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A PILOT STUDY ON THE ENCODING OF A PERCEPTUAL LEARNING TASK FOLLOWING SLEEP DEPRIVATION

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Summary

Memory encoding sometimes must occur during a period of sleep deprivation. The question was whether one night of sleep deprivation inhibits encoding on a perceptual learning task (the texture discrimination task). The sample was 18 human participants (M age = 22.1 yr., $SEM = 0.5$; 8 men). The participants were randomized to a sleep deprivation or sleep control condition and, after the manipulation, were given two administrations of the texture discrimination task. All participants were given an opportunity for a 90 min. nap between the two administrations. Performance was measured by the interpolated stimulus-to-mask-onset asynchrony (i.e., the inter-stimulus interval), at which the percentage of correct responses for the stimuli in the participant's peripheral vision fell below 80%. Offline consolidation was defined as a decrease in this index between the two administrations. Participants who were sleep deprived prior to encoding exhibited similar offline consolidation ($M = -5.3$ msec., $SEM = 2.3$) compared to participants who were not sleep deprived prior to encoding ($M = -6.2$ msec., $SEM = 3.9$); the two-way interaction between time and condition was not significant. In light of reports in the literature, these results indicate

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encoding following sleep deprivation may be influenced by both the type of task encoded and the brain regions involved in memory processing.

Memory processing is most commonly divided into three stages: encoding, consolidation, and retrieval. Encoding results in an unstable memory representation. Consolidation is the stabilization or enhancement of the memory. Methodologically, sleep-dependent memory consolidation studies typically have two memory retrieval sessions: one immediately after encoding and another after sleep or an equivalent period of sleep deprivation. Such empirical data supports the idea that sleep contributes to memory consolidation by integrating the memory into preexisting neocortical networks (Walker & Stickgold, 2006; Diekelmann & Born, 2010). Although each sleep stage may make a relatively larger contribution to one memory system versus another, the sequential processing of a memory by multiple sleep stages may be more important than the individual contribution of one sleep stage (Giuditta, Ambrosini, Montagnese, Mandile, Cotugno, Grassi Zucconi, *et al.*, 1995; Rauchs, Desgranges, Foret, & Eustache, 2005).

In terms of memory consolidation, sleep after training on a perceptual learning task like the texture discrimination task (Karni & Sagi, 1991) facilitates offline consolidation beyond the consolidation that is observed with the passage of time alone (Karni, Tanne, Rubenstein, Askenasy, & Sagi, 1994; Stickgold, James, & Hobson, 2000; Mednick, Nakayama, Cantero, Atienza, Levin, Pathak, *et al.*, 2002; Mednick, Nakayama, & Stickgold, 2003), and this consolidation is dependent upon slow-wave and rapid eye movement (REM) sleep (Gais, Plihal, Wagner, & Born, 2000; Stickgold, Whidbee, Schirmer, Patel, & Hobson, 2000). Importantly, Mednick, *et al.* (2003) reported that a nap produced the same consolidation as a night of sleep, and a nap combined with a night of sleep produced the same consolidation as two nights of sleep.

Although many studies have examined the effect of sleep deprivation on consolidation, less is known about its effect on encoding. This is important because memory encoding sometimes must occur during a period of sleep deprivation. To fill this gap in the literature, researchers must manipulate encoding while holding consolidation constant. In the context of sleep research, this is typically accomplished with the following design: participants in one condition are sleep deprived at encoding, those in the other condition are well rested at encoding, and participants in both conditions are allowed to sleep during the consolidation period. The rest of the design is identical to the design described above on sleep-dependent consolidation: two retrieval sessions separated by a consolidation period. Utilizing this design, Yoo, Hu, Gujar, Jolesz, and Walker (2007) found that d' scores decreased on a picture-naming task for participants who encoded the task after a night without sleep compared to participants who encoded the task after a normal night of sleep. The picture-naming task is a declarative memory task. Whether sleep deprivation has similar effects on a nondeclarative task remains an open question because no studies exist on the effects of total sleep deprivation on nondeclarative memory encoding.

In the current study, the effect of one night of total sleep deprivation on the encoding of the texture discrimination task (a nondeclarative memory task) was tested. Total sleep deprivation was chosen so that as few design features as possible would be changed between

the experiment by Yoo, *et al.* (2007) and the current experiment. The task was chosen because it is retinotopically specific; the changes in the brain that support consolidation on this task are restricted to the primary visual cortex because performance gains based on training in one visual field do not transfer to another visual field.

Based on the prior declarative memory encoding study, a similar result was expected in this nondeclarative task. A two-way interaction between condition (sleep deprivation, sleep control) and time of testing (morning before nap, evening after nap) was hypothesized for stimulus-to-mask-onset asynchrony threshold scores. No differences in stimulus-to-mask-onset asynchrony threshold scores between the conditions at the morning administration and no differences in stimulus-to-mask-onset asynchrony threshold scores between the morning and evening administration were expected for the sleep deprivation condition, and a significant decrease (i.e., better performance) in stimulus-to-mask-onset asynchrony threshold scores was expected between the morning and evening administration for the sleep control condition.

Method

Participants

All procedures were approved by the National Institutes of Health Combined Neurosciences Institutional Review Board and the Walter Reed Army Institute of Research Institutional Review Board. The participants were typically undergraduate students at local universities or Post-Baccalaureate Fellows at the National Institutes of Health. They were recruited by posted flyers in common spaces such as residence facilities and building hallways and with snowball sampling. All participants gave written informed consent. The participants were monetarily compensated \$200 (nonsleep-deprived) or \$400 (sleep-deprived) for research-related discomforts (e.g., sleep deprivation) and inconveniences (e.g., overnight laboratory visits) according to National Institutes of Health guidelines.

Inclusion/exclusion criteria were applied before enrollment and after data collection. Before enrollment, the participants were required to be 18–28 years of age with normal or corrected-to-normal vision. They were also screened for a clinical history of sleep disorders. A nurse/physician team collected a comprehensive medical history and performed a physical examination. Participants were excluded if they had a chronic medical condition that was a contraindication for sleep deprivation or if they had a family history of a monogenetic neurologic disorder. A psychiatric screening was performed using an abbreviated version of the Structured Clinical Interview for DSM-IV–TR Axis I Disorders (First, Spitzer, Gibbon, & Williams, 2002). Participants were excluded if they had a past diagnosis or current presentation of an Axis I disorder. They were tested for abuse of drugs by providing a urine sample and excluded accordingly. A total of 132 participants were screened and 89 passed screening; many participants who passed screening did not complete the study because their schedules could not be accommodated or because they moved out of the area. The participants were further screened after data collection: they were required to have spent at least 30 sec. in slow-wave or REM sleep during the nap opportunity.

Eighteen participants (8 men, 10 women) were included in the final sample, with nine participants in each condition. Their mean age was 22.1 yr. ($SD = 2.2$ yr.). The data from 10 participants were not included in this final sample. High rates of exclusion were expected. The reasons for excluding seven of the participants were as follows. Two participants did not attain any slow-wave or REM sleep during the nap opportunity. The exclusion of these participants was essential to the question because only prior sleep deprivation was to be manipulated and all participants were required to sleep during the nap opportunity. One participant failed the urine drug screen at admission despite passing it at screening. Three of the first six participants did not perform above chance because the instruction and training procedures had not been optimized. One participant did not complete the first administration of the task due to a computer malfunction. The reasons for excluding three other participants were not expected. One participant had extremely poor performance at baseline (stimulus-to-mask-onset asynchrony threshold score = 376 msec). Two participants did not follow task instructions and sacrificed accuracy for speed. This was verified by direct observation during test administration and by analyzing time to completion for the task. These two participants were ranked second ($z = -1.03$) and third ($z = -0.87$) for the morning time to completion and second ($z = -1.07$) and third ($z = -0.98$) for the evening time to completion. Compared to the excluded participants, included participants were slightly younger (22.1 vs 24.1 yr.), but the included participants were not significantly different in age ($t_{26} = 2.04, p = .05, d = 0.80$), sex ($\chi^2_1 = 2.49, p = .34$), or randomized condition ($\chi^2_1 = 0.40, p = .53$).

Procedure

For two weeks immediately prior to the study, the participants were required to undergo a sleep hygiene, extension, and condensation protocol to eliminate any pre-existing sleep debt that might have occurred from chronic, partial sleep deprivation (Rupp, Wesensten, Bliese, & Balkin, 2009). The participants were required to obtain a continuous period of 10 hr. time in bed at approximately the same time every night, and they were not allowed to nap. Adherence to this protocol was verified with wrist actigraphy (Mini Motionlogger, Ambulatory Monitoring, Ardsley, NY) and a telephone log of into- and out-of-bed times. Actigraphs use a piezoelectric accelerometer to record activity, and the actigraphs were programmed to store activity based on zero crossings or the number of times the accelerometer waveform crossed zero for each recording epoch. During the first 11 days, the participants were required to consume no more than one caffeinated beverage per day, to consume no more than one alcoholic beverage per day, and to discontinue their use of over-the-counter medications. During the last 3 days, they were required to abstain from all caffeine, stimulants, sleeping aids, tobacco, and alcohol.

On Day 1 of the study, the participants were admitted to an inpatient unit at the National Institutes of Health Clinical Center. Actigraphy and telephone log data were reviewed, and those who did not follow instructions were withdrawn from the study. The participants were tested again for abuse of drugs and excluded accordingly. The 18 remaining participants were randomly assigned into a sleep deprivation or sleep control condition. Participants from each condition did not differ in age ($t_{16} = 1.19, p = .25, d = 0.56$) or sex ($\chi^2_1 = 2.10, p = .77$). Those in the sleep deprivation condition were kept awake overnight, whereas those in the sleep control condition were given an opportunity to sleep for 10 hours. This means they

were assigned a bed in the inpatient unit and instructed to try to sleep for 10 hours. Inpatient nurses monitored them during this period to ensure they did not get out of bed. At all times during their inpatient visit, excluding sleep opportunities, the participants were kept awake by monitoring them closely and eliciting responses to direct questions. No stimulants were provided or allowed. During sleep deprivation, the participants were entertained by research assistants with conversation and games. Provided that they did not show signs of drowsiness, they were also allowed to study or entertain themselves by watching movies.

On Day 2 of the study, the texture discrimination task was administered at approximately 0830 hr. (morning administration) and again at approximately 1800 hr. (evening administration). Each administration lasted approximately 1.5 hours, so the offline delay between administrations was approximately 8 hours. What the authors mean by an “offline delay” is the period when the participants were not performing the task. This is important because it is when offline consolidation occurs. In between the two administrations, all participants were given an opportunity for a 90 min. nap with polysomnography at approximately 1230 hr. The participants were given the following instructions for the nap opportunity: “Please try to sleep. If you cannot sleep, that is fine, but please try to sleep until we say the test is over.”

Texture Discrimination Task

The task was administered using a Perl implementation that was running on a Windows XP computer with a cathode ray tube monitor. The participants had no prior experience with the task. Prior to each task administration, participants were given 30 min. of instruction and training on the task. The task was administered in dim light, and the monitor was positioned approximately 55 cm from the participants’ eyes.

To initiate each trial, the participants pressed the space bar when a fixation cross appeared in the center of the screen. Each trial had a blank delay screen (250 msec.), a stimulus (17 msec.), a variable stimulus-to-mask-onset asynchrony (i.e., the inter-stimulus interval), a mask (100 msec.), and a blank screen. The participants gave their responses at the final blank screen (Fig. 1a).

The stimulus consisted of three diagonal bars in either the lower right or lower left visual field in either a horizontal or vertical array. The position in the visual field was randomized for each participant, but they were tested in the same position in the visual field for both task administrations without crossover. The diagonal bars were displayed against a background of horizontal bars with the letter *T* or *L* displayed at the fixation point. The participants were asked to determine whether the letter at the fixation point had been a *T* or *L* and whether the array of diagonal bars in the periphery had been horizontally or vertically oriented (Fig. 1b).

During the 1,250 administered trials, the stimulus-to-mask-onset asynchrony was progressively decreased, thereby increasing the difficulty of the task. The session began with 50 trials at each of the following stimulus-to-mask-onset asynchronies: 500, 400, 300, and 200 msec. The session continued with 150 trials at each of the following stimulus-to-mask-onset asynchronies: 180, 160, 140, 120, 100, 80, and 60 msec. The interpolated stimulus-to-mask-onset asynchrony at which the percentage of correct responses for the horizontal/

vertical response fell below 80% was used as the overall performance index for each administration. Performance on the *T/L* response merely ensured central fixation throughout the trial so that the horizontal/vertical stimuli were consistently mapped to the same part of the primary visual cortex, whereas performance on the horizontal/vertical response was relevant to perceptual learning. Trials in which the participants gave an incorrect *T/L* response were not included when calculating the percentage of correct responses. Offline consolidation was defined as a decrease in the interpolated stimulus-to-mask-onset asynchrony for the horizontal/vertical response in the evening compared to the morning.

Polysomnography

Electrode placement followed American Academy of Sleep Medicine (2007) standards. Data were recorded and analyzed using Easy EEG III hardware and software (Easy EEG III, Cadwell, Kennewick, WA). Sleep staging was performed manually from C₃ according to American Academy of Sleep Medicine (2007) procedures and criteria. For example, a band-pass filter of 0.5–20.0 Hz was used for electroencephalography and electro-oculography channels and a high-pass filter of 10 Hz and a low-pass filter of 70 Hz with a notch filter at 60 Hz for the electromyography channel.

Analysis

An *a priori* power analysis was not performed for this study. Although it is not appropriate to perform a *post hoc* power analysis using the current sample (Hoenig & Heisey, 2001), the published data from studies of the effects of sleep deprivation on declarative memory encoding (Yoo, *et al.*, 2007) were used to estimate the likelihood of finding a false negative in the current sample. In the prior study, the effect size for the behavioral results was very large ($d = 2.21$). To be conservative, this value was rounded down to 2.0. At $\alpha = .05$ and 1 degree of freedom for the effect of interest (i.e., the 2×2 interaction; Appendix D from Murphy, Myers, & Wolach, 2009), 10 participants per condition were needed to obtain power = 0.80.

Stimulus-to-mask-onset asynchrony threshold scores for the texture discrimination task were analyzed with a mixed-model repeated-measures analysis of variance (ANOVA) with condition (sleep deprivation, sleep control) as the between-subjects variable and time of testing (morning before nap, evening after nap) as the within-subjects variable. This analysis was performed with raw scores from each administration. Simple effects were also examined with either paired-samples *t* tests of the change in scores between the two administrations or independent-samples *t* tests of the raw scores between the two conditions. Minutes in each sleep stage during the 90-min. nap opportunity were compared between the two conditions with independent-samples *t* tests. Pearson correlations were calculated for the relationship between offline consolidation in the task and minutes in each sleep stage. To compare the significance of the difference between two correlations, Fisher's *z* transformation was performed and was followed by a *z* test of the difference between the transformed correlations. SPSS was used for all analyses (SPSS, IBM, Armonk, NY). Statistical significance was set at .05 for all tests.

Results

Main Hypothesis

All participants maintained central fixation throughout the morning and evening administrations of the task. This was ascertained from high scores on the *T/L* response for both the morning ($M = 91.7\%$, $SEM = 1.9$) and evening ($M = 94.1\%$, $SEM = 1.4$) administrations. There were no significant differences between the sleep deprivation and sleep control conditions (morning: $t_{16} = 1.54$, $p = .14$, $d = 0.73$; evening: $t_{16} = 0.73$, $p = .48$, $d = 0.34$).

For the horizontal/vertical response, the interaction between condition and time of testing ($F_{1, 16} = 0.04$, $p = .85$, $\eta^2 = 0.002$) was not significant (Fig. 2). The main effect of condition ($F_{1, 16} = 0.58$, $p = .46$, $\eta^2 = 0.04$) was not significant, whereas the main effect of time of testing ($F_{1, 16} = 6.49$, $p < .05$, $\eta^2 = 0.29$) was significant. Although the interaction was not significant, the simple effects were examined. By means of paired-samples *t* tests, the mean decrease in stimulus-to-mask-onset asynchronies ($M = -5.3$ msec., $SEM = 2.3$) for the sleep-deprived participants was statistically significant ($t_8 = 2.28$, $p < .05$, $d = 0.23$). In controls, the decrease ($M = -6.2$ msec., $SEM = 3.9$) was not significant ($t_8 = 1.60$, $p = .07$, $d = 0.30$). Comparison of the two conditions by means of independent-samples *t* tests indicates that performance at the morning ($t_{16} = 0.72$, $p = .48$, $d = 0.34$) and evening ($t_{16} = 0.77$, $p = .45$, $d = 0.36$) administrations were not significantly different.

Ancillary Analyses

Errors were also analyzed, such as false starts (i.e., when the participant attempted to enter the responses before the cue to do so or when the participant attempted to initiate the subsequent trial before entering both responses for the current trial). Participants in the sleep deprivation condition exhibited more errors ($M = 21.3$, $SEM = 5.2$ vs $M = 5.7$, $SEM = 1.8$) at the morning administration ($t_{16} = 2.85$, $p < .05$, $d = 1.34$). There were no differences at the evening administration ($t_{16} = 1.01$, $p = .33$, $d = 0.48$).

As might be expected, prior sleep deprivation increased sleep during the 90-min. nap opportunity (Table 1). Time in slow-wave sleep was threefold higher in the sleep-deprived condition compared with controls. Similarly, participants in the sleep-deprived condition spent significantly less time in wakefulness and stage N1 than controls. The disadvantage of being sleep-deprived at encoding might have been offset by the advantage of sleeping better during consolidation. To address this potential confound, two ancillary analyses were performed. First, the mixed-model repeated-measures ANOVA was repeated, with minutes in stage N3 as a covariate. The interaction was still not significant ($F_{1, 15} = 2.11$, $p = .17$, $\eta^2 = 0.12$). Second, the correlation between offline consolidation and minutes in each sleep stage was calculated. This was done separately for participants in the sleep deprivation and sleep control conditions. None of the raw correlations were statistically significant, and none of the between-conditions correlation comparisons were significantly different (Table 2).

Discussion

Sleep deprivation did not seem to inhibit perceptual memory encoding on the texture discrimination task. Sleep-deprived participants encoded the task and showed offline consolidation following a nap.

While acknowledging the deleterious effects of sleep deprivation on declarative memory encoding (Yoo, *et al.*, 2007), the results suggest that prior sleep deprivation did not prevent memory encoding on a nondeclarative task. The principal distinction between the designs of the current and previous study is that the current study assessed a nondeclarative memory system, whereas the previous study was designed to assess a declarative memory system. This distinction may be important because the texture discrimination task relies on lower-order processing in primary visual cortex (Karni, *et al.*, 1994; Schwartz, Maquet, & Frith, 2002), whereas declarative memory tasks rely on the hippocampus (Milner, Squire, & Kandel, 1998). It may be that sleep deprivation has a greater effect on memory tasks that depend on some brain regions compared to others (Hagewoud, Havekes, Tiba, Novati, Hogenelst, Weinreder, *et al.*, 2010). In accord with this idea are results of studies in sleep-deprived mice in which an absence of performance changes was seen as mice shifted from a hippocampus-dependent cognitive strategy to a striatum-dependent cognitive strategy for completion of a spatial learning task. This shift was accompanied by a shift in the phosphorylation of cyclic adenosine monophosphate response-element binding proteins from the hippocampus to the striatum (Hagewoud, *et al.*, 2010).

Another difference between the two studies is the assessment method inherent to each task. In the current study, two administrations of the texture discrimination task were used, whereas Yoo, *et al.* (2007) had one surprise recognition test. By using the texture discrimination task, encoding and performance assessment were combined into a single procedure. In contrast, the encoding procedure for the picture-naming task used by Yoo and colleagues involved exposing participants to the stimuli and asking them to differentiate whether the picture was an indoor or outdoor scene. Another difference between the two studies is the time lag between encoding and retrieval. This study used an 8-hr. delay, whereas Yoo and colleagues used a 48-hr delay.

Although the current findings were somewhat unexpected, there are results for other nondeclarative tasks that were measured in the context of relatively similar designs. The investigators from one study (Van Der Werf, Altena, Schoonheim, Sanz-Arigita, Vis, De Rijke, *et al.*, 2009) were interested in the effects of reducing slow-wave activity (0.4–4.0 Hz) on declarative memory encoding in elderly individuals. Using auditory stimuli during a normal nocturnal sleep opportunity, they succeeded in reducing slow-wave activity, and this caused decreased d' scores on a picture-naming task for participants who encoded the task after a night with reduced slow-wave activity compared to participants who encoded the task after a normal night of sleep. The investigators included the serial reaction time task as a nondeclarative memory negative control: average reaction times for the fixed minus random sequences were unaffected by the manipulation. In a second study (Mander, Santhanam, Saletin, & Walker, 2011), the effects of a normal diurnal period of 16 hr. of wakefulness on declarative memory encoding were assessed. Theories on the function of sleep contain the

postulate that wakefulness saturates the brain's capacity to encode and that sleep is necessary to restore this capacity. To test this postulate a face-naming task was given at 1200 hr. and 1800 hr., and half of the participants were given a nap opportunity in between these two administrations. Because these investigators were interested in the effects of a normal diurnal period of 16 hr. of wakefulness, no sleep deprivation was employed. As hypothesized, percent of faces correctly recalled progressively decreased in the No-nap condition but was revived in the Nap condition. The investigators included the finger-tapping task as a non-declarative negative control, and both speed of tapped sequences and error rate per sequence was unaffected by the manipulation. The designs of these recent studies were dissimilar to the current study, of course. Each study was designed to address a question that was different from the question in the current study, and each study employed a unique non-declarative task. However, there are enough similarities to the current study to suggest the results are not completely out of line with the literature.

During the nap opportunity in the current study, participants in the sleep deprivation condition had less wakefulness and stage N1 sleep and more slow-wave sleep than controls. This might have resulted in better consolidation for the participants in the sleep deprivation condition. In other words, the disadvantage of being sleep-deprived at encoding might have been offset by the advantage of sleeping better during consolidation. However, including N3 as a covariate did not change the results, and there were no differences in the sleep-performance correlations between the sleep deprivation and sleep control conditions. This argues against the idea that the participants in the sleep deprivation condition had greater memory consolidation. The participants' overnight sleep in the control condition was unmonitored, so the amount and quality of sleep that they experienced is not known. To address this issue, future studies should utilize wrist actigraphy or polysomnography during this phase. It is also possible that there was simply not enough statistical power to detect a difference between the conditions. However, the *post hoc* power analysis indicates sufficient statistical power to detect an effect of the size that was expected based on prior studies (Yoo, *et al.*, 2007). Nevertheless, the results should be interpreted cautiously due to the small sample size. It may also be said that perceptual threshold data is unreliable. Response bias has indeed played a critical role in the formulation of signal detection theory (Palmer, 1999), but it is less important in the context of the current study (i.e., with perceptual discrimination data vs perceptual threshold data) because the participants were forced to choose between two equal responses, so it is not possible to adopt a conservative or liberal detection strategy. The results were compared with the results of a previously published study that used a declarative task. Future research should directly compare the results from a declarative and non-declarative task within the same participants. The inclusion of women in the sample without regard to the stage of hormonal cycle may have influenced the results, but the inclusion of women increases the generalizability of the results. Future investigators may wish to perform a study specifically designed to measure the interaction of hormonal cycle stage in women with the effects of sleep deprivation on memory encoding.

The results do not suggest it is safe for individuals to perform sustained vigilance tasks (e.g., driving) while sleepy. It is clear that sleep deprivation produces performance lapses on simple reaction time tasks (Dinges & Powell, 1985). A secondary metric that is unrelated to the central purpose of the texture discrimination task is errors. The participants in the sleep

deprivation condition exhibited significantly more errors at the morning administration. This secondary metric that can be extracted from the texture discrimination task may be sensitive to the effects of sleep deprivation on vigilance. However, there was no difference between the conditions on perceptual discrimination at the morning administration, so the effect on vigilance may be dissociable from the effect on memory encoding.

Memory encoding for nondeclarative tasks may be less affected by prior sleep deprivation when compared to declarative tasks. The effect of encoding variability on the success of consolidation may depend on the type of task that the individual is required to perform and the brain region involved in the memory processing associated with that task. These factors may be important to note in cases where encoding must take place during a period of sleep deprivation. For example, the results suggest the feasibility of daytime brain imaging studies of sleep-deprived participants undergoing memory consolidation during sleep. Future studies could be designed to extend these findings by assessing the memory encoding resiliency of other primary sensory cortices under conditions of sleep deprivation.

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Fig. 1.
a) Trial timeline for the texture discrimination task. b) Examples of the four possible stimuli that were shown to subjects.

Fig. 2.

Raw stimulus-to-mask-onset asynchrony (SOA) threshold scores across time of testing for each condition (means and *SEMs*). Statistical significance of the difference between morning and evening scores by means of paired *t* test. * $p < .05$. † $p < .10$.

Table 1

Total Minutes in Each Sleep Stage During the 90-min. Nap Opportunity

Sleep Stage	Time in Sleep Stage (min.)				t_{16}	d
	Sleep Deprived ($n = 9$)		Sleep Control ($n = 9$)			
	M	SEM	M	SEM		
Wake	5.78	2.18	22.44	5.45	-2.84 *	1.34
N1	2.94	0.86	11.0	1.93	-3.81 *	1.80
N2	27.17	4.86	33.28	3.67	-1.00	0.47
N3	53.94	5.43	17.39	5.68	4.65 ‡	2.19
REM	2.39	1.00	5.78	2.14	-1.43 †	0.68
Total sleep time	86.44	1.04	67.44	5.42	3.45 *	1.62

Note.—Statistical significance of the difference in sleep stages between conditions by means of independent samples t test.

* $p < .05$.

† $p < .10$.

‡ $p < .001$.

Table 2

Sleep–performance Correlations

Sleep Stage	Sleep Deprivation ($n = 9$) r 95% CI		Sleep Control ($n = 9$)		Difference		
	r	95% CI	r	95% CI	$r_2 - r_1$	95% CI	z
N1	.49 *	−0.26, 0.87	−.14	−0.73, 0.58	−.62	−1.49, 0.24	1.16
N2	.34	−0.42, 0.82	.05	−0.63, 0.69	−.29	−1.18, 0.61	0.52
N3	−.44	−0.86, 0.31	−.51 *	−0.88, 0.23	−.07	−0.88, 0.74	0.16
REM	.13	−0.59, 0.73	.07	−0.62, 0.70	−.05	−0.97, 0.87	0.09
Total sleep time	−.22	−0.77, 0.52	−.53 *	−0.88, 0.21	−0.31	−1.16, 0.54	0.63

Note.— $r_2 - r_1$ = the difference between the correlations; 95% CI = 95% confidence interval.

* $p < .10$.