studies was the origin of the studies. Typically, studies on sleep learning from the former Soviet Union or other countries of Eastern Europe found that sleep learning occurred. However, few of their studies employed EEG to monitor whether subjects were actually asleep during the presentation of the stimuli. Instead, the focus of the studies was on the practical application of sleep learning with attention to subject and stimulus characteristics (Dodge & Lamont, 1969, cited in Aarons, 1976). In contrast, most of the studies done in the United States have been interested in the conceptual issues of what types of learning are possible during different sleep stages. These experiments have examined the interplay among stimulus characteristics, EEG parameters, and subsequent memory performance.

Definitions

It appears that most researchers utilize a slightly different definition of, if not term for, sleep learning. A thoughtful, general definition is provided by Aarons (1976), who used the term *sleep-assisted instruction* (SAI).

> All situations in which the learning of verbal material takes place or is enhanced through its presentation to a sleeping person. In one sense, it is a neutral phrase that minimizes the terminological confusion of learning during sleep, sleep learning, hypnopedia . . . (SAI) anticipates the importance of practical effects, but cannot resolve the criterion problem of the sleep–wake distinction. (p. 3)

Others' definitions are not quite so broad. Some definitions do not include the strengthening of previously learned information, limiting themselves to the learning of new associations or information during sleep.

Evidence for Sleep Learning

The stage model of human memory presupposes the existence of three, serial components: sensory store, short-term memory, and long-term memory

(Atkinson & Shiffrin, 1968). A stimulus reaches a sense organ, is transduced into sensory store, goes along to short-term (or working) memory, and is eventually consolidated into long-term (or permanent) memory. Currently, there is no consensus as to the duration of time needed for information to be consolidated into long-term memory. In fact, failure of subsequent information retrieval from long-term memory could be attributable to several sources: impoverished encoding of the original stimulus, a failure of consolidation, a decay of the memory while in storage, or insufficient cues for retrieval.

In order for sleep learning to occur in this model, the stimuli would have to reach a subject's sensory store, enter short-term memory, and be consolidated into long-term memory. However, the information value of the typical item in a sleep-learning experiment, say a single word, may not be enough to allow for subsequent retrieval. To facilitate later retrieval, the stimuli would need to receive elaborated encoding. Such encoding might require access to information already in long-term memory while items are still in short-term memory. Thus, the following steps are likely required for sleep learning of semantic material: (a) A stimulus word is presented, (b) the stimulus reaches sensory store, (c) the stimulus is transferred into short-term memory, (d) the stimulus is processed with the aid of information brought into short-term memory from long-term memory, and (e) the stimulus and various associations are consolidated into long-term memory.

Such a system requires that, during sleep, information be able to move both to and from short- and long-term stores. Some cognitive processing during sleep might require only one or two steps rather than all five. As we see later, there is evidence for cognitive processing during sleep but substantially less evidence for elaborated processing of semantic information.

Sensory Store

An important first question is whether stimuli presented during sleep reach the cortex. After all, one of the defining characteristics of sleep is a relative unresponsiveness to external stimuli. For example, there is an increase in auditory awakening thresholds during sleep, particularly during SWS (Bonnet, Johnson, & Webb, 1978; Rechtschaffen, Hauri, & Zeitlin, 1966).

That the sleeper does not awaken, however, is not evidence that cognitive processing is absent. Fortunately, through the evaluation of event-related brain potentials (ERPs), we can measure directly whether sensory information is processed. Using EEG assessment, ERPs can be recorded in response to auditory stimuli whether the individual is awake or asleep. Surprisingly, given the differences in waking thresholds, the auditory evoked potential threshold does not differ between sleep and wake. The early to middle components of the ERP (the first 100 msec) are seen in both wake and sleep. Although the amplitude of the ERPs are often somewhat reduced in sleep, they show the same predictable relationships with the frequency and intensity of the stimuli whether the person is awake or asleep (Kutas, 1990). Auditory stimuli are processed through the brainstem and reach the auditory cortex even if the sleeper does not awaken. Later components of ERPs, which have been associated with more elaborated processing, are delayed or missing during sleep (Kutas, 1990). This would have implications for the degree of processing that is possible, but at least it is known that auditory information reaches the cortex even during sleep.

Perception and Short-Term Memory for External Stimuli During Sleep

Numerous studies have been able to convincingly demonstrate that sleeping subjects can perceive and discriminate stimuli presented during sleep, indicating at least a minimal degree of cognitive processing. At some level, we are all aware of this degree of processing. Typically, individuals do not fall out of bed despite turning over and moving during sleep. We appear to have learned to process cues regarding the edge of the bed despite the fact that we do not remember doing so.

There is also considerable evidence that we can be awakened more easily to meaningful than nonmeaningful stimuli. The common observation that parents can sleep through a thunderstorm but awaken to the cry of their child has been evaluated by comparing EEG responses to meaningful and nonmeaningful sounds. One of the earliest demonstrations was that individuals were more cortically responsive to their own first name than to an equally loud nonmeaningful and complex sound (Oswald, Taylor, & Treisman, 1960b).

One of the difficulties in evaluating whether information is processed during sleep is that morning reports of events that took place during the night appear to be quite unreliable. For example, individuals can be taught to respond to external stimuli in all stages of sleep, but the next morning they have little memory of doing so. In one study, sleepers were taught to take a deep breath whenever they heard a tone (Badia, Harsh, Balkin, O'Rourke, & Burton, 1985). In the morning, the sleepers were asked how often they heard the tone. Despite taking deep breaths 50 to 100 times in response to a tone, the sleepers reported that they only heard and responded to the tone six to eight times during the night.

To evaluate more directly how much information is processed during sleep, some investigators have awakened subjects soon after the stimuli were presented. Lasaga and Lasaga (1973) tested recall and recognition of numbers presented verbally to eight sleeping subjects. After 15 sec had elapsed since stimulus presentation, the experimenters awakened the subjects and asked them to recall the number just presented. Following this, the subjects were given tests of recognition memory. Looking across trials in which the stimuli were presented during REM sleep, Stage 2, and SWS, the subjects' memory performance declined in a stepwise fashion. Subjects were most accurate for stimuli presented during REM sleep and least accurate for stimuli presented during SWS, though still significantly more accurate than chance. Of particular interest was the finding that in the 10-sec period following the majority of stimulus presentations, regardless of sleep stage, the subjects' EEG became "lighter." In the context of the study, lightening denoted either a descending stage change, or an EEG frequency and/or amplitude change without a corresponding stage change.

Using a similar procedure, Bootzin, Fleming, Perlis, Wyatt, and Schacter (1991) played random alphabetic letters over earphones to 19 college students every 2 to 3 min during the second half of an experimental night. Subjects were called 10 sec after two selected presentations from wake, Stage 2, SWS, and REM sleep and were asked to recall the last letter heard. Overall, subjects were correct for 90.3% of presentations during wake after lights out, 10.5% during Stage 2 sleep, 3.0% during SWS, and 15.2% during REM sleep. The least processing took place during SWS.

Other investigators have also found evidence for less cognitive processing during SWS. Some have found it more difficult to get subjects to respond behaviorally to stimuli presented during SWS (Okuma, Nakamura, Hayashi, & Fujimori, 1966; Williams, Morlock, & Morlock, 1966). Others have failed to find EEG changes in response to stimuli presented during SWS or have found decreased responsivity (Nielsen-Bohlman, Knight, Woods, & Woodward, 1991) or even a deepening of sleep EEG (Busby & Pivik, 1985; Pivik & Busby, 1990). One hypothesis about this reduction in responsivity during SWS is that there may be sleep-stage dependent changes in activity in those brain regions involved in cognitive processing (Nielsen-Bohlman et al., 1991).

The findings with regard to REM sleep have been mixed. Most commonly, however, subjects in REM sleep fail to respond or respond quite slowly to neutral stimuli either behaviorally (Langford, Meddis, & Pearson, 1974; Williams, Morlock, & Morlock, 1966) or with EEG changes (i.e., faster EEG frequencies or alpha activity; Langford, Meddis, & Pearson, 1974; Williams, Tepas, & Morlock, 1962). Neutral stimuli are typically differentiated from novel stimuli (e.g., a change in pattern of stimuli) and from meaningful stimuli (e.g., subject's first name), both of which subjects respond to faster and more reliably. One popular explanation for subjects' failure to respond during REM sleep proposes that subjects indeed perceive the stimuli but incorporate them into the ongoing REM mentation or dreams (Augustyn et al., 1972; Bradley & Meddis, 1974; Dement & Wolpert, 1958; Kinney, Kramer, & Bonnet, 1981; Okuma et al., 1966). Presumably, very important or novel stimuli would lead instead to awakening. On the other hand, when subjects are awakened from REM soon after the stimulus, it is apparent that many have perceived the stimulus (Bootzin et al., 1991; Lasaga & Lasaga, 1973).

Evidence has also been obtained that the threshold to elicit a behavioral response to auditory external stimuli during REM sleep may be different in phasic (i.e., during rapid eye movements or irregular respiration) as compared to tonic REM sleep (Price & Kremen, 1980) The thresholds for response appear to increase significantly from tonic REM sleep to phasic REM sleep to Stage 2 NREM sleep (from 52.6 dB to 59.8 dB to 63.6 dB, respectively). Peripheral sensory input may be attenuated during phasic REM and the subject may also be less able to respond behaviorally, due to transiently increased levels of muscle atonia. The authors also hypothesized that the focus of the sleeper's attention may take on a more internal and less external focus during phasic REM activity.

Access to Long-Term Memory During Sleep

Conditioned discrimination. Subjects conditioned during wakefulness to discriminate between two tones of different frequencies have been shown to be able to continue the discrimination while asleep (McDonald, Schicht, Frazier, Shallenberger, & Edwards, 1975). Responses in Stage 2 were seen in a certain EEG waveform, called a "k-complex," thought to reflect perception of a stimuli. Responses in Stage 4 were seen in heart rate and finger plethysmograph. However, responses of either type were absent in REM, perhaps indicating differential processing of external stimuli or differential access to various components of memory during different stages of sleep.

Threat of punishment. One result that supports a conclusion that information from long-term memory, acquired during previous waking episodes, can be transferred into short-term memory involves experimenters' threats to punish subjects' incorrect responses or failures to respond. It has been shown that when subjects were warned of incorrect response contingent punishment (i.e., a very loud tone or a moderately painful electric shock) during waking, their ability to discriminate between stimuli during sleep appeared to be quite intact (Williams, Morlock, & Morlock, 1966). These results support the idea that information learned during the waking state can be accessed during sleep. Principles of state-dependent memory do not seem to apply for information learned during wake periods and tested during sleep.

Lucid dreaming. Lucid dreaming refers to the ability to recognize that one is dreaming, during a dream. Several researchers have found that subjects are able to respond behaviorally during lucid dreams. Subjects can be instructed to signal that they recognize that they are dreaming by engaging in a previously learned pattern of eye movements (LaBerge, Levitan, Rich,

& Dement, 1988). To engage in the response, the sleeping subject would need to remember, during REM sleep, that he or she was supposed to act out such movements. Attempts to identify the physiological characteristics of lucid dreams have found that lucidity is associated with increased central nervous system arousal, as indicated by increased scalp skin potential responses and increased eye movements (LaBerge, 1990). Increased arousal may be necessary for access to long-term memory.

From Cognitive Processing During Sleep to Long-Term Memory

Conditioned responses. In an important demonstration of new learning during sleep, electric shock at a level just below that required to produce awakening was administered as an unconditioned stimulus. It was found that stimulus tone–EEG response associations acquired during sleep transferred to the waking state (Beh & Barratt, 1965).

In animals, habituation has been shown to transfer from SWS to REM sleep, from REM to SWS sleep, from wake to either REM or SWS sleep, and, to a lesser extent, from either sleep stage to waking (Yehuda, Chorover, & Carasso, 1979). In addition, significantly better facilitation of a previously conditioned association has been found when rats are reexposed to the conditioned stimulus as a cue during REM sleep, versus similar cueing during waking (Hars, Hennevin, & Pasques, 1985).

Behavioral responses. In an unusual series of experiments to evaluate whether subjects would respond to hypnoticlike suggestions during sleep, Evans and colleagues (Evans, Gustafson, O'Connell, Orne, & Shor, 1969, 1970) found that highly hypnotizable subjects who were instructed to perform a behavioral response during REM sleep performed the response on the learning night and during subsequent testing occasions—whether on the next night or 5 months hence. These responses during sleep occurred even though the subjects had no waking knowledge of them. This would appear to suggest that state-specific learning had occurred during sleep. However, the investigators did not measure EMG during sleep, which would make the verification of REM sleep, as compared to wake, difficult. A later attempt to replicate these findings with improved methodology (Perry, Evans, O'Connell, Orne, & Orne, 1978) was unsuccessful.

Verbal information. One of the first EEG sleep-learning studies found virtually no learning of verbal material presented to sleeping subjects (Emmons & Simon, 1956; Simon & Emmons, 1956). Recall tests revealed near-zero levels of performance, and recognition task performance was near chance levels. Recognition performance, however, was significantly better than control levels on items whose presentations were followed by alpha

EEG activity within 10 sec. The authors concluded that learning during true sleep did not occur but that there might be some practical interest in pursuing learning of material presented during the "drowsy state" (alpha EEG activity, as is seen prior to the onset of sleep or during awakenings from sleep). Subsequent studies have found a similar pattern of results. If care is taken so that stimuli are presented during EEG-defined stages of sleep, there is little evidence of learning for verbal information in the absence of alpha EEG activity or EEG speeding in the 15 sec following stimulus presentation. However, almost all of these studies have employed explicit, rather than implicit, tests of memory.

In other areas of research, there has been accumulating evidence that information can be processed outside of conscious awareness (Kihlstrom, 1987). For example, research with brain-injured subjects and with patients under anesthesia has found that information can be stored in memory and exert an influence on later performance despite the absence of explicit memory for the information (Kihlstrom, Schacter, Cork, Hurt, & Behr, 1990; Schacter, 1987a).

To evaluate whether there is implicit memory for stimuli presented during sleep, Wood, Bootzin, Kihlstrom, and Schacter (1992) employed two commonly used tests of implicit memory. The first was a homophone spelling task. Word pairs in which the second word is a homophone (e.g., "tortoise–hare") were presented during sleep to subjects who were later asked to spell the homophones. Priming effects have been demonstrated with this task (Eich, 1984), with subjects more likely to give spellings consistent with the earlier presentation ("h-a-r-e" rather than "h-a-i-r"). The second task involved category–instance pairs. Subjects were presented during sleep with a category name followed by an instance of that category (e.g., "a metal–gold"). Later, when awake, they were given the category name and asked the first instance that came to mind.

Wood et al. (1992) found no evidence for either implicit or explicit memory during EEG-defined stages of sleep. Out of 474 word-pair presentations during unambiguous sleep, there were only 4 instances in which subjects explicitly recalled the word pair. In all 4 instances, the subject awakened within 15 sec of the presentation. Although some researchers have found sleep learning in the absence of alpha activity following the stimuli (e.g., Levy, Coolidge, & Staab, 1972), most studies have found that memory is related to subsequent arousal (e.g., Emmons & Simon, 1956; Koukkou & Lehmann, 1973; Lasaga & Lasaga, 1973). Transfer of stimuli presented during sleep to long-term memory appears to be facilitated by and may require arousal within a few seconds of the stimulus presentation. In this regard, the information processing during sleep appears to be different from that under anesthesia.

Another possible explanation for the lack of either explicit or implicit memory during sleep is that the tasks used have required elaborate semantic processing that may be beyond the capacity of the sleeping individual. Perhaps a perceptual priming task in which prior presentations of a single word to prime its later recognition would be more successful. To evaluate this possibility, Bootzin et al. (1991) employed a perceptual priming test in which subjects had to identify words, presented or unpresented during the first hour of sleep, embedded in white noise. This is perceptual rather than semantic priming because subjects do not need to process the meaning of the word during sleep for it to be primed for its recognition.

Priming, the measure of implicit memory, occurred only for words presented during wake. Subjects accurately identified 63.2% of the words presented during wake as compared to 24.8% for control words not previously presented. Accuracy for words presented during sleep was not significantly higher than for the control words: 32.4% during Stage 1, 17.3% during Stage 2 sleep, and 26.7% during SWS. On free recall and recognition tests, measures of explicit memory, subjects showed memory only for words presented during wake and Stage 1. Subjects accurately recalled only 3 of 110 words presented during Stage 2 sleep and 0 of 89 words presented during SWS. Because words were presented during the first hour of sleep, no data were available for REM sleep. Even for perceptual priming, substantial cognitive arousal appears to be necessary for the processing of verbal information.

Methodological Issues and Conclusions

A number of serious methodological flaws or confounds exist in most of the experiments that examined sleep learning. In some experiments, subjects were sleep deprived anywhere from a few hours to 36 hr prior to the experiment, greatly limiting the generalizability of the data to normal nocturnal sleep (Evans et al., 1970; Oswald, Taylor, & Treisman, 1960a, 1960b). Other researchers have administered hypnotic drugs to their subjects, artificially blocking arousal during sleep (Beh & Barratt, 1965; Evans et al., 1970; Oswald et al., 1960b). Still other studies have tested subjects during periods other than nocturnal sleep (i.e., during daytime naps), thus introducing circadian rhythm considerations (Nielsen-Bohlman et al., 1991).

In addition to having confounded protocols, most studies have not employed multiple measurement techniques to assess alpha activity or EEG speeding during sleep. Computer and human scoring could be used as convergent measures for EEG data. Likewise, sleep studies that test the multiple memory systems proposed by current memory research are rare. Furthermore, experimenters need to focus on a systematic delineation of the subject characteristics and methodological concerns that influence sleep learning. It has already been suggested that multiple training nights (Levy et al., 1972), time-of-night effects (Bierman & Winter, 1989), waking memory performance (Simon & Emmons, 1956), and hypnotizability (Aarons, 1976) are factors of direct relevance to the study of sleep learning.

CONCLUSION

Sleep and sleep deprivation exert powerful influences on performance. As we have seen, sleep produces amnesia for activities that occur just before sleep. As a practical matter there are a number of steps that could be taken to increase alertness so that sleep is less likely to occur at work. Interventions that have the most potential for short-term alerting effects include the optimal timing of work breaks, social activity during breaks, sensory stimulation (such as bright light and background music), imagery, exercise, and physiological self-regulation (see Penn & Bootzin, 1990, for a review of interventions for enhancing alertness and job performance).

One method for enhancing alertness, the use of naps, has been studied extensively. As we saw, awakening from sleep can produce sleep inertia and can have detrimental effects on cognitive performance when individuals are sleep deprived. In contrast, naps can also improve performance during critical periods if time is provided for recovery from sleep inertia.

Interventions aimed at short-term alerting effects may not be sufficient. It may be necessary to look at the root causes of sleep deprivation such as poor sleeping conditions, inadequate sleep scheduling, and sleep disorders. It is also important to consider the psychological adjustment of workers, including their capacities to cope with stress. Stress reduction methods such as relaxation training have broad applicability in areas such as work-related stresses, sleeping aids, enhancement of the recuperative value of rest breaks, and the facilitation of autoregulating physiological systems (Penn & Bootzin, 1990).

If individuals must engage in important activities at times when sleep is likely to occur, safeguards must be considered to ensure that appropriate decisions are being made and that there is an independent record of the decisions. The nature of the safeguards will vary depending on the job. In some work situations, it may be sufficient to have the individual record information and decisions as they are being made. In other situations, automated recording may be sufficient. In still others, it may be necessary to have more than one person processing the same information. As discussed earlier, an inability to recall what happened during a 3-min interval can have disastrous consequences in many jobs. The finding that cues can shorten the interval suggests that the deficits in memory might be reduced by systematically employing cues from a variety of sensory domains to help the individual reconstruct the events to be recalled.

Finally, although there is substantial evidence for cognitive processing during sleep (e.g., the discrimination of meaningful and nonmeaningful stimuli, conditioning, and habituation), the sleep learning of verbal material does not appear to be very promising. First, the amount of sleep learning that occurs, even in transition stages, is modest. More can usually be gained by one learning trial while fully awake than through multiple trials while asleep. Second, if learning is to occur, the sleeper must be kept near or at waking during the presentations. Thus, the night's sleep is likely to be disrupted. Next-day alertness and performance may well be negatively affected because of sleep disruption. Thus, more benefits for job performance are likely to be obtained by a good night's sleep than through sleep learning.

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