MEMORY, AROUSAL, AND PERCEPTION OF SLEEP

By

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Dedication

I can only dedicate this dissertation to Dick Bootzin. Without you, it would not have been. Without you it is. I wish you were here to see it.

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Abstract

People with insomnia overestimate how long it takes to fall asleep and underestimate the total amount of sleep they attain. While memory is normally decreased prior to sleep onset, this decrease is smaller in insomnia. Insomnia generally and the phenomena of underestimation of sleep and greater memory prior to sleep area associated with arousal including cortical, autonomic, and cognitive arousal. The goal of the present study was to simultaneously examine arousal across these domains in relation to memory and accuracy of sleep estimation.

Forty healthy adults completed baseline measures of sleep, psychopathology, and memory, then maintained a regular sleep schedule for three nights at home before spending a night in the sleep laboratory. On the night of the sleep laboratory study, participants completed measures of cognitive arousal, were allowed to sleep until five minutes of contiguous stage N2 sleep in the third NREM period. They were then awoken and asked to remain awake for fifteen minutes, after which they were allowed to resume sleeping. For the entire duration that they were awake, auditory stimuli (recordings of words) were presented at a rate of one word per 30 seconds. Participants slept until morning, estimated how long they were awake and then completed memory testing, indicating whether they remembered hearing each of the words previously presented along with an equal number of matched distracter words.

Memory was greatest for words presented early in the awakening, followed by the middle and end of the awakening. High cortical arousal prior to being awoken was associated with better memory, particularly for the early part of the awakening. High autonomic arousal was associated with better memory for the late part of the awakening. Cognitive arousal was not associated with memory. Longer duration of sleep prior to being awoken was associated with better memory for the middle of the awakening. Better memory at baseline was associated with better memory, specifically

in the middle of the awakening. Contrary to expectation, memory for the awakening was not associated with accuracy of the perceived length of the awakening.

The present study found complementary associations between cortical and autonomic arousal and memory for an awakening from sleep. This suggests that decreasing arousal in both domains may reduce the discrepancy between subjective and objective sleep in insomnia. This also suggests the initial magnitude of decrements in cognitive performance after being awoken are related to deeper proximal sleep initially, while speed of improvement in cognitive performance is related to longer prior sleep duration.

Introduction

People with insomnia tend to underestimate their total sleep duration and overestimate their sleep latency (Carskadon et al., 1976; Edinger & Fins, 1995; Maes et al., 2014; Manconi et al., 2010; Means, Edinger, Glenn, & Fins, 2003; Perlis, Smith, Andrews, Orff, & Giles, 2001), particularly when objective sleep duration is at least six hours (Fernandez-Mendoza et al., 2011). People with insomnia also need to be asleep longer in order to recall having slept (Knab & Engel, 1988). The neurocognitive model of insomnia postulates that this discrepancy, often referred to as sleep misperception, is a significant factor in insomnia and that conditioned cortical hyperarousal contributes to increase cognitive activity, including information processing and memory encoding, during sleep/wake transitions (Perlis, Giles, Mendelson, Bootzin, & Wyatt, 1997). This discrepancy has negative prognostic implications including greater likelihood of relapse to drinking in alcohol dependence (Conroy et al., 2006) and failure of conventional insomnia treatment (McCall & Edinger, 1992).

Several studies have shown that memory for the transition from wake to sleep is relatively diminished (Guilleminault & Dement, 1977; Wyatt, Bootzin, Allen, & Anthony, 1997; Wyatt, Bootzin, Anthony, & Bazant, 1994). This mesograde amnesia is comprised of anterograde amnestic effects of decreasing arousal while approaching sleep onset, and anterograde sleep interfering with early consolidation (Wyatt et al., 1997). The three to four minute duration of this amnesia prior to sleep onset is consistent with a study of nocturnal awakenings, which found that, on average, awakenings shorter than four minutes by objective measurement were not subjectively recalled (Winser, McBean, & Montgomery-Downs, 2013).

Cortical arousal, as measured by relative beta EEG power, prior to sleep onset is associated with decreased mesograde amnesia in good sleepers, possibly due to continued processing of consolidation of stimuli prior to sleep (Wyatt et al., 1997). This is consistent with the finding that subjective underestimation of sleep time in insomnia is associated with cortical arousal (Krystal, Edinger, Wohlgemuth, & Marsh, 2002; Maes et al., 2014; Perlis et al., 2001). Delta EEG power, on the other hand, may be associated with decreased memory. Bonnet (1983) found memory to be worse when participants were woken from delta-rich stage 4 sleep as compared to stage 2 sleep. Delta power in the frontal cortex has also been shown to be associated with hippocampal sleep spindles during the final four minutes of wakefulness prior to sleep onset (Sarasso et al., 2014). Further, delta power in the last 10 minutes of sleep prior to waking has been shown to be associated with subsequent decrements in cognitive performance (Tassi et al., 2006). Taken together, these findings suggest that cortical arousal is associated with basic cognitive functioning, memory, and estimation of sleep duration.

Arousal in insomnia is not restricted to cortical arousal. Insomnia is also associated with increased autonomic arousal and metabolic rate (Bonnet & Arand, 1995, 1997, 1998; Maes et al., 2014). Insomnia is also associated with cognitive arousal, including anxiety and worry (Fernandez-Mendoza et al., 2011). Cognitive and physiological arousal are in turn associated with accuracy of time estimation (Tang & Harvey, 2004, 2005).

The tendency toward disrupted sleep in response to stress, "sleep reactivity," is predictive of future development of chronic insomnia (Drake, Pillai, & Roth, 2014). High sleep reactivity is associated with greater sleep disruption on the first night of a laboratory sleep study and in response to caffeine-induced physiologic arousal (Drake, Jefferson, Roehrs, & Roth, 2006; Drake, Richardson, Roehrs, Scofield, & Roth, 2004). Neither sleep misperception nor peri-sleep mesograde amnesia have been previously examined in relation to sleep reactivity. Since sleep misperception has been suggested to be an earlier stage of insomnia disorder, preceding "objective insomnia", sleep misperception may be associated with sleep reactivity.

Prior studies have focused on the association of only one or two forms of arousal with sleep misperception. The few studies that have investigated memory have included measures of arousal. Thus, the goal of the present study was to simultaneously measure cortical, autonomic, and cognitive arousal, memory across the transition from sleep to wake and back to sleep, and the accuracy of subjective duration of this wakefulness. Specifically, we hypothesized:

Hypothesis 1: That memory for the first and last third of an awakening from sleep would be lower than from the middle third, due to sleep inertia and mesograde amnesia, respectively.

Hypothesis 2: That memory for awakenings later in the night would be better than for awakenings earlier in the night due to lower homeostatic sleep pressure.

Hypothesis 3: That greater cortical arousal prior to awakening, while awake, and after returning to sleep, would be associated with better memory during the sleep/wake transition.

Hypothesis 4: That autonomic arousal would be associated with better memory during the sleep/wake transition.

Hypothesis 5: That cognitive arousal would be associated with better memory during the sleep/wake transition.

Hypothesis 6: That sleep reactivity would be associated with better memory during the sleep/wake transition.

Hypothesis 7: That greater memory during the sleep/wake transition would be associated with longer perceived duration of wakefulness relative to objective duration of wakefulness.

Methods

Participants

Participants were 40 young adults (65% female), with a mean age of 20.28 (standard deviation = 2.31), and were primarily white and non-Hispanic (see Table 1 for demographics). Inclusion criteria included being age 18-30, a native English speaker, reported habitual weeknight bedtime between 9:00PM-1:00AM, habitual wake time between 5:00-9:00AM, typical sleep onset latency less than 20 minutes, typical total sleep of six to nine hours, and willingness to abstain from alcohol and nicotine and limit caffeine use during the study period.

Exclusion criteria included any reported medical condition or use of medication known to affect sleep or memory, any reported sleep disorder, current DSM-IV Axis I disorder as assessed with the Mini International Neuropsychiatric Interview or by self-report, history of insomnia disorder as assessed with the Duke Structured Interview for Sleep Disorders, and high risk of obstructive sleep apnea, as assessed with the STOP-BANG.

Measures

Clinician-Administered Measures

The Mini International Neuropsychiatric Interview (Sheehan et al., 1997) (MINI) is a structured clinical interview that assesses for the presence of the most common DSM-IV Axis I disorders, as well as antisocial personality disorder. The Duke Structured Interview for Sleep Disorders (DSISD) is a structured interview that assesses for symptoms of sleep disorders. The present study used only the insomnia module. The STOP-BANG is an 8-item screening measure for assessing risk of obstructive sleep apnea (Chung et al., 2008) including anatomical measurements to assess BMI and neck circumference. The Rey Auditory Verbal Learning Test (AVLT; Rey, 1964) is an auditory list-learning memory test including tests of immediate, delayed, and recognition memory for a list of 15 words. The Verbal Paired Associates test (VPA) is a measure of immediate, delayed, and recognition memory for 14 word pairs (Wechsler, 2009).

Self-Report Measures

The Ford Insomnia Response to Stress Test (FIRST; Drake, Richardson, Roehrs, Scofield, & Roth, 2004) is a nine-item measure of sleep reactivity: the tendency to have disturbed sleep in response to stress. The State Trait Anxiety Inventory (STAI; Spielberger, Gorsuch, & Lushene,

1970) is a self-report measure with 20 items relating to trait anxiety and 20 items relating to state anxiety. The Short Form Perceived Stress Scale (PSS; Warttig, Forshaw, South, & White, 2013) is a 4-item measure of perceived stress, in this case worded to reflect the level of stress for the day of administration.

Polysomnography

The polysomnography montage included 11 EEG leads (Fp1/2, F3/z/4, C3/z/4, Pz, O1/2), left and right EOG, left and right mastoids, submental EMG, nasal pressure transducer, oro-nasal thermistor, respiratory inductance plethysmography, pulse oximetry, anterior tibialis EMG, and hand EMG. EEG signals were referenced online to CPz, high pass filtered at 0.3 Hz, and low pass filtered at 70 Hz. Signals were sampled and stored at 400 Hz. Sleep records were scored in 30-second epochs according to standard criteria (Iber, Ancoli-Israel, Chesson, & Quan, 2007) by a trained sleep researcher (SCD).

EEG Spectral Analysis

EEG signals were re-referenced offline to average mastoids and analyzed in nonoverlapping six-second epochs after application of a Hamming window. Following semi-automated artifact rejection, power was calculated for the following bands: delta (0.5 to <4.0 Hz), theta (4.0 to <8.0 Hz), alpha (8.0 to <12.0 Hz), sigma (12.0 to <16.0 Hz), beta1 (16.0 to <20.0 Hz), and beta2 (20.0 to <35 Hz). Relative power was calculated by dividing the power in the band of interest by the sum of power in all bands.

Autonomic Arousal

EKG data was extracted, converted to an inter-beat interval series, and then transformed into a time series of instantaneous heart rate, using linear interpolation. The natural log of spectral high frequency power (.12-.4 Hz), referred to as respiratory sinus arrhythmia (RSA), was used as a measure of parasympathetic control of cardiac rate. Heart rate variability and average heart rate were also calculated.

Memory Assessment

Two lists of 98 words were used as stimuli. Each word was two syllable and low in frequency of use. Words were spoken by one adult woman, recorded digitally, normalized in volume, and edited to remove pops and clicks. Low frequency words were chosen to facilitate episodic memory: these words would be relatively unlikely to have been heard at other points during the prior day.

Recognition was completed in the morning in the bedroom where participants had slept the prior night, while they sat on the bed. All stimuli presented during the awakening were again presented via the same speakers in randomized order along with an equal number of stimuli from the other list. Participants were instructed to respond "yes" to each word that they remembered hearing and to respond "no" to each word they did not remember hearing. Once the response to each word was coded, the next word was automatically presented.

Several measures of memory were computed. These included overall accuracy on recognition testing, percent of stimuli recognized, corrected percent of stimuli recognized (true positives minus false positives divided by number of stimuli presented), recognition of stimuli presented during the first, middle, and final third of the awakening, stimuli presented in the first 5 minutes, first 10 minutes, and first 15 minutes of the awakening, and stimuli presented in the final 5 minutes, final 10 minutes, and final 15 minutes of the awakening.

Procedure

Recruitment, Screening, and Baseline Assessment

Participants were recruited using fliers posted on public bulletin boards on a university campus. An initial phone screen established preliminary study eligibility. Participants were then scheduled for in-person screening and baseline assessments. After providing informed consent, eligibility was assessed using the STOP-BANG, MINI, and DSISD, the AVLT and VPA were administered, and participants completed the FIRST and STAI-trait questionnaires, among other measures. Participants were then scheduled for the PSG portion of the study, and agreed to maintain a fixed 8-hour per night sleep schedule for at least three nights prior to PSG and record their sleep schedule in a sleep diary (Carney et al., 2012).

Polysomnography

On the night of the PSG, participants arrived at the laboratory two hours before bedtime and prepared themselves for bed. PSG sensors were attached and participants completed STAI-state and PSS measures. Baseline physiological recordings were obtained for five minutes while participants laid in bed with their eyes open and then for five minutes with their eyes closed. Lights were then turned out and participants were allowed to sleep. See Figure 1 for PSG protocol. PSG was monitored online by a trained sleep researcher (SCD), and participants were woken via intercom after five minutes of contiguous N2 sleep in the third NREM period. Participants were initially asked to remain awake and pinch their thumb and index finger each time they heard a word and understood it in order to evoke a response on the hand EMG recording. During this initial period, participants were prompted to remain awake if they showed polysomnographic signs of sleep. After fifteen minutes, participants were told they could resume sleeping. Once participants confirmed they were awake, recorded auditory stimuli were presented automatically every thirty seconds until participants resumed sleeping. They were allowed to sleep until scheduled wake time, eight hours after lights out, and then awoken. After sensors were removed, participants returned to the bedroom and completed subjective estimates of sleep onset latency, time asleep prior to experimental awakening, duration of the period of enforced wakefulness, duration of subsequent sleep latency, total duration of wakefulness, number of spontaneous awakenings and their duration, and total sleep time. Participants completed recognition testing, and then were debriefed, compensated, and allowed to leave.

Results

General Descriptive Analyses

Participant demographics are presented in Table 1. This sample was predominantly White, Non-Hispanic, and female, with an average age of 20.28 and BMI of 25.08.

Baseline memory, sleep, and self-reported arousal measures are reported in Table 2. On average, participants had average auditory memory assessed by the AVLT compared to age-matched peers (Geffen, Moar, O'hanlon, Clark, & Geffen, 1990), and high-average immediate and delayed auditory memory, as assessed by the Verbal Paired Associates Test. Average scores on measures of sleep disturbance fell in the normal range. Sleep stage parameters are reported in Table 3. Apart from increased wake time after sleep onset due to study protocol, sleep parameters were generally within expectation. Heart rate, RSA, and HRV are reported in Table 4. Raw and relative Spectral EEG power are reported in tables 5-7.

Table 8 presents subjective and objective sleep relationships. Subjective sleep onset latency was significantly correlated with latency to N2 sleep but not latency to N1 sleep. Subjective total sleep time was significantly correlated with polysomnographic total sleep time. Subjective estimates and objective measures of the duration of time from sleep onset to awakening were not significantly correlated, and subjective estimates were more than 30 minutes shorter than objective measurements. Subjective and objective duration of the enforced awakening were not significantly correlated. However, subjective and objective duration of subsequent time to return to sleep and of the entire awakening were non-significantly positively correlated with a small to medium effect size.

Hypothesis 1: Primacy and Recency

Overall memory statistics including memory by third of the awakening are presented in Table 9. Percent recognition by third of the awakening is shown in Figure 2. There was a significant difference in the number of stimuli recognized according to third of the awakening, $F(2, 117)=30.25$, $p<.0001$. Contrary to expectations, recognition for stimuli presented during the first third (61.77%) was greater than the middle third (43.69%), which was in turn greater than the final third (30.80%), Bonferroni corrected post-hoc tests all $p<.01$. These remained significant after controlling for number of stimuli presented.

Hypothesis 2: Recognition by Time of Night/Duration of Prior Sleep

Consistent with expectations, there were non-significant small to medium size correlations between recognition and time elapsed between sleep onset and awakening. Specifically, there non-significant positive correlations with small to medium effect size between greater recognition of stimuli presented while participants were returning to sleep and longer time elapsed since N1 sleep onset, $r(40)=.27$, $p=.0925$ and time since N2 sleep onset, $r(40)=.28$, $p=.0755$. There were non-significant positive correlations with small to medium effect size between greater recognition for stimuli presented during the middle third of the awakening and longer time since N1 sleep onset, $r(40)=.28$, $p=.08$, and time since N2 sleep onset, $r(40)=.30$, $p=.06$.

There was a significant correlation between more stimuli being presented and longer time elapsed since lights out ($r=.43$, $p=.0061$), since N1 sleep onset ($r=.42$, $p=.0063$), and since N2 sleep onset ($r=.42$, $p=.0072$). After controlling for number of stimuli presented, both longer time since N1 sleep onset and time since N2 sleep onset were significantly positively correlated with greater memory for stimuli presented in the middle third of the awakening (N1 onset: $r=.33$, $p=.0374$; N2 onset: $r=.35$, $p=.0291$).

After accounting for the number of stimuli presented, there was a significant negative correlation between the duration of time between return to sleep and morning awakening and memory for stimuli presented during the second third of the awakening, $r=-.33$, $p=.0386$.

Hypothesis 3: Cortical Arousal

Correlations between memory measures and selected cortical arousal measures are presented in tables 10-13. As hypothesized, greater delta power at frontal sites prior to waking was associated with lower recognition. As shown in Tables 12 and 13 and Figure 3, this effect was strongest for stimuli presented early in the awakening. Greater relative theta and beta1 power at frontal sites prior to waking was associated with greater recognition of stimuli presented early in the awakening.

Contrary to expectation, greater theta and alpha power at frontal sites during the awakening was associated with greater memory. This relationship was strongest for stimuli presented in the middle of the awakening. Greater relative sigma, beta1, and beta2 at frontal sites were associated with less recognition of stimuli. Also contrary to expectation, greater delta power at frontal sites while participants were returning to sleep was associated with better recognition of stimuli presented during that same time.

Contrary to expectation, greater delta power at frontal sites during the five minutes of sleep immediately following the awakening was associated with greater recognition of stimuli while participants were returning to sleep. Greater relative alpha and sigma power at frontal sites was associated with less recognition of stimuli presented late in the awakening.

Hypothesis 4: Autonomic Arousal

The relationship between RSA and memory for stimuli presented during each third of the awakening is presented in Figure 4. As hypothesized, there was a significant negative correlation between RSA during the awakening and recognition memory, though this was specific to stimuli presented during the final third of the awakening, $r=-.32$, $p<.05$.

There was a significant negative correlation between RSA during the five minutes of sleep after the awakening and recognition of stimuli presented during the final five minutes of the awakening, r=-.32, p=0473.

There were non-significant correlations of small to medium effect size in the expected direction between HRV and memory, such that higher HRV was associated with poorer recognition memory for stimuli presented during the final third (r=-.27, p=.0981) and final five minutes of the awakening (r=-.29, p=.0703). There were no significant correlations between heart rate and memory.

Hypothesis 5: Cognitive Arousal

Contrary to expectation, there were no significant correlations between PSS or STAI-state and memory.

Hypothesis 6: Sleep Reactivity

There were no significant correlations between FIRST and memory. As shown in Table 15, when FIRST was dichotomized by median split (≥14), there were non-significant medium effect size differences in the expected direction between those higher in sleep reactivity and those low in sleep reactivity for stimuli presented during the first ten minutes of the awakening and during the first 15 minutes of the awakening.

Hypothesis 7: Memory and Perception

There were no significant correlations between memory measures and accuracy of perception of duration of the awakening, sleep onset latency, or total sleep time.

Associations between Arousal Measures

Table 16 shows correlations between cognitive arousal measures. Trait and state anxiety and perceived stress were significantly positively correlated, while sleep reactivity was significantly positively correlated only with trait anxiety. Tables 19-19 show correlations between autonomic arousal measures. Heart rate at each time point was generally positively correlated with heart rate at other time points and negatively correlated with RSA and HRV across time points. RSA and HRV were generally positively correlated at each time point. Table 20 shows correlations between cortical arousal measures. Prewake cortical arousal measures were significantly correlated, with positive relationships among all except delta power, which was negatively correlated with the other prewake EEG measures. Theta and alpha EEG power during the awakening were positively correlated with one another, but negative correlated with sigma EEG power.

Tables 21-25 show correlations between arousal measures between domains. As shown in Table 21, greater relative theta power prior to waking, averaged across Fp1 and Fp2 was associated with greater sleep reactivity. Greater relative beta1 power prior to waking, averaged across Fp1, Fp2, and Fz was associated with higher state anxiety as measured by STAI Trait, greater sleep reactivity, and higher stress as measured with the PSS, but a similar relationship with trait anxiety was not statistically significant. Greater relative beta2 power averaged across Fp1 and Fp2 was associated with higher stress and greater sleep reactivity; relationships with trait and state anxiety were of medium effect size but not statistically significant.

As shown in Table 22, greater delta power prior to waking, averaged across Fp1, Fp2, and Fz was associated with higher heart rate prior to waking and after falling back to sleep after the awakening. Greater normalized relative sigma power across all sites during the entire awakening was associated with lower heart rate across most time periods investigated: eyes open baseline, the entire baseline recording, prior to waking, during the awakening, and after falling back to sleep. Only eyes closed heart rate was not significantly associated with normalized relative sigma averaged across all sites during the entire awakening.

As shown in Table 23, greater delta power prior to waking, averaged across Fp1, Fp2, and Fz was associated with lower RSA during both the entire awakening and, when examined individually, the period when wakefulness was enforced. Greater relative beta1 power prior to waking, averaged across Fp1 and Fp1 or across Fp1, Fp2, and Fz, was associated with higher RSA prior to being awoken and across the entire awakening. Greater relative beta1 power prior to waking, averaged across Fp1 and Fp1 was also associated with higher RSA during the period that wakefulness was enforced. Log transformed theta power average across Fp1 and Fp2 was associated with lower RSA during the period that wakefulness was enforced. Greater normalized relative sigma power across all sites during the entire awakening was associated with higher RSA during both the entire awakening and, when examined individually, the period when wakefulness was enforced.

As shown in Table 24, greater delta power prior to waking, averaged across Fp1, Fp2, and Fz was associated with lower HRV during the entire awakening, and the period where wakefulness was enforced specifically. Greater relative beta1 power prior to waking, averaged across Fp1, Fp2, and Fz, was associated with higher HRV prior to the awakening, during the entire awakening, and the period where wakefulness was enforced specifically. Greater relative beta2 power prior to waking, averaged across Fp1 and Fp2 was associated with higher HRV, but only prior to the awakening. Log transformed theta power average across Fp1 and Fp2 was associated with lower during the period that wakefulness was enforced.

As shown in Table 25, higher STAI Trait was associated with higher RSA and HRV during the period where wakefulness was enforced, higher RSA after falling back to sleep, and higher HRV during the entire awakening. Higher BIS was associated with higher RSA and HRV prior to being awoken.

Cortical Arousal, Autonomic Arousal, and Memory

Table 26 shows the parameter estimates (beta weights) for multiple regression models predicting memory measures using both prewake delta power and RSA during the awakening. After controlling for RSA during the awakening, greater prewake delta power at frontal sites was associated with lower memory overall and specifically during the first third of the awakening. During the middle third of the awakening, neither prewake delta nor RSA was associated with memory. In the final third, the pattern was reversed such that higher RSA during the awakening was associated with lower memory after controlling for prewake delta. Figure 5 shows the change in parameter estimates (beta weights) across thirds of the awakening.

Cortical Arousal, Time of Awakening, and Memory

Table 27 shows the parameter estimates (beta weights) from regression models predicting memory measures from prewake delta power and time elapsed between lights out and experimental awakening, after controlling for the number of stimuli presented. In these models, stimuli number was not significantly associated with any of the memory measures, p's > .2. Higher prewake delta power remained significantly associated with lower memory overall and specifically during the first third of the awakening. There was a non-significant association of medium effect size between longer time between lights out and the awakening and memory during the middle third of the awakening. Figure 6 shows the change in parameter estimates across thirds of the awakening.

Baseline and Experimental Memory

Figures 7 and 8 show the relationship between baseline paired associates memory and memory for stimuli by third of the awakening. There was a significant positive correlation between VPAI raw score and recognition of stimuli from the middle third (r=.37, p=.-0174). There were significant negative correlations between VPAII scaled score and recognition of stimuli from the last ten minutes of the awakening (r=-.35, p=.0252), last fifteen minutes of the awakening (r=-.33, p=.0395), while trying to resume sleeping (r=-.41, p=.0091), and the final third of the awakening (r=-.36, p=.0216).

Figure 9 shows the relationship between initial learning on AVLT trial 1 and memory for stimuli presented during each third of the awakening. There was a significant positive correlation between AVLT trial 1 score and recognition of stimuli from the middle third (r=.33, p=.0388).

There was a significant negative correlation between AVLT trial 7 and memory for stimuli presented while trying to resume sleeping ($r=-.34$, $p=.034$).

Discussion

The present study found that episodic memory during awakenings from sleep is strongest for the beginning of the awakening and diminishes across the course of the time awake. This memory is associated with several factors. These include homeostatic sleep pressure, depth of sleep, cortical arousal, parasympathetic control of heart rate, and baseline memory ability.

Recognition was greatest for stimuli presented during the first third of the awakening, followed by the middle and final thirds. This suggests that the primacy effect remains intact, and may even be augmented, while the recency effect is diminished to the point of nonexistence as seen in prior research involving encoding during an awakening from sleep (Bonnet, 1983). Arousal modulated recognition memory in a manner dependent on time and arousal domain.

Because the protocol for determining when to awaken participants depended on progression to the third NREM period, inter-individual variability in sleep architecture resulted in varying durations of sleep prior being awoken. Recognition was greater when participants were awakened after more time had passed since initial sleep onset, when sleep homeostatic pressure would be expected to be lower. Since this effect was specific to the middle of the awakening, it appears that the initial magnitude of sleep inertia is related to depth of proximal sleep, while dissipation of sleep inertia is related to prior sleep duration, reflecting homeostatic sleep pressure.

Early Memory

Recognition memory for stimuli presented early in the awakening was related to several forms of arousal. Greater arousal, as reflected by lower delta power, and greater beta1 and beta2 power, was associated with better recognition memory for stimuli presented early in the awakening. Later experimental awakenings, when sleep homeostatic pressure would be lower, were also associated with better memory. Taken together, greater delta and lower beta1 and beta2 may be considered to be neural correlates of deeper sleep that results in greater sleep inertia, which in turn appears to interfere with initial memory encoding and/or consolidation. The association of greater delta with worse memory are consistent with earlier findings of worse memory following awakenings from stage 4 sleep as compared to stage 2 sleep (Bonnet, 1983). The current findings show that a statistically significant effect can be found with much smaller variations in delta power, as all participants in the current study were in stage N2 sleep for five minute prior to being woken. Even if taken as a causal relationship, such that lower cortical arousal causes memory for the early part of an awakening, it is not sufficient to overcome the observed primacy effect.

There was a trend toward participants higher in sleep reactivity to have better recognition for stimuli presented early in the awakening. Sleep reactivity reflects the tendency to report have disturbed sleep in response to stress, laboratory-based sleep studies can evoke poor such poor sleep (Drake et al., 2004), and being woken from sleep almost certainly compounds this disruption. Accordingly, those participants high in sleep reactivity may be particularly sensitive to a perceived threat of sleep loss, leading to cognitive arousal in the form of greater salience/threat, and thus stronger encoding of stimuli. This effect was limited to the early part of the awakening, suggesting that those high in sleep-reactivity were faster to arouse, rather than having a greater overall level of arousal.

Middle Memory

Recognition memory for stimuli presented in the middle of the awakening was associated with baseline measures of immediate auditory memory. Since similar relationships were not seen for the beginning or end of the awakening, it is most likely that this middle period of the awakening is least affected by individual differences in arousal and instead is closely related to memory during a time less proximal to sleep. Later awakenings, when sleep homeostatic pressure should be lower, were associated with better memory during the middle of the awakening. There were also EEG correlates of recognition memory for stimuli presented during the middle of the awakening. Lower frequency activity (delta, theta, alpha) was positively associated with recognition memory, while high frequency activity (beta1, beta2) was negatively associated with recognition memory, suggesting that cortical hyperarousal may interfere with memory encoding and early consolidation. Sigma power was also associated with worse recognition memory. This may reflect cortical arousal like beta1 and beta2, or may reflect early signs of sleep, particularly sleep spindles, though none were observed.

Late Memory

Recognition memory for stimuli presented during the final third of the awakening was significantly lower than for stimuli presented during the first and middle thirds. Recognition memory for stimuli presented during this period was also negatively associated with parasympathetic control of heart rate. This suggests that greater autonomic arousal increases initial memory encoding and early consolidation. Greater delta power during the five minutes of sleep following the awakening was associated with better recognition memory for stimuli presented while participants were returning to sleep. Since delta power has been shown to be associated with declarative memory consolidation, this association may reflect early memory consolidation (Marshall & Born, 2007).

The present study also replicated a previous counterintuitive finding (Wyatt et al., 1997) that recognition of stimuli presented close to sleep onset is negatively associated with delayed memory on a paired associates learning test. The present study extended this finding, showing that 1) delayed auditory list memory is also negatively associated with recognition of stimuli presented close to sleep onset, and 2) this relationship is strongest close to sleep onset.

Implications

Since memory was strongest for stimuli presented early in the awakening, it is likely that people awaken frequently from sleep, such as people with insomnia (Frankel, Coursey, Buchbinder,

& Snyder, 1976; Terzano et al., 2003), may recall each awakening. These awakenings may then combine into a subjective experience of continuous wakefulness, particularly when the sleep between these awakenings is short in duration and shallow in depth, (Knab & Engel, 1988). Greater cerebral metabolic activity (Nofzinger et al., 2004) during sleep, particularly in the default mode network (Kay et al., 2016), along with increased sensory processing (Bastien, Turcotte, St-Jean, Morin, & Carrier, 2013) likely reflect this continued experience of wakefulness among people with insomnia.

Since both higher delta power and sleep homeostatic drive were associated with less memory, that interventions that increase sleep homeostatic drive and delta power, such as cognitive behavioral therapy for insomnia (Cervena et al., 2004; Krystal & Edinger, 2010) and sleep restriction therapy (Spielman, Saskin, & Thorpy, 1987) may ameliorate some of the discrepancies between subjective and objective measure of sleep in people with insomnia. Interventions to decrease autonomic arousal (e.g., diaphragmatic breathing) may also decrease this discrepancy in addition to any directly soporific effects. Further, the effects of such interventions may be additive rather than redundant. Similarly, cognitive behavioral therapy may address the perceived threat of sleep disruption by targeting dysfunctional beliefs about sleep (Edinger, Wohlgemuth, Radtke, Marsh, & Quillian, 2001) and increasing insomnia-related self-efficacy (Bouchard, Bastien, & Morin, 2003), which may reduce sleep misperception among people prone toward losing sleep in response to stress and who are vulnerable to developing chronic insomnia.

Unlike cortical and autonomic measures of arousal, cognitive arousal as measured by state anxiety and perceived stress was not related to memory. This suggests that interventions targeting cognitive arousal may not be effective in reducing sleep misperception in insomnia. It is important to note, however, that ratings of state anxiety and perceived stress were generally very low, and so the lack of association in the present study may not generalize to higher levels of anxiety and stress.

Assuming subsequent memory is an accurate reflection of sleep inertia at the time of encoding, the present study's results suggest that both duration of prior sleep and proximal depth of sleep are likely to influence cognitive performance when awoken from sleep. Since sleep duration is shortest and sleep is deepest early in the night, this is when performance is likely to be most adversely affected. Cognitive performance after being awoken later in the night, after more sleep has been attained and sleep is less deep, is less likely to be negatively affected. Thus, on-call professionals such as first responders and medical personnel could be expected to perform worse when woken earlier in their sleep period rather than later.

Limitations

The present study was of a modestly sized sample of healthy young adults without sleep or psychiatric disorders, and who were not using medications known to affect sleep or memory. Accordingly, the present findings may not generalize to people outside of this age range or who have medical or psychiatric comorbidities. Because stimuli were presented to participants for 15 minutes plus their subsequent sleep latency, participants were presented with varying number of stimuli. Without being able to control or predict a participant's sleep latency, this is unavoidable in studies seeking to understand memory of stimuli presented immediately prior to sleep onset. Using recognition testing instead of free recall made the task easier for participants, and the number of stimuli was not associated with any memory measures. During pilot testing, participants were able to remember few, if any, stimuli during free recall. Since recognition testing could be affected by prior free recall testing, free recall testing was omitted. Collecting baseline memory measures prior to the sleep study may have affected participants' subsequent recognition morning. When study procedures were explained to participants, several asked whether they would be asked to recall stimuli in the morning. The present study also utilized an 11-lead EEG montage, which allowed better characterization of topography than a conventional six-lead montage, but lacks the spatial resolution of high density EEG. The present study used parasympathetic control of cardiac rate as a measure of autonomic arousal using ECG sampled at 400hz. Faster sampling rates (e.g., 500hz or greater; Berntson et al., 1997) may allow for more accurate measurement of parasympathetic control of cardiac rate. Physiological measures specific to sympathetic nervous system arousal, such as pre-ejection period measured with impedance cardiography, would allow more comprehensive measurement of autonomic arousal.

Summary

The present study demonstrated that memory is greatest earlier in the course of an awakening from sleep, and that arousal is related to memory for sleep/wake transition periods, and that different types of arousal have different relationships with memory over the course of a period of wakefulness. Early memory was associated with sleep homeostatic pressure and sleep reactivity; middle memory was associated delta, theta, and alpha EEG power and with participants' memory during baseline evaluation; late memory was associated with autonomic arousal.

Table 1. Demographics

	Mean	SD
Age	20.28	2.31
Height (inches)	65.70	3.29
Weight (pounds)	154.88	31.02
BMI	25.08	3.85
Sex	Number	Percent
Female	26	65%
Male	14	35%
Race	Number	Percent
American Indian or Alaska Native	2	5%
Asian	3	7.50%
Black	1	2.50%
White	31	77.50%
Other	1	2.50%
Multiracial	2	5%
Ethnicity	Number	Percent
Hispanic	7	17.50%
Non-Hispanic	33	82.50%

Table 2. Baseline Descriptive Statistics

Memory	Mean (SD)
VPA I	46.3 (4.96)
VPA II	13.6 (0.78)
VPA I scaled score*	12.1 (2.09)
VPA II scaled score*	12.03 (1.12)
AVLT A1	7.18 (1.60)
AVLT A1 to A5	54.83 (6.83)
AVLT A7	11.8 (2.24)
AVLT A1 scaled score*	8.87 (3.80)
AVLT A1 to A5 scaled score*	10.45 (3.34)
AVLT A7 scaled score	11.05 (3.64)
Sleep	Mean (SD)
PSQI	2.63 (1.37)
ESS	6 (3.69)
ISI	2.38 (1.93)
FIRST	14.5 (3.7)
Cognitive Arousal	Mean (SD)
STAI trait	31.18 (5.99)
STAI state	26.23 (6.3)
PSS	2.4 (1.78)

*scaled scores reflect performance relative to age-matched norms; normative mean=10, SD=3.

Table 3. Polysomnographic Sleep

PSG	Mean (SD)
TST	405.21 (40.1)
N1 latency	10.74 (6.61)
N2 latency	15.15 (8.5)
REM latency	90.96 (42.36)
Sleep efficiency	85.04% (7.64%)
N1%	6.85% (3.95%)
N2%	45.37% (6.61%)
N3%	24.70% (6.32%)
REM%	23.08% (5.19%)
N1 (min)	26.94 (13.84)
N2 (min)	183.56 (31.14)
N3 (min)	100.45 (28.94)
REM (min)	94.26 (25.21)
MT (min)	4.84 (2.98)
TWT (min)	63.98 (37.09)
WASO (min)	58.75 (35.74)

Table 4. Heart Rate and Respiratory Sinus Arrhythmia

	HR	RSA	HRV
Baseline	65.32 (9.13)	7.02 (0.92)	7.91 (0.82)
Prewake	62.53 (10.22)	7.10 (1.30)	8.16 (0.99)
Awakening	64.84 (9.03)	7.15 (1.08)	8.38 (0.88)
Postwake	58.99 (8.51)	7.24 (1.24)	8.15 (1.10)

Table 5. Prewake EEG

	Delta		Theta		Alpha		Sigma		Beta1		Beta2	
	Raw	Relative	Raw	Relative	Raw	Relative	Raw	Relative	Raw	Relative	Raw	Relative
Fp1	20.48 (20.87)	84.57% (6.85%)	1.25 (0.52)	7.8% (3.91%)	0.65 (0.38)	4.01% (2.24%)	0.41 (0.31)	2.48% (1.39%)	0.11 (0.05)	0.8% (0.57%)	0.05 (0.03)	0.35% (0.4%)
Fp2	21.54 (24.68)	84.4% (6.95%)	1.3 (0.55)	7.86% (3.97%)	0.67 (0.37)	4.02% (2.24%)	0.44 (0.36)	2.56% (1.47%)	0.12 (0.05)	0.8% (0.51%)	0.05 (0.04)	0.35% (0.35%)
F3	18.5 (13.44)	80.65% (7.31%)	1.74 (0.86)	9.69% (4.65%)	0.83 (0.5)	4.53% (2.33%)	0.71 (0.55)	3.75% (2.14%)	0.16 (0.09)	0.97% (0.73%)	0.06 (0.05)	0.41% (0.45%)
Fz	25.52 (16.55)	81.07% (6.28%)	2.72 (1.23)	10.4% (4.55%)	1.12 (0.7)	4.18% (1.75%)	0.89 (0.68)	3.22% (1.6%)	0.19 (0.09)	0.8% (0.57%)	0.06 (0.04)	0.32% (0.36%)
F4	17.93 (11.45)	80.03% (6.74%)	1.87 (0.88)	9.94% (4.39%)	0.88 (0.44)	4.7% (2.22%)	0.76 (0.55)	3.85% (2.11%)	0.18 (0.1)	1.05% (0.72%)	0.07 (0.04)	0.43% (0.45%)
C3	13.33 (8.69)	75.63% (7.74%)	1.82 (0.86)	12.06% (4.43%)	0.78 (0.34)	5.56% (2.58%)	0.75 (0.44)	5.08% (3.2%)	0.16 (0.1)	1.19% (0.91%)	0.06 (0.05)	0.47% (0.53%)
Cz	19.52 (10.16)	73.45% (7.67%)	3.53 (1.78)	14.05% (4.69%)	1.18 (0.55)	5.21% (2.4%)	1.28 (0.85)	5.6% (4.24%)	0.24 (0.15)	1.24% (1.16%)	0.08 (0.05)	0.45% (0.52%)
C4	13.73 (8.95)	74.51% (7.48%)	2.06 (1)	12.64% (4.39%)	0.9 (0.49)	5.95% (3.07%)	0.85 (0.6)	5.27% (3.12%)	0.17 (0.1)	1.22% (0.85%)	0.06 (0.04)	0.42% (0.35%)
Pz	12.09 (6.2)	69.1% (7.88%)	2.32 (1.06)	14.03% (3.88%)	1.23 (0.77)	7.76% (4.22%)	1.23 (0.94)	7.43% (4.57%)	0.18 (0.11)	1.26% (0.94%)	0.06 (0.03)	0.42% (0.4%)
O1	6.36 (4.71)	66.95% (7.61%)	1.47 (0.81)	16.53% (4.56%)	0.81 (0.59)	9.15% (4.98%)	0.45 (0.23)	5.35% (2.33%)	0.12 (0.06)	1.52% (0.77%)	0.04 (0.03)	0.51% (0.33%)
O2	7.84 (9.28)	68.46% (7.74%)	1.55 (0.79)	16.09% (4.2%)	0.85 (0.63)	8.67% (4.58%)	0.46 (0.27)	4.91% (2.16%)	0.13 (0.07)	1.39% (0.67%)	0.04 (0.03)	0.47% (0.31%)

Table 6. Awakening EEG

	Delta		Theta		Alpha		Sigma		Beta1		Beta2	
	Raw	Relative	Raw	Relative	Raw	Relative	Raw	Relative	Raw	Relative	Raw	Relative
Fp1	98.16 (131.31)	91.78% (5.49%)	2.45 (2.4)	3.58% (2.25%)	1.1 (0.64)	2.31% (2.02%)	0.38 (0.11)	0.93% (0.81%)	0.31 (0.14)	0.77% (0.73%)	0.25 (0.14)	0.63% (0.7%)
Fp2	111.44 (159.16)	92.28% (5.21%)	2.63 (2.81)	3.3% (1.7%)	1.13 (0.68)	2.15% (1.8%)	0.39 (0.11)	0.92% (0.92%)	0.32 (0.15)	0.74% (0.79%)	0.25 (0.14)	0.6% (0.77%)
F3	18.79 (13.99)	79.17% (9.96%)	1.48 (0.82)	7.76% (4.52%)	1.17 (0.76)	6.31% (4.66%)	0.46 (0.19)	2.58% (1.28%)	0.43 (0.3)	2.3% (1.5%)	0.36 (0.35)	1.88% (1.63%)
Fz	18.63 (12.92)	76.76% (11.03%)	2 (1.1)	9.73% (5.36%)	1.53 (1)	7.65% (5.57%)	0.5 (0.18)	2.6% (1.19%)	0.37 (0.2)	1.98% (1.25%)	0.24 (0.14)	1.27% (1.07%)
F4	21.85 (18.23)	79.71% (9.47%)	1.64 (0.87)	7.79% (4.31%)	1.27 (0.79)	6.14% (4.17%)	0.51 (0.21)	2.54% (1.27%)	0.44 (0.28)	2.14% (1.36%)	0.34 (0.26)	1.68% (1.42%)
C3	10.34 (5.87)	70.73% (11.68%)	1.36 (1.01)	9.94% (5.28%)	1.4 (1.06)	10.47% (7.24%)	0.47 (0.24)	3.6% (1.38%)	0.41 (0.35)	2.95% (1.71%)	0.34 (0.46)	2.3% (2.13%)
Cz	13.06 (10.09)	69.21% (12.2%)	2.01 (1.22)	11.92% (5.34%)	1.79 (1.32)	10.91% (8.13%)	0.56 (0.22)	3.6% (1.51%)	0.41 (0.23)	2.7% (1.59%)	0.25 (0.15)	1.67% (1.33%)
C4	16.65 (16.92)	73.33% (13.64%)	1.59 (1.19)	9.41% (5.23%)	1.6 (1.38)	9.61% (7.92%)	0.51 (0.3)	3.26% (1.83%)	0.39 (0.25)	2.51% (1.76%)	0.28 (0.23)	1.9% (2.09%)
Pz	19.65 (20.73)	71.21% (15.95%)	2 (1.8)	9.29% (5.76%)	2.68 (2.6)	13.05% (11.67%)	0.61 (0.29)	3.31% (2.09%)	0.36 (0.19)	1.92% (1.27%)	0.21 (0.13)	1.22% (1.38%)
O1	8.85 (6.93)	62% (16.91%)	1.26 (1.19)	9.45% (5.16%)	2.61 (2.9)	18.85% (14.67%)	0.55 (0.28)	4.8% (2.84%)	0.33 (0.16)	2.99% (2.19%)	0.21 (0.13)	1.92% (2%)
O2	16.01 (16.75)	67.33% (18.43%)	1.36 (1.19)	8.08% (5.08%)	2.84 (3.13)	16.66% (14.73%)	0.59 (0.33)	3.81% (2.51%)	0.36 (0.2)	2.45% (2.1%)	0.22 (0.14)	1.67% (2.1%)

Table 7. Postwake EEG

	Delta		Theta		Alpha		Sigma		Beta1		Beta2	
	Raw	Relative	Raw	Relative	Raw	Relative	Raw	Relative	Raw	Relative	Raw	Relative
Fp1	14.14 (19.49)	79.77% (6.72%)	1.2 (0.46)	9.17% (3.25%)	0.69 (0.32)	5.33% (2.44%)	0.54 (0.33)	4.03% (2.27%)	0.14 (0.1)	1.07% (0.66%)	0.08 (0.09)	0.63% (0.77%)
Fp2	15.72 (24.02)	79.55% (7.46%)	1.26 (0.5)	9.22% (3.35%)	0.72 (0.37)	5.4% (2.74%)	0.58 (0.37)	4.11% (2.32%)	0.15 (0.1)	1.08% (0.71%)	0.08 (0.09)	0.64% (0.86%)
F3	13.19 (7.55)	75.24% (6.84%)	1.75 (0.92)	10.95% (3.4%)	0.93 (0.57)	5.82% (2.28%)	1 (0.82)	6.03% (3.57%)	0.19 (0.14)	1.25% (0.89%)	0.11 (0.12)	0.72% (0.94%)
Fz	19.33 (9.94)	76.63% (6.32%)	2.74 (1.24)	11.79% (3.77%)	1.17 (0.62)	5.02% (1.74%)	1.21 (0.76)	5.12% (2.4%)	0.2 (0.13)	0.93% (0.6%)	0.1 (0.1)	0.51% (0.72%)
F4	13.85 (7.93)	74.72% (7.37%)	1.85 (0.82)	11.05% (3.42%)	1 (0.63)	5.85% (2.35%)	1.1 (0.79)	6.4% (3.77%)	0.2 (0.12)	1.27% (0.88%)	0.11 (0.13)	0.72% (1.02%)
C3	11.14 (5.69)	72.1% (7.67%)	1.83 (0.79)	12.87% (3.51%)	0.79 (0.46)	5.54% (2.42%)	1.02 (0.67)	7.38% (4.39%)	0.19 (0.15)	1.4% (1.04%)	0.1 (0.13)	0.7% (0.77%)
Cz	17.41 (7.95)	70.97% (7.14%)	3.53 (1.7)	14.56% (3.36%)	1.16 (0.66)	5.1% (2.39%)	1.67 (1.01)	7.45% (4.34%)	0.26 (0.17)	1.3% (1.2%)	0.12 (0.11)	0.61% (0.74%)
C4	11.47 (5.95)	71.25% (7.23%)	2.06 (0.96)	13.56% (3.58%)	0.88 (0.56)	5.86% (2.78%)	1.07 (0.62)	7.17% (3.07%)	0.19 (0.13)	1.4% (1.02%)	0.1 (0.12)	0.77% (1.19%)
Pz	12.78 (9.5)	66.89% (8.61%)	2.47 (1.16)	14.48% (3.83%)	1.15 (0.85)	6.85% (4.05%)	1.67 (1.01)	9.9% (4.48%)	0.21 (0.15)	1.3% (0.96%)	0.09 (0.1)	0.57% (0.56%)
O1	5.63 (3.65)	63.71% (5.94%)	1.65 (1.22)	18.52% (4.32%)	0.73 (0.58)	8.24% (3.9%)	0.53 (0.24)	6.69% (2.34%)	0.15 (0.1)	1.83% (1.13%)	0.07 (0.09)	1% (1.33%)
O2	6.49 (4.17)	65.28% (6.94%)	1.77 (1.12)	18.24% (4.72%)	0.75 (0.56)	7.66% (3.54%)	0.56 (0.3)	6.19% (2.4%)	0.15 (0.11)	1.68% (1.03%)	0.08 (0.1)	0.94% (1.42%)

Table 8. Subjective and Objective Sleep

	Subjective	Objective	Difference	Correlation
SOL: N1	23.51 (20.83)	10.74 (6.61)	12.78 (20.16)	0.26
SOL: N2	23.51 (20.83)	15.15 (8.5)	8.36 (19.58)	0.35*
TST	414 (58.32)	405.21 (40.1)	8.79 (48.37)	0.57***
SOL N1 to awakening	161.84 (71.09)	196.30 (54.77)	-36.54 (94.29)*	-0.10
SOL N2 to awakening	161.84 (71.09)	191.89 (55.83)	-32.52 (94.66)*	-0.10
Enforced Awakening	18.08 (8.5)	15.61 (0.27)	-0.4 (17.77)	-0.18
Return to Sleep	12.58 (10.02)	15.45 (14.26)	2.47 (8.56)	0.27†
Entire Awakening	30.65 (15.28)	31.05 (14.23)	-2.87 (15.03)	0.28†

† p< .10, * p<.05, **p<.01, ***p<.001

Table 9. Memory

Recognition of Stimuli	Mean (SD)
Number of Stimuli Recognized	25.40 (10.89)
Number of Stimuli Presented	54.48 (16.78)
Percent of Stimuli Recognized	46.88% (16.14%)
Recognition Testing	Mean (SD)
Recognition Test Score (TP+TN)	69.83 (22.39)
Number of Stimuli in Recognition test	109.00 (33.69)
Recognition Test Score Percent	64.27% (8.29%)
Memory by Third	Mean (SD)
First Third Percent	61.77% (17.76%)
Middle Third Percent	43.69% (21.02%)
Final Third Percent	30.80% (14.23%)
Early Memory	Mean (SD)
First 5 minutes	64.00% (17.07%)
First 10 minutes	58.88% (18.52%)
First 15 minutes	55.50% (19.27%)
Late Memory	Mean (SD)
Return to Sleep	34.51% (14.93%)
Final 15 minutes	38.33% (16.91%)
Final 10 minutes	35.38% (16.85%)
Final 5 minutes	27.75% (13.87%)
Detection	Mean (SD)
Sensitivity	46.88% (16.14%)
Specificity	81.64% (13.17%)
Positive Predictive Value	73.90% (12.38%)
Negative Predictive Value	61.12% (7.27%)
False Positive Rate	9.18% (6.58%)

Table 10. Cortical Arousal and Overall Memory for Stimuli Presented During the Awakening

	Overall Memory		
Prewake	Recognition score	% stimuli recognized	% stimuli recognized (corrected)
Delta at Fp1/Fz/Fp2	-0.35*	-0.22	-0.35*
Relative Theta at Fp1/Fp2	0.27†	0.24	0.27†
Relative Beta1 at Fp1/Fz/Fp2	0.34*	0.17	0.33*
Relative Beta2 at Fp1/Fp2	0.20	0.02	0.20
Awakening			
Log Theta at Fp1/Fp2	0.34*	0.35*	0.34*
Alpha at Fp1/Fp2	0.48**	0.39*	0.48**
Global normalized relative sigma	-0.35*	-0.36*	-0.35*
Relative Beta1 at Fp1/Fp2	-0.37*	-0.34*	-0.37*
Relative Beta2 at Fp1/Fp2	-0.39*	-0.47**	-0.39*
Delta at Fp1/Fp2/Fz RTS	0.04	0.17	0.04
Postwake			
Delta at Fp1/Fz/Fp2	0.01	0.16	0.01
Relative alpha at Fp1/Fz/Fp2	0.11	-0.04	0.11
Normalized relative sigma at Fp1/Fz/Fp2	0.01	-0.13	0.01

Table 11. Cortical Arousal and Memory for Stimuli Presented at the Beginning of the Awakening

	Early Memory		
Prewake	First 5 minutes	First 10 minutes	First 15 minutes
Delta at Fp1/Fz/Fp2	-0.45**	-0.34*	-0.31†
Relative Theta at Fp1/Fp2	0.35*	0.34*	0.35*
Relative Beta1 at Fp1/Fz/Fp2	0.41**	0.39*	0.37*
Relative Beta2 at Fp1/Fp2	0.20	0.21	0.19
Awakening			
Log Theta at Fp1/Fp2	0.21	0.32*	0.31*
Alpha at Fp1/Fp2	0.35*	0.36*	0.38*
Global normalized relative sigma	-0.19	-0.33*	-0.30†
Relative Beta1 at Fp1/Fp2	-0.23	-0.29†	-0.30†
Relative Beta2 at Fp1/Fp2	-0.34*	-0.40*	-0.42**
Delta at Fp1/Fp2/Fz RTS	0.01	0.07	0.05
Postwake			
Delta at Fp1/Fz/Fp2	0.00	0.04	0.07
Relative alpha at Fp1/Fz/Fp2	0.12	0.12	0.10
Normalized relative sigma at Fp1/Fz/Fp2	0.13	0.07	0.01

Table 12. Cortical Arousal and Memory for Stimuli Presented at the End of the Awakening

	Late Memory			
Prewake	Return to Sleep	Final 5 minutes	Final 10 minutes	Final 15 minutes
Delta at Fp1/Fz/Fp2	0.07	0.08	-0.02	-0.13
Relative Theta at Fp1/Fp2	-0.09	-0.15	0.05	0.11
Relative Beta1 at Fp1/Fz/Fp2	-0.17	-0.24	-0.12	0.04
Relative Beta2 at Fp1/Fp2	-0.19	-0.34*	-0.21	-0.07
Awakening				
Log Theta at Fp1/Fp2	0.26	0.16	0.26†	0.35*
Alpha at Fp1/Fp2	0.14	0.10	0.30†	0.36*
Global normalized relative sigma	-0.27†	-0.34*	-0.35*	-0.37*
Relative Beta1 at Fp1/Fp2	-0.25	-0.21	-0.25	-0.35*
Relative Beta2 and Fp1/Fp2	-0.39*	-0.31†	-0.37*	-0.45**
Delta at Fp1/Fp2/Fz RTS	0.34*	0.25	0.27†	0.23
Postwake				
Delta at Fp1/Fz/Fp2	0.33*	0.22	0.25	0.23
Relative alpha at Fp1/Fz/Fp2	-0.33*	-0.27†	-0.25	-0.10
Normalized relative sigma at Fp1/Fz/Fp2	-0.24	-0.25	-0.35*	-0.23

Table 13. Cortical Arousal and Memory by Third of the Awakening

	Memory by Third		
Prewake	First Third	Middle Third	Final Third
Delta at Fp1/Fz/Fp2	-0.35*	-0.19	-0.03
Relative Theta at Fp1/Fp2	0.35*	0.21	0.04
Relative Beta1 at Fp1/Fz/Fp2	0.33*	0.15	-0.06
Relative Beta2 at Fp1/Fp2	0.15	0.01	-0.12
Awakening			
Log Theta at Fp1/Fp2	0.25	0.38*	0.25
Alpha at Fp1/Fp2	0.36*	0.46**	0.17
Global normalized relative sigma	-0.29†	-0.32*	-0.33*
Relative Beta1 at Fp1/Fp2	-0.31†	-0.38*	-0.17
Relative Beta2 and Fp1/Fp2	-0.41**	-0.49**	-0.30†
Delta at Fp1/Fp2/Fz RTS	0.05	0.11	0.30†
Postwake			
Delta at Fp1/Fz/Fp2	0.01	0.17	0.25
Relative alpha at Fp1/Fz/Fp2	0.11	0.05	-0.31†
Normalized relative sigma at Fp1/Fz/Fp2	0.09	-0.14	-0.30†

Table 14. Significant Arousal-Memory Associations by Third

	First	Middle	Final
Pre-wake Fp1/Fp2/Fz Delta	-0.35*	-0.19	-0.03
Prewake Fp1/Fp2 relative Theta	0.35*	0.21	0.04
Prewake Fp1/Fp2/Fz relative beta1	0.33*	0.15	-0.06
Awakening global relative sigma	-0.33*	-0.34*	-0.34*
Awakening Fp1/Fp2 Alpha	0.36*	0.46*	0.17
Awakening Fp1/Fp2 average relative beta2	-0.39**	-0.41**	-0.30†
Awakening log Fp1/Fp2 Theta	0.25	0.38*	0.25
AVLT trial 1	0.10	0.33*	0.12
VPA I raw score	0.25	0.37*	-0.02
VPA II scaled score	-0.10	-0.20	-0.36*
RSA	-0.12	-0.05	-0.32*

† $p < .10$, * $p < .05$, ** $p < .01$

Table 15. Sleep Reactivity and Early Memory

	All Participants (N=40)	Low Sleep Reactivity (N=19)	High Sleep reactivity (N=21)	t	p	D
First 10 Min	58.88% (18.52%)	53.4% (19.2%)	63.81% (16.8%)	1.82	0.0760	0.56
First 15 Min	55.5% (19.27%)	49.47% (19.67%)	60.95% (17.6%)	1.95	0.0589	0.60

Table 16. Self-Report Measure Correlations

	STAI Trait	STAI State	PSS	FIRST
STAI Trait	1.00	0.65****	0.60****	0.38*
STAI State	0.65****	1.00	0.55***	0.26†
PSS	0.60****	0.55***	1.00	0.25
FIRST	0.38*	0.26†	0.25	1.00

† $p < .10$, * $p < .05$, ** $p < .01$, *** $p < .001$, ****$p < .0001$

Table 17. Heart Rate Correlations with Other Cardiovascular Measures

		EO	EC	Baseline	Prewake	Enforced Awake	RTS	Postwake	All Awakening
HR	EO	1.00	0.96****	0.99****	0.75****	0.63****	0.69****	0.73****	0.71****
	EC	0.96****	1.00	0.99****	0.73****	0.60****	0.64****	0.71****	0.68****
	Baseline	0.99****	0.99****	1.00	0.75****	0.62****	0.67****	0.73****	0.70****
	Prewake	0.75****	0.73****	0.75****	1.00	0.68****	0.85****	0.87****	0.80****
	Enforced Awake	0.63****	0.60****	0.62****	0.68****	1.00	0.83****	0.69****	0.96****
	RTS	0.69****	0.64****	0.67****	0.85****	0.83****	1.00	0.90****	0.93****
	Postwake	0.73****	0.71****	0.73****	0.87****	0.69****	0.90****	1.00	0.84****
	All Awakening	0.71****	0.68****	0.70****	0.80****	0.96****	0.93****	0.84****	1.00
RSA	EO	-0.34*	-0.25	-0.30†	-0.29†	-0.15	-0.33*	-0.43**	-0.23
	EC	-0.44**	-0.38*	-0.42**	-0.36*	-0.18	-0.33*	-0.41**	-0.26
	Baseline	-0.41**	-0.33*	-0.37*	-0.34*	-0.17	-0.34*	-0.43**	-0.25
	Prewake	-0.37*	-0.27†	-0.32*	-0.50**	-0.36*	-0.60****	-0.60****	-0.43**
	Enforced Awake	-0.44**	-0.36*	-0.40*	-0.55***	-0.56***	-0.66****	-0.65****	-0.61****
	RTS	-0.37*	-0.30†	-0.34*	-0.52***	-0.31*	-0.55***	-0.58****	-0.40*
	Postwake	-0.44**	-0.37*	-0.41**	-0.50**	-0.30†	-0.48**	-0.59****	-0.40*
	All Awakening	-0.46**	-0.37*	-0.42**	-0.57***	-0.48**	-0.64****	-0.68****	-0.56***
HRV	EO	-0.36*	-0.27†	-0.32*	-0.41**	-0.25	-0.47**	-0.51***	-0.35*
	EC	-0.39*	-0.31†	-0.35*	-0.33*	-0.22	-0.37*	-0.39*	-0.30†
	Baseline	-0.39*	-0.30†	-0.35*	-0.38*	-0.25	-0.44**	-0.47**	-0.33*
	Prewake	-0.28†	-0.18	-0.23	-0.34*	-0.29†	-0.53***	-0.52***	-0.37*
	Enforced Awake	-0.41**	-0.34*	-0.38*	-0.53***	-0.41**	-0.62****	-0.67****	-0.51***
	RTS	-0.41**	-0.38*	-0.40*	-0.51***	-0.29†	-0.46**	-0.53***	-0.37*
	Postwake	-0.46**	-0.41**	-0.44**	-0.52***	-0.24	-0.46**	-0.54***	-0.36*
	All Awakening	-0.46**	-0.39*	-0.43**	-0.58***	-0.39*	-0.62****	-0.68****	-0.50**

Note: columns refer to heart rate at the listed time periods, whereas the three groups of rows refer to HR, RSA, or HRV.
† p < .10, * p < .05, ** p < .01, *** p < .001, ****p < .0001

Table 18. RSA Correlations with Other Cardiovascular Measures

		EO	EC	Baseline	Prewake	Enforced Awake	RTS	Postwake	All Awakening
HR	EO	-0.34*	-0.44**	-0.41**	-0.37*	-0.44**	-0.37*	-0.44**	-0.46**
	EC	-0.25	-0.38*	-0.33*	-0.27†	-0.36*	-0.30†	-0.37*	-0.37*
	Baseline	-0.30†	-0.42**	-0.37*	-0.32*	-0.40*	-0.34*	-0.41**	-0.42**
	Prewake	-0.29†	-0.36*	-0.34*	-0.50**	-0.55***	-0.52***	-0.50**	-0.57***
	Enforced Awake	-0.15	-0.18	-0.17	-0.36*	-0.56***	-0.31*	-0.30†	-0.48**
	RTS	-0.33*	-0.33*	-0.34*	-0.60****	-0.66****	-0.55***	-0.48**	-0.64****
	Postwake	-0.43**	-0.41**	-0.43**	-0.60****	-0.65****	-0.58****	-0.59****	-0.68****
	All Awakening	-0.23	-0.26	-0.25	-0.43**	-0.61****	-0.40*	-0.40*	-0.56***
RSA	EO	1.00	0.87****	0.97****	0.72****	0.68****	0.81****	0.78****	0.76****
	EC	0.87****	1.00	0.97****	0.68****	0.70****	0.81****	0.79****	0.78****
	Baseline	0.97****	0.97****	1.00	0.73****	0.71****	0.84****	0.81****	0.80****
	Prewake	0.72****	0.68****	0.73****	1.00	0.84****	0.87****	0.81****	0.88****
	Enforced Awake	0.68****	0.70****	0.71****	0.84****	1.00	0.86****	0.78****	0.97****
	RTS	0.81****	0.81****	0.84****	0.87****	0.86****	1.00	0.91****	0.94****
	Postwake	0.78****	0.79****	0.81****	0.81****	0.78****	0.91****	1.00	0.88****
	All Awakening	0.76****	0.78****	0.80****	0.88****	0.97****	0.94****	0.88****	1.00
HRV	EO	0.92****	0.79****	0.88****	0.70****	0.68****	0.81****	0.77****	0.75****
	EC	0.84****	0.91****	0.90****	0.61****	0.64****	0.76****	0.72****	0.72****
	Baseline	0.92****	0.88****	0.93****	0.68****	0.69****	0.82****	0.77****	0.77****
	Prewake	0.69****	0.63****	0.68****	0.94****	0.79****	0.80****	0.75****	0.84****
	Enforced Awake	0.66****	0.67****	0.69****	0.83****	0.94****	0.86****	0.81****	0.95****
	RTS	0.75****	0.82****	0.81****	0.71****	0.79****	0.93****	0.88****	0.86****
	Postwake	0.72****	0.74****	0.76****	0.76****	0.70****	0.87****	0.93****	0.82****
	All Awakening	0.73****	0.75****	0.77****	0.87****	0.92****	0.93****	0.88****	0.97****

Note: columns refer to RSA at the listed time periods, whereas the three groups of rows refer to HR, RSA, or HRV.
† $p < .10$, * $p < .05$, ** $p < .01$, *** $p < .001$, ****$p < .0001$

Table 19. Heart Rate Variability Correlations with Other Cardiovascular Measures

		EO	EC	Baseline	Prewake	Enforced Awake	RTS	Postwake	All Awakening
HR	EO	-0.36*	-0.39*	-0.39*	-0.28†	-0.41**	-0.41**	-0.46**	-0.46**
	EC	-0.27†	-0.31†	-0.30†	-0.18	-0.34*	-0.38*	-0.41**	-0.39*
	Baseline	-0.32*	-0.35*	-0.35*	-0.23	-0.38*	-0.40*	-0.44**	-0.43**
	Prewake	-0.41**	-0.33*	-0.38*	-0.34*	-0.53***	-0.51***	-0.52***	-0.58***
	Enforced Awake	-0.25	-0.22	-0.25	-0.29†	-0.41**	-0.29†	-0.24	-0.39*
	RTS	-0.47**	-0.37*	-0.44**	-0.53***	-0.62****	-0.46**	-0.46**	-0.62****
	Postwake	-0.51***	-0.39*	-0.47**	-0.52***	-0.67****	-0.53***	-0.54***	-0.68****
	All Awakening	-0.35*	-0.30†	-0.33*	-0.37*	-0.51***	-0.37*	-0.36*	-0.50**
RSA	EO	0.92****	0.84****	0.92****	0.69****	0.66****	0.75****	0.72****	0.73****
	EC	0.79****	0.91****	0.88****	0.63****	0.67****	0.82****	0.74****	0.75****
	Baseline	0.88****	0.90****	0.93****	0.68****	0.69****	0.81****	0.76****	0.77****
	Prewake	0.70****	0.61****	0.68****	0.94****	0.83****	0.71****	0.76****	0.87****
	Enforced Awake	0.68****	0.64****	0.69****	0.79****	0.94****	0.79****	0.70****	0.92****
	RTS	0.81****	0.76****	0.82****	0.80****	0.86****	0.93****	0.87****	0.93****
	Postwake	0.77****	0.72****	0.77****	0.75****	0.81****	0.88****	0.93****	0.88****
	All Awakening	0.75****	0.72****	0.77****	0.84****	0.95****	0.86****	0.82****	0.97****
HRV	EO	1.00	0.85****	0.97****	0.69****	0.69****	0.75****	0.74****	0.75****
	EC	0.85****	1.00	0.96****	0.61****	0.63****	0.76****	0.69****	0.70****
	Baseline	0.97****	0.96****	1.00	0.68****	0.68****	0.78****	0.75****	0.76****
	Prewake	0.69****	0.61****	0.68****	1.00	0.82****	0.64****	0.73****	0.84****
	Enforced Awake	0.69****	0.63****	0.68****	0.82****	1.00	0.79****	0.77****	0.98****
	RTS	0.75****	0.76****	0.78****	0.64****	0.79****	1.00	0.86****	0.88****
	Postwake	0.74****	0.69****	0.75****	0.73****	0.77****	0.86****	1.00	0.86****
	All Awakening	0.75****	0.70****	0.76****	0.84****	0.98****	0.88****	0.86****	1.00

Note: columns refer to HRV at the listed time periods, whereas the three groups of rows refer to HR, RSA, or HRV.
† $p < .10$, * $p < .05$, ** $p < .01$, *** $p < .001$, ****$p < .0001$

Table 20. Cortical Arousal Correlations

	1	2	3	4	5	6	7	8
1. Prewake Delta at FpFz	1.00	-0.65****	-0.59****	-0.43**	0.08	-0.07	-0.04	-0.19
2. Prewake Relative Theta at Fp	-0.65****	1.00	0.61****	0.41**	0.04	0.20	0.02	0.17
3. Prewake Relative Beta1 at FpFz	-0.59****	0.61****	1.00	0.90****	-0.14	0.00	0.14	0.07
4. Prewake Relative Beta2 at Fp	-0.43**	0.41**	0.90****	1.00	-0.13	-0.06	0.07	0.02
5. All Awakening Log Theta at Fp	0.08	0.04	-0.14	-0.13	1.00	0.48**	-0.69****	-0.15
6. All Awakening Alpha at Fp	-0.07	0.20	0.00	-0.06	0.48**	1.00	-0.23	0.07
7. All Awakening Normalized Relative Sigma Across Sites	-0.04	0.02	0.14	0.07	-0.69****	-0.23	1.00	0.04
8. Time elapsed since lights out	-0.19	0.17	0.07	0.02	-0.15	0.07	0.04	1.00

† $p < .10$, * $p < .05$, ** $p < .01$, *** $p < .001$, ****$p < .0001$

Table 21. Self-Report and Cortical Arousal Correlations

	STAI trait	STAI State	PSS	FIRST
Prewake Delta at FpFz	-0.10	-0.16	-0.26	-0.20
Prewake Relative Theta at Fp	0.20	0.27†	0.17	0.31*
Prewake Relative Beta1 at FpFz	0.29†	0.34*	0.39*	0.36*
Prewake Relative Beta2 at Fp	0.30†	0.28†	0.39*	0.39*
All Awakening Log Theta at Fp	-0.11	-0.36*	-0.20	0.05
All Awakening Alpha at Fp	0.06	-0.20	-0.10	-0.02
All Awakening Normalized Relative Sigma Across Sites	0.13	0.21	0.21	-0.18
Time elapsed since lights out	0.27†	0.04	0.30†	0.21

† $p < .10$, * $p < .05$

Table 22. Heart Rate and Cortical Arousal Correlations

	EO	EC	Baseline	Prewake	Enforced Awake	RTS	Postwake	All Awakening
Prewake Delta at FpFz	0.29†	0.28†	0.29†	0.36*	0.19	0.22	0.39*	0.26
Prewake Relative Theta at Fp	-0.16	-0.19	-0.18	-0.11	0.05	0.03	-0.18	-0.02
Prewake Relative Beta1 at FpFz	-0.11	-0.06	-0.09	-0.03	-0.08	-0.11	-0.25	-0.13
Prewake Relative Beta2 at Fp	-0.03	-0.01	-0.02	0.08	-0.06	-0.03	-0.15	-0.07
All Awakening Log Theta at Fp	0.10	0.05	0.08	0.10	0.25	0.19	0.28†	0.25
All Awakening Alpha at Fp	0.18	0.16	0.17	0.02	0.03	0.11	0.18	0.06
All Awakening Normalized Relative Sigma Across Sites	-0.35*	-0.29†	-0.32*	-0.36*	-0.40*	-0.39*	-0.40*	-0.39*
Time elapsed since lights out	-0.15	-0.19	-0.17	-0.17	0.06	-0.13	-0.26	-0.08

† $p < .10$, * $p < .05$

Table 23. Respiratory Sinus Arrhythmia and Cortical Arousal Correlations

	EO	EC	Baseline	Prewake	Enforced Awake	RTS	Postwake	All Awakening
Prewake Delta at FpFz	-0.24	-0.29†	-0.27†	-0.30†	-0.32*	-0.23	-0.28†	-0.33*
Prewake Relative Theta at Fp	0.10	0.18	0.15	0.06	0.07	0.03	0.09	0.11
Prewake Relative Beta1 at FpFz	0.29†	0.27†	0.29†	0.32*	0.31†	0.22	0.22	0.33*
Prewake Relative Beta2 at Fp	0.27†	0.27†	0.28†	0.24	0.29†	0.18	0.15	0.28†
All Awakening Log Theta at Fp	-0.19	-0.11	-0.16	-0.23	-0.36*	-0.18	-0.14	-0.31†
All Awakening Alpha at Fp	-0.14	-0.07	-0.11	-0.18	-0.12	-0.08	-0.16	-0.13
All Awakening Normalized Relative Sigma Across Sites	0.28†	0.22	0.26	0.28†	0.36*	0.25	0.16	0.34*
Time elapsed since lights out	0.12	0.09	0.11	0.09	0.14	0.04	0.08	0.12

† $p < .10$, * $p < .05$

Table 24. Heart Rate Variability and Cortical Arousal Correlations

	EO	EC	Baseline	Prewake	Enforced Awake	RTS	Postwake	All Awakening
Prewake Delta at FpFz	-0.19	-0.17	-0.19	-0.22	-0.31*	-0.25	-0.23	-0.32*
Prewake Relative Theta at Fp	0.02	0.04	0.03	0.02	0.12	0.06	0.10	0.14
Prewake Relative Beta1 at FpFz	0.19	0.15	0.18	0.37*	0.32*	0.17	0.21	0.33*
Prewake Relative Beta2 at Fp	0.20	0.18	0.20	0.33*	0.26	0.14	0.16	0.25
All Awakening Log Theta at Fp	-0.21	-0.12	-0.17	-0.25	-0.34*	-0.08	-0.05	-0.27†
All Awakening Alpha at Fp	-0.11	-0.07	-0.09	-0.23	-0.21	-0.01	-0.16	-0.18
All Awakening Normalized Relative Sigma Across Sites	0.26	0.15	0.22	0.18	0.28†	0.14	0.06	0.27†
Time elapsed since lights out	0.16	0.09	0.13	0.12	0.20	0.06	0.09	0.16

† $p < .10$, * $p < .05$

Table 25. Self-Report and Autonomic Arousal Correlations

	STAI trait	STAI State	PSS	FIRST
EO HR	-0.24	-0.14	-0.14	-0.07
EC HR	-0.22	-0.10	-0.05	-0.05
Baseline HR	-0.23	-0.12	-0.10	-0.06
Prewake HR	-0.12	-0.05	-0.04	0.15
Enforced Awake HR	-0.12	-0.14	-0.10	0.09
RTS HR	-0.12	-0.04	-0.08	0.14
Postwake HR	-0.22	-0.15	-0.09	0.01
All Awakening HR	-0.13	-0.12	-0.12	0.07
EO RSA	0.20	0.04	0.08	0.12
EC RSA	0.25	-0.02	0.10	0.21
Baseline RSA	0.23	0.01	0.09	0.17
Prewake RSA	0.24	0.06	0.05	0.10
Enforced Awake RSA	0.31*	0.15	0.17	0.02
RTS RSA	0.26	0.02	0.03	0.02
Postwake RSA	0.31*	0.05	0.01	0.15
All Awakening RSA	0.30†	0.11	0.14	0.05
EO HRV	0.18	0.00	0.06	0.05
EC HRV	0.15	-0.04	0.10	0.13
Baseline HRV	0.17	-0.02	0.08	0.09
Prewake HRV	0.21	0.06	0.08	0.14
Enforced Awake HRV	0.33*	0.16	0.15	0.03
RTS HRV	0.21	-0.06	-0.05	-0.01
Postwake HRV	0.30†	0.06	0.04	0.08
All Awakening HRV	0.32*	0.12	0.13	0.06

† $p < .10$, * $p < .05$

Table 26. Parameter Estimates from Models Predicting Memory from Delta and RSA

	Prewake Delta	RSA
Recognition percent	-0.38*	-0.08
Corrected recognition percent	-0.38*	-0.08
First third	-0.44**	-0.26
Middle third	-0.23	-0.13
Final third	-0.15	-0.37*

* $p < .05$, ** $p < .01$

Table 27. Parameter Estimates from Models Predicting Memory from Delta and Awakening Time

	Prewake Delta	Time of Awakening
Recognition percent	-0.36*	0.12
Corrected recognition percent	-0.36*	0.12
First third	-0.36*	0.07
Middle third	-0.16	0.32†
Final third	0.01	0.24

† $p < .1$, * $p < .05$, controlling for number of stimuli

Figure 1. PSG Protocol

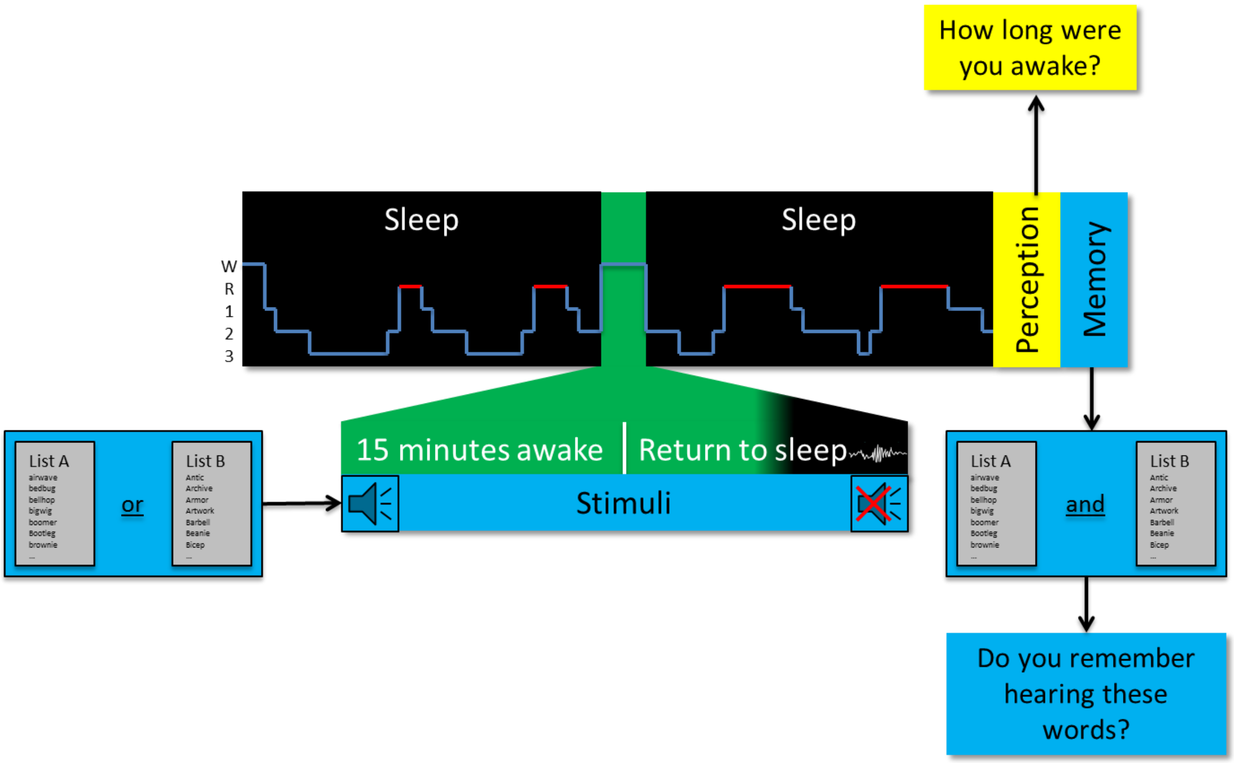


Figure 2. Percent Recognition of Stimuli by Third

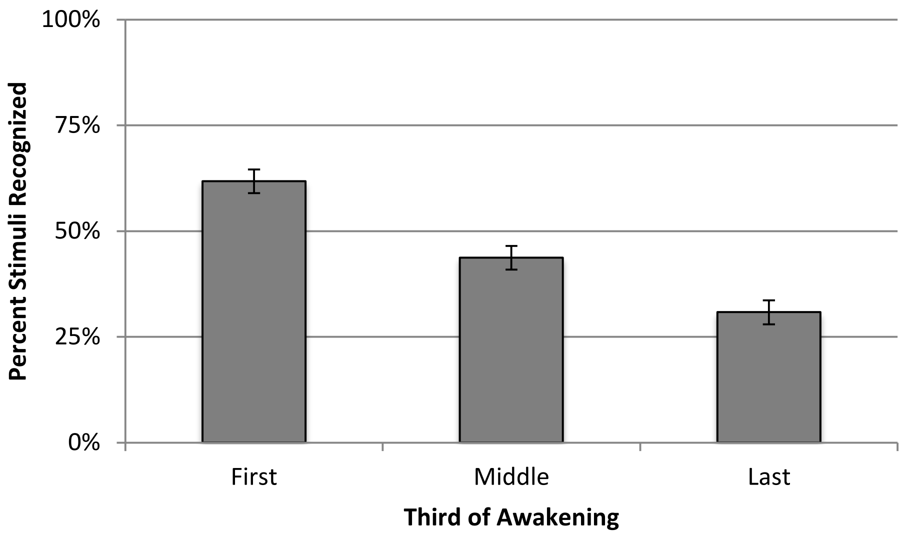


Figure 3. Prewake Delta and Memory by Third

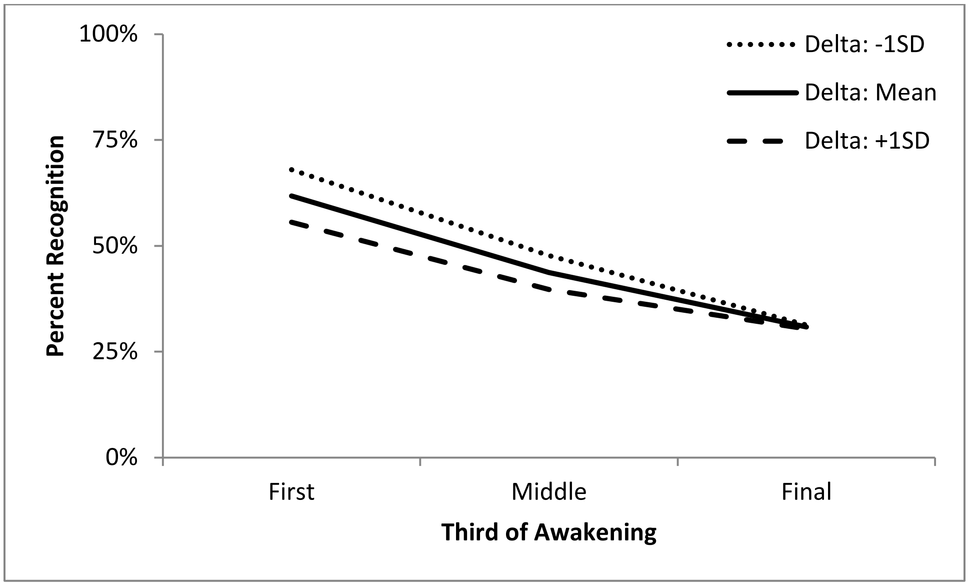


Figure 4. Awakening RSA and Memory by Third

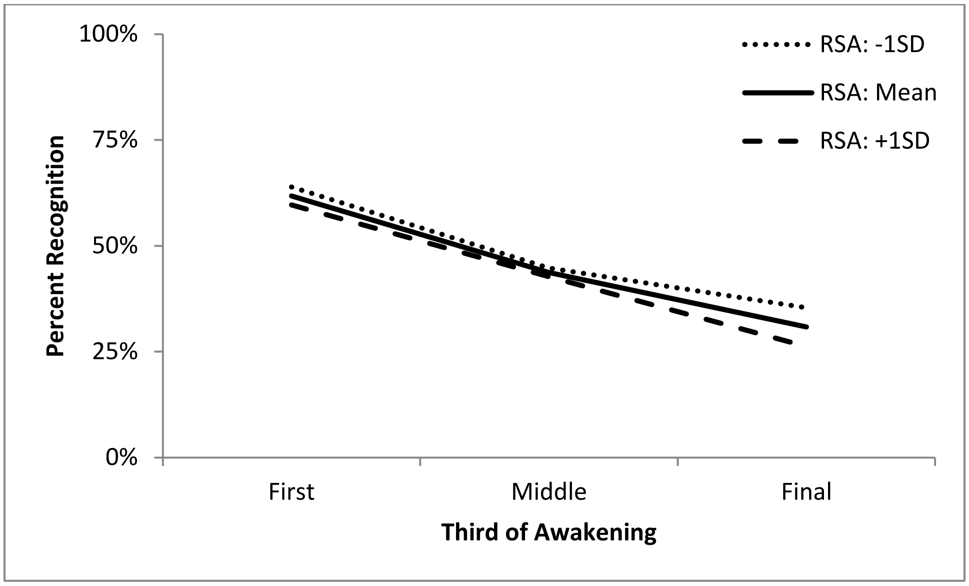


Figure 5. Association between Memory at Each Third of the Awakening with Prewake Delta and Awakening RSA

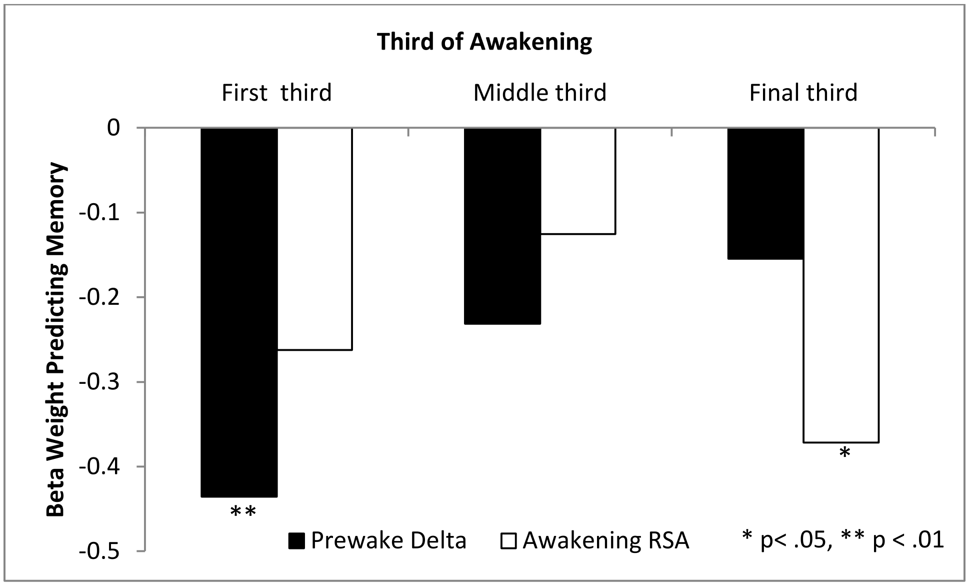


Figure 6. Association between Memory at Each Third of the Awakening with Prewake Delta and Time of Awakening

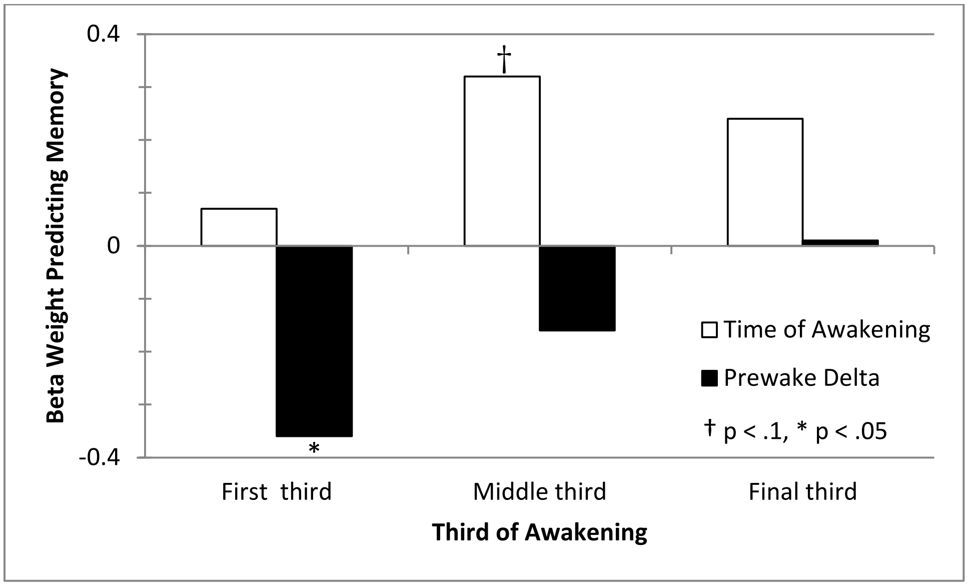


Figure 7. VPA I and Memory by Third

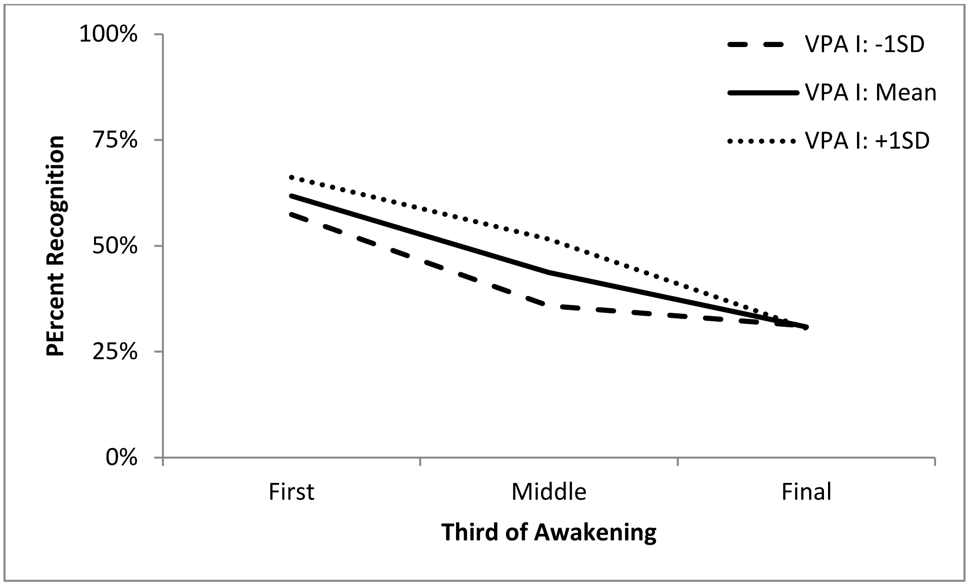


Figure 8. VPA II and Memory by Third

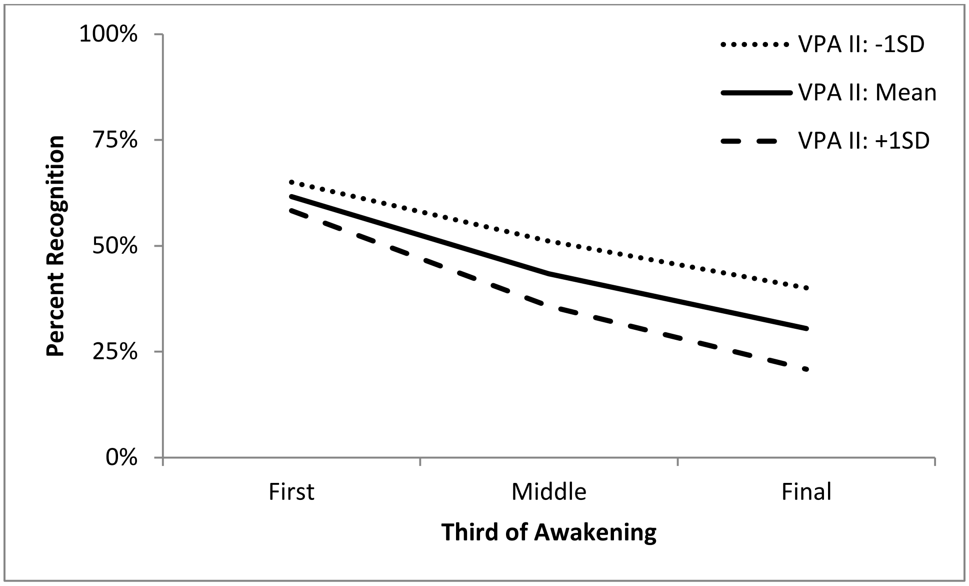
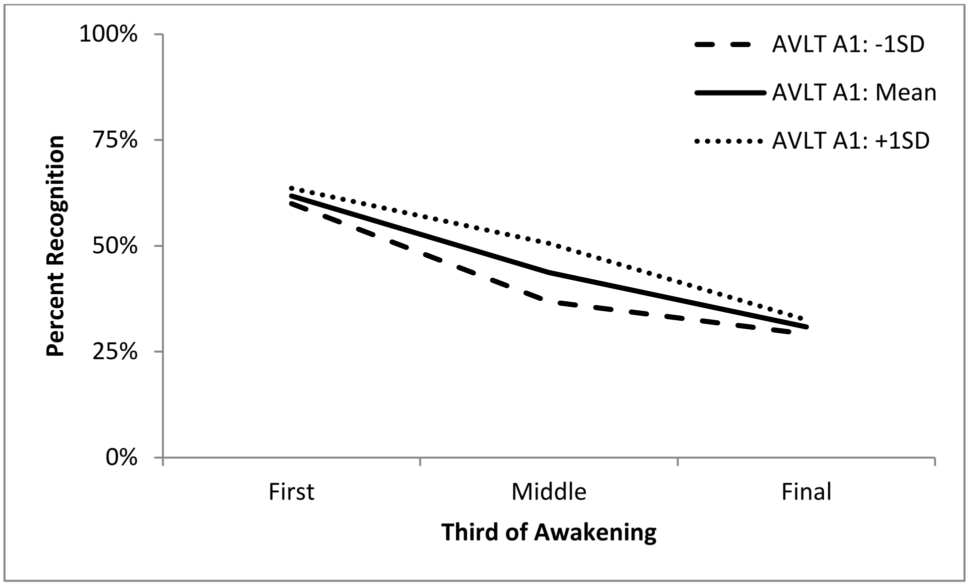


Figure 9. AVLT Trial 1 and Memory by Third



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