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WASHINGTON UNIVERSITY

Department of Psychology

**Sleeping to Remember: Spontaneous Retrieval of Prospective Memories Across
Sleep and Wake Delays**

by

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A thesis presented to the
Graduate School of Arts and Sciences
of Washington University in
partial fulfillment of the
requirements for the
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Table of Contents

Acknowledgments	ii
List of Tables and Figures	iv
Summary	v
Epigraph	1
Introduction	2
Prospective Memory and Retention Interval	5
Theories of Prospective Memory Retrieval	7
The Present Experiment	9
Methods	11
Participants, Design, and Task Overview	11
Procedure	12
Results	14
Syllable Learning and Recall	15
Working Memory Performance	17
Prospective Memory Performance	18
Cost Before and After Target Cues	22
Additional Analyses	26
Discussion	28
Sleep and Memory	29
Theoretical Implications for Prospective Memory	31
Conclusions and Future Directions	33
Reference	34

List of Tables and Figures

Table 1. Performance on the syllable recall task as measured by mean trials to criterion, mean syllables recalled during criterion learning, and final recall following retention interval (standard deviations in parentheses) across condition and retention intervals.

Figure 1. Prospective memory performance across encoding time, delay, and ongoing task.

Summary

Laboratory-based prospective memory tasks have rarely examined the effect of retention interval on later remembering. In the current study, participants had to remember to perform an intended action (press Q in response to a target cue) after a short delay (approximately 20 min), a 12-hr sleep delay, or a 12-hr wake delay. The results demonstrated a large decline in prospective memory performance after a 12-hr wake delay (relative to the short delay condition). Interestingly, prospective remembering was not only better following a 12-hr sleep delay than a 12-hr wake delay but performance in this condition did not differ significantly from performance in the short delay condition. Cost analyses (i.e., ongoing task performance decline associated with embedding a prospective memory task) demonstrated that spontaneous retrieval processes primarily supported prospective remembering. These results are discussed in relation to theories of prospective memory retrieval and sleep-dependent memory consolidation.

“It is astonishing how much strength the interval of a night gives [memory]...the very time which is generally thought to cause forgetfulness is found to strengthen the memory.”

--Roman rhetorician Quintilian, First century, AD

Sleeping to Remember: Spontaneous Retrieval of Prospective Memories Across Sleep and Wake Delays

In recent years there has been a resurgence of interest in the effect of sleep on memory. Interestingly, the idea that sleep could benefit memory is millennia old (see Quintilian quote) and the history of recorded sleep-related memory benefits is as old as the empirical study of memory. In his seminal study, Ebbinghaus (1885) observed a reduction in forgetting from 9 hrs to 24 hrs (2.1%), which can be compared to the forgetting rate from 1 hr to 9 hrs (8.4%) and from 24 hrs to 48 hrs (6.1%). Even though the reduced forgetting rate was observed during an interval that included the first night of sleep following learning, Ebbinghaus concluded that the reduction was “not credible” (p. 77), and even lamented that the effect was his “least satisfactory” (p. 77) result.

Ebbinghaus’s (1885) results were no accident. In a classic study, Jenkins and Dallenbach (1924) examined memory for nonsense syllables across sleep and wake retention intervals of 1 to 8 hrs. Not only was recall greater following sleep delays (59%) than wake delays (26%), but recall was actually better following an 8-hr sleep delay (56.5%) than a 1-hr wake delay (46%). These results led Jenkins and Dallenbach to conclude that sleep serves to protect against “the interference, inhibition, or obliteration of the old by the new” (p. 612). In other words, sleep (passively) protects against retroactive interference (Wixted, 2004).

Another general account for sleep-related memory benefits contends that memories are reactivated and restructured during sleep, and thereby (actively) consolidated (e.g., see Moggross, Guillem, & Godbout, 2008; Rasch, Buchel, Gais, & Born, 2007; Sejnowski & Destexhe, 2000). Rasch et al. demonstrated that memories can

be selectively reactivated during sleep and therefore enhanced. Participants learned a visuospatial object-location task (the game “Concentration”) that involved recalling the location of card pairs following a sleep or wake interval. Importantly, during learning, a rose scent (or an odorless control) was repeatedly presented and participants were re-exposed to the rose scent (or control) while they slept. Performance on the memory task following sleep demonstrated that memory was enhanced when the rose scent (relative to the odorless control) was presented both during learning and sleep (specifically, the slow-wave-sleep stage) phases. In contrast, no memory enhancement was observed if the rose scent was presented at learning and again during a wake interval. In addition, using functional magnetic resonance imaging (fMRI), Rasch et al. demonstrated that rose scent re-exposure led to greater hippocampal area activation (an area that is critical to memory encoding and retrieval) during sleep than while awake. Thus, Rasch et al.’s behavioral and neurophysiological evidence powerfully demonstrated that, beyond simply protecting against retroactive interference (Jenkins & Dallenbach, 1924; Wixted, 2004), sleep might also enhance memory by reactivating and strengthening associative links.

In addition to Rasch et al.’s (2007) evidence for sleep-dependent memory consolidation, other researchers have demonstrated that sleep preferentially benefits associative memory (e.g., see Barrett & Ekstrand, 1972; Fowler, Sullivan, & Ekstrand, 1973; Talamani, Nieuwenhuis, Takashima, & Jensen, 2008; Yaroush, Sullivan, & Ekstrand, 1971). More specifically, sleep has been demonstrated to cause weak associations to become stronger (for a brief review, see Diekelmann, Wilhelm, & Born, in press) and memory representations to become more elaborated (Mogras et al., 2008; see also Charlton & Andras, 2009, for a similar theory). For example, Stickgold, Scott,

Rittenhouse, and Hobson (1999) gave participants a semantic priming task that consisted of weak and strong primes before and after sleep. Their results demonstrated that weak primes led to more priming than even strong primes following a sleep interval (that contained dreaming).

The effect of sleep on weak associations has also been observed in cued recall and recognition memory tasks. Using an A-B, A-C paired associate learning paradigm, Drosopoulos, Schulze, Fischer, and Born (2007) demonstrated a sleep-related benefit for the A-B list over the A-C list. The authors reasoned that, even though learning the second list (A-C) initially weakened the associative strength of first list pairs (A-B) (via retroactive interference), sleep restrengthened these weak associations.

Mograss et al. (2008) examined event-related potentials to provide converging evidence that sleep affects the structure of a memory via strengthening associative links. In their recognition memory study, Mograss et al. examined the medial-temporal-lobe-generated late-positive-component (LPC) effect on old items (compared to new items) in sleep and wake conditions. The magnitude of the LPC effect is theorized to reflect the amount of binding and elaboration that a memory has undergone (Allan, Wilding, & Rugg, 1998). Thus, Mograss et al. interpreted the finding of a larger LPC effect after a sleep delay than a wake delay as evidence that sleep-dependent “consolidation consists of restructuring or reorganizing weak associations in order to strengthen associative links” (p. 431). Therefore, an emerging hypothesis is that sleep may benefit memories by *binding* weak associations.

In the present study, I investigated the binding view’s hypothesis of sleep’s effect on memory (as compared to the interference view, Jenkins & Dallenbach, 1924) by

embedding a prospective memory task in several contexts, one of which was weakly associated with the prospective memory intention. According to the interference view (Jenkins & Dallenbach), sleep should benefit prospective remembering in each context equally, whereas the binding view (e.g., Brankack, Platt, & Riedel, 2009; Mograss et al., 2008) predicts that, because sleep strengthens weak associations, the greatest sleep-related prospective memory benefit will obtain in the context that was (initially) weakly associated with the intention.

Prospective Memory and Retention Interval

Prospective memory refers to the ability to remember to perform an intended action in the future. Examples of real world prospective memory tasks include remembering to take one's medication with breakfast and calling one's mother on her birthday. The typical laboratory-based prospective memory task (Einstein & McDaniel, 1990) involves performing some ongoing task (e.g., rating faces) and remembering to perform a designated action that is different from the normal ongoing task response (e.g., raise hand) if a target cue (e.g., face with glasses) is presented (Maylor, 1996). This paradigm was designed as an analogue to real world situations in which individuals are engaged in some ongoing activity (e.g., getting ready for work) when they encounter a cue (e.g., medicine box) that signals that they should disengage their normal response and execute a prospective memory response (e.g., take medication).

One striking difference between laboratory-based prospective memory tests and prospective memory in the real world is the delay between forming and executing the intention. Many (if not most) real world prospective memory tasks include retention intervals of hours or days, but nearly all laboratory-based prospective memory studies

have retention intervals of 5 min or less, few studies have retention intervals greater than 10 min (Einstein, Holland, McDaniel, & Guynn, 1992; Guynn, McDaniel, & Einstein, 1998; Hicks, Marsh & Russell, 2000) and only one published study had a retention interval greater than 20 min (Nigro & Cicogna, 2000). Perhaps because of this tradition of using short retention intervals, there has yet to be an (published) examination of the effects of sleep on prospective memory. Indeed, few prospective memory studies have even manipulated retention interval, and the studies that have done so have produced results that were highly counterintuitive. For example, Hicks et al. reported that prospective memory performance was *better* following longer delays (e.g., 15 min) than shorter delays (e.g., 3 min).

Hicks et al.'s (2000) results were highly surprising but the nature of their prospective memory task may help explain their pattern of results. Because their ongoing task (pleasantness-rating) promoted processing of the pleasantness of a given word whereas their prospective memory task included a categorical cue (any word that represented an animal), the prospective memory task can be considered nonfocal to the ongoing task (i.e., categorical information is not necessarily activated in the service of pleasantness rating). Therefore, to remember to perform the prospective memory action participants were required to divert attention away from the ongoing task to check (i.e., monitor) for the categorical prospective memory cue (McDaniel & Einstein, 2000). Such an attention-demanding task should benefit from self-reminders (e.g., by increasing monitoring for the prospective memory cue in the correct context), and if the effects of self-reminders are cumulative (as suggested by Hicks et al.), then prospective memory performance could increase over long retention intervals. Thus, another prediction for the

effect of sleep on prospective memory is possible. According to the self-reminders view, because conscious self-reminders are possible while one is awake but will be minimal during a sleep-filled retention interval, the self-reminder hypothesis would predict that prospective memory performance should be better after a wake delay than a sleep delay.

Theories of Prospective Memory Retrieval

To gain further leverage on the memory (retrieval) processes that are benefited by sleep we next consider (and examine in the present study) two general theories for how individuals remember to perform prospective memory intentions: the monitoring theory and the multiprocess theory. Monitoring theory (Guynn, 2003; Smith, 2003) argues that, for an intention to be retrieved, one must engage effortful monitoring processes *prior* to a target cue. Monitoring processes (e.g., trial-by-trial checking for prospective memory cues) are nonautomatic and require working memory capacity or attentional resources. Furthermore, according to monitoring theory, prospective memory performance is primarily driven by the ability to monitor for a target; therefore, sleep should only benefit prospective remembering if it increases the likelihood or effectiveness of monitoring immediately before a prospective memory cue.

The multiprocess theory of prospective memory retrieval (McDaniel & Einstein, 2000; McDaniel & Einstein, 2007) offers a different prediction for sleep's effect on prospective remembering. According to the multiprocess theory, in addition to engaging monitoring processes, individuals may spontaneously retrieve prospective memory intentions without having to devote attentional resources or working memory capacity to monitoring for the prospective memory cues. One factor that determines the probability of an intention being spontaneously retrieved is the extent to which a prospective

memory cue is focally processed. For a target cue to be focally processed the ongoing activity must direct the individual to process the important features of the target cue, and especially those features that were encoded during intention formation (see also the encoding specificity hypothesis, Tulving, 1983; Tulving & Thompson, 1973). Thus, if contextual features are associated with the prospective memory intention, then spontaneous retrieval of the prospective memory should be more likely during that specific context due to increased focal processing of the target cue (i.e., the overlap between processing at retrieval and the features of the stored prospective memory). The multiprocess theory therefore predicts that when conditions encourage individuals to rely on spontaneous retrieval rather than monitoring (as is likely with long retention intervals; see Kvavilashvili & Fisher, 2007; Scullin, McDaniel, Shelton, & Lee, 2009), sleep can benefit prospective memory by strengthening the intention link with the contextual factors that will be relevant during retrieval (cf. binding view of memory consolidation).

Consistent with previous research (Einstein et al., 2005; Scullin, McDaniel et al., 2009; Smith, 2003) I assessed whether participants were relying on spontaneous retrieval or more effortful monitoring processes by examining ongoing task cost (i.e., slower ongoing task performance due to directing attention toward the prospective memory intention) before prospective memory cues. Monitoring theory predicts that because costly monitoring processes must be activated *preceding* target cues for an intention to be retrieved (Smith, Hunt, McVay, & McConnell, 2007), cost should emerge before target cues, and further that a strong correlation between pre-target cost and prospective memory performance should obtain. On the other hand, according to the multiprocess theory (McDaniel & Einstein, 2007), when the delay between intention formation and

execution is substantial (Scullin et al., 2009, Experiment 4), most participants will rely on spontaneous retrieval processes that do not require monitoring. If participants are relying on (relatively automatic) spontaneous retrieval processes then cost should *not* be observed prior to target cues (or associated with prospective memory performance).

The Present Experiment

The primary goal of the present experiment was to use a prospective memory paradigm (and prospective memory theories) to gain a deeper understanding of the processes by which sleep benefits memory. In contrast to typical laboratory-based prospective memory tasks, but consistent with many real world prospective memory intentions, the present study employed several ongoing tasks and long retention intervals. Previous research (Scullin et al., 2009) suggested that such conditions should promote reliance on spontaneous retrieval processes rather than monitoring processes. Therefore, focal prospective memory cues were employed to ensure that the intention could be spontaneously retrieved (McDaniel & Einstein, 2007).

The present study included both short and long delays between intention encoding and execution. In the short delay conditions, the first target cue appeared approximately 20 min after the prospective memory intention was encoded. In the long delay conditions, the retention interval was approximately 12 hrs. Participants were tested in the morning or evening such that the retention interval included intervals of nighttime sleep or daytime wake. Importantly, to avoid strong associations between the ongoing task context and the prospective memory task, participants were told that the prospective memory cues could occur at any time during the experiment, and following the retention interval, the target cues occurred in 3 separate ongoing tasks. Though two of these

contexts (living/nonliving task, lexical decision task) should not have been associated with the prospective memory intention, the third context (semantic categorization) was weakly associated with the intention by means of temporal proximity (see Drosopoulos, Windau, Wagner, & Born, 2007, for evidence that sleep enhances temporal order in associative memory).

At least three predictions for the effects of the sleep delay on prospective memory are possible. First, according to Hicks et al.'s (2000) suggestion that prospective memory performance increases over delays because of increased self-reminders, prospective remembering should be *worse* in the sleep delay condition than the wake conditions (if participants rely on monitoring processes instead of spontaneous retrieval processes to support prospective remembering). Second, according to Jenkins & Dallenbach's (1924) interference view, if prospective memory is subject to retroactive interference, then a sleep delay should produce better prospective remembering relative to an equally-long wake delay across all ongoing task contexts by protecting the intention from interference. According to the binding view of memory consolidation, which contends that sleep promotes the strengthening of weak associative links, sleep should benefit prospective memory, but primarily during the semantic categorization context, which was weakly associated with the prospective memory intention during encoding (and presumably strengthened during sleep). Such a finding would be consistent with previous research that demonstrated that weak temporal associations are strengthened during sleep (Drosopoulos, Windau, et al., 2007).

To eliminate interpretational ambiguity and strengthen the conclusion that the retention interval manipulation caused the obtained prospective memory pattern in the

present study I also included a nonsense recall task (following Jenkins & Dallenbach, 1924) and a working memory task (reading span). According to the binding and interference views, sleep should benefit recall (as demonstrated by Jenkins & Dallenbach; see also Ebbinghaus, 1885), but not working memory performance.

Method

Participants and design. Washington University undergraduates (N = 124) participated for class credit or monetary compensation at 0900 hrs and/or 2100 hrs. Data collection occurred in groups of 1-10 and participants returning for a second experimental session performed all tasks at the same computer station as during the first session. Testing lasted 1.25-2.00 hrs.

The design was a 2 x 2 factorial in which encoding time (morning or evening), and delay (short or long) were between subjects variables. Two participants in the evening encoding/long delay condition (hereforth referred to as the sleep delay condition) and one participant in the morning encoding/long delay condition (hereforth referred to as the wake delay condition) were excluded for not returning for the second experimental session. In addition to the previously described groups (n = 24 in each group), a control group (n = 25) that never received the prospective memory task was tested in the short delay conditions (n = 13 in evening group) to serve as a baseline against which to measure ongoing task cost in the prospective memory groups. Participants in the short delay conditions were randomly assigned to prospective memory and control groups.

Task overview. The first experimental session included, in the following order, reading span, living/nonliving decision, lexical decision, semantic categorization, prospective memory task encoding (except in the control condition), Symptom Checklist-

90 (SCL-90) questionnaire, demographics forms, and nonsense syllable learning tasks. In the second experimental session participants performed the Morningness-Eveningness Questionnaire (MEQ; Horne & Ostberg, 1976), syllable free recall, reading span, living/nonliving decision, lexical decision, semantic categorization, and symmetry span.

Procedure. The reading span was an automated working memory task that required participants to maintain letters in mind while determining whether sentences made sense (for an elaboration on this task and procedure see Unsworth, Redick, Heitz, Broadway, & Engle, 2009).

After performing the reading span task the experimenter loaded the program that contained the rest of session 1's experimental tasks. The first 3 tasks were "ongoing tasks"—living/nonliving task, lexical decision task, and semantic categorization task—that would include prospective memory target cues during the next experimental session. In each of these ongoing tasks participants were given the task instructions and a 12-trial practice block (that included speed and accuracy feedback). Then they performed a 164-trial experimental block in which the first 6 and last 6 trials were considered buffers. In each task, participants responded using the keys marked Y and N (1 and 2 on the number pad, respectively). The task instructions in the living/nonliving task were to determine as quickly and accurately as possible whether a presented noun represented a living (e.g., dog) or nonliving (e.g., chair) object. In the lexical decision task they were instructed to determine as quickly and accurately as possible whether a string of letters formed a word (e.g., kite) or nonword (e.g., itek). Furthermore, in the semantic categorization task a capitalized word appeared on the right side of the screen and a lowercase word appeared on the left side of the screen, and participants were instructed to quickly and accurately

determine whether the lowercase word (e.g., hockey) was a member of the category word (e.g., SPORT).

Immediately following completing the semantic categorization task, participants encoded the prospective memory task (except for participants in the control condition). Participants were told that, in addition to the different tasks they had been doing and would be doing, there was a secondary interest in their memory for performing an action in the future. Participants were instructed to press the Q key if they ever saw the words *table* or *horse* during any point in the experimental session (or also in the next session, in the long delay conditions). Furthermore, they were told to press the Q key when they remembered having seen their target word, even if that trial was no longer on the screen. Participants were told that they would not be reminded of the target words or the target key and that their primary goal was to focus on whichever task they were performing. To check their understanding of the prospective memory instructions they were required to write down the instructions. If a participant failed to recall a target word, the target key, or seemed to misunderstand the instructions otherwise, the experimenter verbally explained the instructions to the participant (using the same instructions as above) who then was asked to write down the instructions again.

Participants were next given a few questionnaires (SCL-90 and demographics questionnaires) and were then told that they would be studying a list of nonsense syllables (e.g., cen, tor), which they would need to remember for a later test (Jenkins & Dallenbach, 1924). During the study phase, the 10 syllables each appeared for 4 sec. The study phase was followed by an immediate request to recall all the syllables on a notepad. Participants that failed to recall at least 8 syllables (supervised by the experimenter)

repeated the study-test phases until they were able to learn the syllables to criterion. Following criterion learning participants in the short delay conditions were allowed a break before continuing onto the second half of the experiment. Participants in the sleep and wake delay conditions were given a notecard that included their subject ID and testing room numbers and were asked to bring it back for the next experimental session.

Participants began the second session (or second half of the experimental session in the short delay condition) by filling out the MEQ, which assesses an individual's optimal time of day, and answering sleep-related questions (e.g., estimated asleep and wake times the previous night and whether they had taken a nap that day).

Following the questionnaires, participants were given 3 min to recall the syllables they had previously studied. Participants then performed the reading span task followed by the 3 ongoing tasks (living/nonliving decision, lexical decision, semantic categorization). During each ongoing task, the first 6 and the last 6 trials were considered buffer items and the target words appeared on trials 107 and 158. The remaining 150 trials were filler items and subjected to reaction time analyses. Two lists of filler items were constructed for each ongoing task (one for each session) and list order was counterbalanced across participants. Then participants performed the automated symmetry span task, a working memory task that required participants to respond whether a pattern was symmetrical while maintaining matrix cell locations in mind (see Unsworth et al., 2009, for elaboration).

Results

Alpha was set to less than .05 for inferring statistical significance. When the omnibus analysis of variance (ANOVA) revealed significant results and there was an α

priori prediction of the pattern of results (e.g., retention interval differences, see introduction), planned comparisons (Dunn t-test for unequal sample size groups) were conducted. Furthermore, because condition (prospective memory versus control) was nested within the short delay groups, the ANOVAs did not test for condition by delay interactions. Therefore, for cost analyses, encoding time by delay interactions were tested using hierarchical regression techniques (when both pre-manipulation and post-manipulation scores were present). Finally, when the sphericity assumption was violated the Huynh-Feldt error term was used and noted.

Syllable learning and recall. Performance on the syllable-learning task was assessed as the number of study trials to learn the syllables to criterion (i.e., at least 8 correctly recalled) as well as the number of syllables recalled on the final study trial. These data are presented in Table 1. A series of 2 x 2 x 2 ANOVAs that included the between subjects factors of condition (prospective memory or control), encoding time (morning or evening) and delay (short or long) showed no significant effects for final study trial recall (largest $F(1, 115) = 1.29$, $MSE = .52$, for the delay main effect) or for number of learning trials to reach the criterion (largest $F(1, 115) = 3.71$, $MSE = 1.76$, $p = .06$, for the encoding time by delay interaction). These results suggest that the groups did not differ prior to the delay manipulation and that embedding a prospective memory task did not cause worse performance on the syllable-learning task (as demonstrated by no condition effects).

Performance on the final syllable recall test was tabulated as the number of syllables perfectly recalled. For the dependent measure of number of correct syllables recalled, a 2 x 2 x 2 between subjects ANOVA that included condition (prospective

Table 1

Performance on the syllable recall task as measured by mean trials to criterion, mean syllables recalled during criterion learning, and final recall following retention interval (standard deviations in parentheses) across condition and retention intervals.

	<u>Trials to Criterion</u>	<u>Syllables Learned</u>	<u>Final Recall</u>
Morning Delay	2.79 (1.02)	8.50 (.78)	7.58 (1.41)
Morning Control	3.58 (1.62)	8.42 (.67)	7.25 (1.60)
Evening Delay	3.13 (1.19)	8.50 (.83)	7.50 (1.06)
Evening Control	3.00 (1.35)	8.31 (.75)	6.62 (2.22)
Sleep Condition	2.75 (1.29)	8.46 (.78)	6.46 (1.89)
Wake Condition	3.46 (1.56)	8.21 (.42)	4.42 (1.89)

memory or control), encoding time (morning or evening), and delay (short or long) was conducted. There was a significant delay main effect, $F(1, 115) = 37.84$, $MSE = 2.81$, but also a significant encoding time by delay interaction, $F(1, 115) = 9.65$, $MSE = 2.81$ (next largest $F = 2.51$ for the encoding time main effect). Planned comparisons demonstrated that syllable recall was similar in the morning and evening short delay conditions (collapsed across prospective memory and control groups) ($t(72) < 1$). When collapsing across all the short delay conditions, planned comparisons demonstrated better syllable recall in the collapsed short delay condition than the wake delay condition, $t(96) = 7.39$, and the sleep delay condition, $t(96) = 2.21$. Importantly, syllable recall was greater in the sleep delay condition than the wake delay condition, $t(47) = 4.22$. Thus, the results replicated Jenkins and Dallenbach's (1924) finding that sleep-filled retention intervals buffered against forgetting of nonsense syllables (see also Ebbinghaus, 1885). Now that the typical sleep-related benefit to syllable recall has been demonstrated, the effect of sleep on working memory performance and prospective memory performance will be evaluated.

Working memory performance. Performance on the reading span task was calculated as the total number of letters recalled in the correct set position. To investigate whether working memory performance depends on quality of delay (as suggested by Kuriyama, Mishima, Suzuki, Aritake, & Uchiyama, 2008, but not predicted by the binding or interference views), a $2 \times 2 \times 2$ ANOVA was conducted on session-1 and session-2 reading span performance that included condition (prospective memory or control), encoding time (morning or evening), and delay (short or long) as between-subjects factors. There were no significant effects for session-1 reading span performance

(largest $F(1, 115) = 2.4$ for the condition main effect), thereby demonstrating no pre-experimental group differences. Importantly, there were also no significant effects for session-2 reading span performance (largest $F(1, 115) = 1.01$ for the encoding time by delay interaction). The lack of a sleep-related working memory benefit was not due to repeating the same working memory task. Performance on the symmetry span task (administered only in session 2) was calculated as the total number of squares recalled in the correct position and subjected to a $2 \times 2 \times 2$ ANOVA that included condition (prospective memory or control), encoding time (morning or evening), and delay (short or long) as between subjects factors. Consistent with the reading span analyses, there were no significant effects [largest $F(1, 115) = 2.04$, $MSE = 57.38$ for the condition main effect]. Thus, in contrast to the syllable recall results, but as predicted by the binding and interference views, sleep does not benefit working memory.

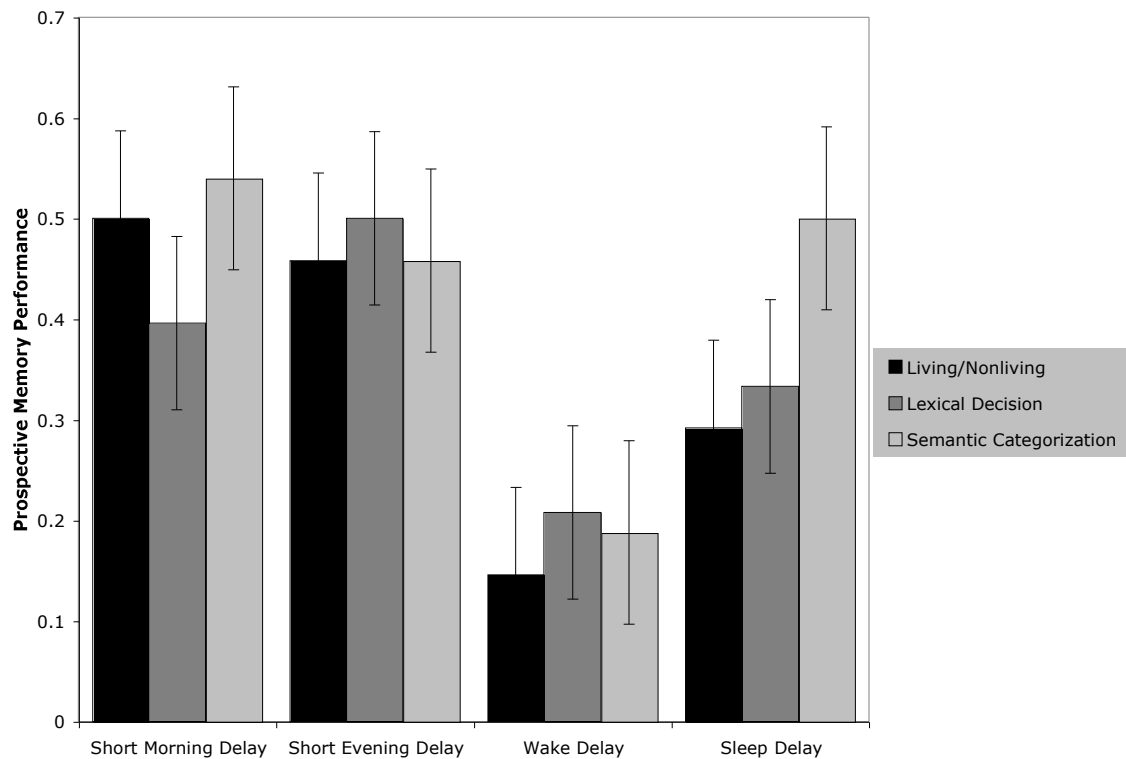
Prospective memory performance. Q presses that followed one target cue but occurred before the next target cue (and were within the same ongoing task) were counted as correct. Prospective memory performance was first assessed as the proportion of participants that remembered to press the Q key at least once in response to a target cue. This measure was motivated by the observation that real world prospective remembering is typically assessed as whether an intention has or has not been executed, regardless of the opportunities to perform the task (e.g., whether or not medication is taken with breakfast, regardless of the time spent eating breakfast). The proportion of participants who performed the prospective memory task at least once did not differ in the short morning delay ($M = .67$) and short evening delay ($M = .71$) conditions ($\chi^2 < 1$), and these conditions were therefore collapsed in the following analyses. There was a

significantly greater proportion of participants who responded to the prospective memory target cues in the short delay conditions than the wake delay condition ($M = .29$), $\chi^2 = 10.15$, but not the sleep delay condition ($M = .58$; $\chi^2 < 1$). Critically, individuals in the sleep delay condition were significantly more likely to respond to at least one target cue than individuals in the wake delay condition, $\chi^2 = 4.15$. Therefore, sleep not only benefited free recall of syllables but also benefited memory for performing intended actions. This result was consistent with the binding and interference views (which both suggest that sleep should benefit prospective memory), but not the self-reminders view (Hicks et al., 2000).

The following analyses examined prospective memory performance across ongoing task contexts to investigate whether the sleep benefit to prospective remembering could be better explained by an interference account or a sleep-dependent binding account. Because prospective memory responding to *horse* was similar to responding to *table* ($F(1, 93) = 2.70$, $MSE = .28$), performance across these targets was collapsed. Furthermore, performance across the first and second target item within ongoing task contexts was also collapsed because performance did not differ between these targets during the living/nonliving ($\chi^2 = 1.12$), lexical decision ($\chi^2 = 1.83$), or semantic categorization tasks ($\chi^2 < 1$). Thus, there were no target item or target order effects. Next, I examined prospective remembering across ongoing task contexts, with particular interest in levels of performance during the semantic categorization task, which was weakly associated with the prospective memory intention during encoding.

Prospective memory performance across contexts is illustrated in Figure 1.

Figure 1



For the dependent measure of proportion of Q presses in response to a target cue (see Figure 1), a 3 x 2 x 2 mixed ANOVA was conducted that included the within subjects variable of ongoing task (living/nonliving decision, lexical decision, and semantic categorization) as well as the between subjects variables of encoding time (morning or evening) and delay (short or long). There was a main effect of ongoing task, $F(2, 184) = 3.15$, $MSE = .05$, and simple effects tests demonstrated that prospective memory performance was greater during the semantic categorization task ($M = .40$) than the living/nonliving task ($M = .31$), $F(1, 95) = 5.39$, $MSE = .05$, and the lexical decision task ($M = .33$), $F(1, 95) = 4.13$, $MSE = .05$, but the latter two tasks did not produce differential performance levels ($F < 1$). There was also a delay condition main effect, F

(1, 92) = 6.10, $MSE = .46$, and, critically, the main effects were qualified by a significant 3-way interaction between encoding time, task, and delay, $F(2, 184) = 4.46$, $MSE = .05$. The interaction is illustrated in Figure 1. A primary reason the interaction obtained was that there was a main effect of task (assessed by simple effects tests) only in the sleep delay condition, $F(2, 46) = 5.55$, $MSE = .05$ ($F_s = 2.03$, < 1 , and 1.43 , in the short morning delay, short evening delay, and wake delay conditions, respectively). In the sleep delay condition, prospective memory performance was greater during the semantic categorization task than the living/nonliving task, $t(23) = 3.16$, and the lexical decision task, $t(23) = 2.56$, and the latter two did not differ ($t < 1$).

I also examined prospective memory performance in each of the three ongoing tasks by conducting 2 x 2 ANOVAs that included encoding time (morning or evening) and delay (short or long) as between subjects factors. These tests only demonstrated delay condition main effects in the lexical decision, $F(1, 92) = 8.99$, $MSE = .18$, and living/nonliving, $F(1, 92) = 4.25$, $MSE = .18$, tasks, but that in the semantic categorization task, a significant encoding time by delay condition interaction obtained, $F(1, 92) = 4.72$, $MSE = .20$. This interaction obtained because prospective memory performance was much lower in the wake delay condition than sleep delay condition, $t(47) = 2.63$, and the (collapsed) short delay condition, $t(71) = 2.77$; interestingly, the sleep delay and short delay conditions did not differ (both $M_s = .50$; $t < 1$). Thus, sleep primarily augmented prospective memory performance during the context that was weakly associated with the prospective memory intention during encoding. This result was not predicted by a simple interference theory (cf. Jenkins & Dallenbach, 1924), but was consistent with the binding view that argues that sleep is involved in the restructuring

of memory representations (Brankack et al., 2009; Mograss et al., 2008) and the strengthening of weak associative links (Stickgold et al., 1999), such as those produced by temporal proximity (Drosopoulos, Windau, et al., 2007). To further understand how sleep-dependent binding improved prospective remembering during the semantic categorization task I examined whether participants relied on spontaneous retrieval processes or monitoring to retrieve their intentions.

Cost before and after target cues. The present experiment was designed to evaluate whether prospective remembering was supported by spontaneous retrieval (predicted by the multiprocess theory) or monitoring (predicted by monitoring theory) processes by examining whether cost emerged before target cues (thereby suggesting reliance on monitoring processes). Each ongoing task block included 150 filler trials and 2 target events, organized such that 100 filler trials preceded the first target trial and then 50 more filler trials intervened between the first and second target trials. Monitoring theory predicts (the presence of and) a relation between cost preceding a target cue and the probability of pressing Q in response to that target cue. Multiprocess theory predicts that no such relation should emerge because spontaneous retrieval processes allow an intention to be reflexively retrieved when a cue is focally processed.

For the dependent measure of mean reaction times preceding the first target cues (i.e., the first 100 trials in each ongoing task block), a 3 x 2 x 2 x 2 mixed ANCOVA (controlling for mean session-1 reaction times on the first 100 trials in each ongoing task) was conducted in which task (living/nonliving, lexical decision, semantic categorization) was a within subject factor and encoding time (morning or evening), delay (short or long), and condition (prospective memory or control) were between subjects factors.

There were no significant effects [largest $F(2, 224) = 2.84$, $MSE = 3415.82$, for the task by encoding time by delay interaction] and estimated cost (i.e., difference between prospective memory and control groups after controlling for session-1 differences) was very low during the living/nonliving (estimated $M_{cost} = 15$ ms), lexical decision (estimated $M_{cost} = 23$ ms), and semantic categorization (estimated $M_{cost} = 13$ ms) tasks. This result suggests that participants relied on relatively automatic spontaneous retrieval processes, instead of the more effortful monitoring processes, to retrieve their prospective memory intentions.

Because the control condition was nested within the short delay groups, the above ANCOVA did not test for group differences in cost. To test for such differences, a series of hierarchical regressions were conducted only in the prospective memory groups. After covarying the corresponding ongoing task's session-1, pre-target mean reaction times, the delay and encoding time main effects were entered (dummy coded) in step 2, followed by the interaction term in step 3. These steps did not explain additional session-2, pre-target mean reaction time variance (i.e., an estimate of cost) during the living/nonliving task (largest $F(1, 91) = 3.23$, $\Delta R^2 = .013$, $p = .08$, for the interaction), lexical decision task (all $Fs < 1$), or semantic categorization task [largest $F(2, 92) = 2.39$, $\Delta R^2 = .011$, $p = .10$, for the main effects]. Thus, pre-target cost did not vary depending on retention interval and the prospective memory benefit in the sleep delay condition (especially during the semantic categorization task) cannot be explained by increased monitoring in that condition.

To establish that the previous null effects were not due to inadequate power to detect cost I next examined whether cost would emerge following the first target cue (i.e.,

the 50 trials following the first target event and preceding the second target event). Rather than implicating preparatory monitoring (which would be suggested by *pre*-target cost), *post*-target cost may indicate action execution, switch costs, and/or intention rumination (Marsh, Hicks, & Watson, 2002). To investigate post-target cost I conducted a 3 x 2 x 2 x 2 mixed ANCOVA that controlled for the corresponding session-1 ongoing task reaction times, included task (living/nonliving, lexical decision, semantic categorization) as a within subjects factor, and included encoding time (morning or evening), delay (short or long), and condition (prospective memory or control) as between subjects factors. In addition to the main effect of task, $F(2, 224) = 5.66$, $MSE = 8387.64$ (Huynh-Feldt), there was a main effect of condition, $F(1, 112) = 9.35$, $MSE = 16574.48$, such that estimated post-target cost (based on statistically adjusted means) was high in the living/nonliving task (estimated $M_{cost} = 53$ ms), lexical decision task (estimated $M_{cost} = 41$ ms), and semantic categorization task (estimated $M_{cost} = 61$ ms). There were no other significant effects (next largest $F = 2.13$ for the encoding time by delay interaction), and the lack of a significant task by condition interaction ($F < 1$) demonstrated that post-target cost was similar in each task. Thus, participants only devoted attention to the prospective memory task and away from the ongoing task (resulting in post-target cost) *after* the first target cue.

For the sake of completeness, I also conducted hierarchical regressions on session-2 post-target reaction times in the same manner as the pre-target reaction time regressions. The delay main effect, encoding time main effect, and delay by encoding time interaction did not explain additional session-2 post-target variance (i.e., an estimate

of cost) during the living/nonliving task (all F s < 1), lexical decision task (all F s < 1), or semantic categorization task [largest $F(1, 91) = 2.37$, $\Delta R^2 = .013$, for the interaction].

To further demonstrate the relation (or lack thereof) between prospective memory performance and cost, a series of partial correlations were conducted between mean session-2 reaction times before target cues (i.e., first 100 trials in each task) and following target cues (i.e., last 50 trials in each task), and the probability of pressing the Q key for the first and second target cue (the corresponding session-1 ongoing task reaction times were partialled). The results were consistent across ongoing tasks. First, in each ongoing task, there was no significant relation (r s (93) = .05, .11, and .13 for the living/nonliving, lexical decision, and semantic categorization tasks, respectively) between pre-target cost and prospective memory performance on the first target in each task. Of further interest was the highly reliable, positive association between prospective memory performance on the first target trial and post-target cost (r s (93) = .37, .36, and .41, for the living/nonliving, lexical decision, and semantic categorization tasks, respectively). Thus, prospective remembering was associated with post-target, but not pre-target, cost.

The results for the partial correlations between performance on the second target and cost on the 50 trials preceding that trial were also interesting. Though the cost relation was positive and significant in the living/nonliving, $r(93) = .20$, lexical decision, $r(93) = .28$, and semantic categorization, $r(93) = .29$ tasks, this relation became negligible (-.09, .10, .01 for living/nonliving, lexical decision, and semantic categorization tasks, respectively) after controlling for first target performance in the corresponding ongoing task. Controlling for performance on the first target is necessary

because prospective memory performance on the first target cue in each task can parsimoniously explain both target-2 performance (mean target 1-target 2 correlation was $r = .67$) and subsequent cost. These results converge on the conclusion that pre-target cost was not necessary for focal prospective memory performance (cf. Smith et al., 2007) and compel the conclusion that spontaneous retrieval processes that required no pre-target cost to trigger intention retrieval supported prospective remembering.

Additional analyses. I also examined group differences in hours slept, SCL-90 score, MEQ score, proportion of notecards returned, and napping frequency. The delay and encoding time conditions did not differ (or interact) in hours slept the night before the memory tests (all F s < 1; M s = 6.81, 7.00, 6.82, and 6.55 hours, for the short morning delay, short evening delay, wake delay, and sleep delay conditions, respectively), or on SCL-90 score (largest $F = 1.35$ for the encoding time main effect) (M s = 53.75, 61.32, 42.58, and 53.88 for the short morning delay, short evening delay, wake delay, sleep delay conditions, respectively). For MEQ score, there was a significant encoding time main effect, $F(1, 116) = 5.17$, $MSE = 91.85$, signaling that participants in the morning encoding (M s = 45.66 and 48.96, for the short morning delay and wake delay conditions, respectively) and evening encoding (M s = 42.93 and 43.56 for the short evening delay and sleep delay conditions, respectively) conditions began the experiment closer to their optimal time of day (note, however, that both mean scores fall under the “neutral” classification). Neither the delay main effect ($F(1, 116) = 1.21$, $MSE = 91.85$) nor the encoding time by delay interaction ($F < 1$) was significant.

One additional group difference of interest was whether participants in the wake and sleep delay conditions remembered to return their notecards (that included the subject

ID and testing room numbers) when returning for session 2. A significantly greater proportion of notecards were returned in the wake delay condition ($M = .75$) than the sleep delay condition ($M = .42$), $\chi^2 = 5.49$. Such a result was unexpected but all participants were asked why they thought they forgot their card and at what point they remembered they had forgotten, and their responses helped explain the pattern of results. Interestingly, 43% of the sleep delay participants who failed to return their notecard reported to having forgotten their notecard because they had just woken up and were rushed to leave to come to the second experimental session. These participants reported to having remembered that they had forgotten their notecard before arriving to the experimental room. Therefore, the ability to compare notecard-return performance between conditions was unfortunately confounded by factors such as differential alertness, that did not appear to be an important factor by the time participants began the experimental tasks (as demonstrated by similar ongoing task and working memory performance during the second experimental session).

One potentially important remaining factor was whether participants in the wake delay condition napped during the retention interval. There were 6 participants in the wake delay condition who napped during the retention interval. Because these naps were short in length ($M = 61$ min) and occurred hours after the first session they were unlikely to contain large amounts of quality sleep (e.g., slow-wave-sleep or rapid-eye-movement sleep stages), and therefore would not confer much protection from immediate retroactive interference (Wixted, 2004), or consolidate the memory (Rasch et al., 2007). Indeed, the short nap did not appear to “pollute” the wake delay condition results (see Table 1 and

Figure 1) and the same retrospective and prospective memory results obtained when analyses were conducted without the participants who napped.

In addition to the group difference analyses above I also conducted some individual differences tests. A series of bivariate correlations between proportion of correct Q responses to target cues and performance on the first reading span task ($r(96) = .05$), the second reading span task ($r(96) = .13$), and the symmetry span task ($r(96) = .10$), demonstrated no significant relation between prospective memory performance and working memory performance. This result was consistent with the finding that prospective remembering did not require attention-demanding monitoring. Syllable recall was correlated with prospective memory performance, $r(96) = .28$, but this effect was eliminated after controlling for encoding time and delay conditions ($p > .10$). Furthermore, the only notable association between prospective memory performance and a questionnaire or questionnaire item was for frequency of vigorous exercise, $r(96) = .18$, $p = .08$. This association became significant, $\beta = .20$, $p < .05$, after controlling for delay, encoding time, and the delay by encoding time interaction, (see Clarkson-Smith & Hartley, 1989, for evidence that exercise may improve cognitive functioning].

Discussion

In the present study, sleep-related benefits were observed for both free recall of syllables (Jenkins & Dallenbach, 1924) and memory for performing an action in response to a cue. In the prospective memory task, a sleep interval (relative to a similar length wake interval) increased the probability that an individual would at some point during the ongoing tasks remember to perform the prospective memory intended action (similar to having to remember to take medication at some point during breakfast). Furthermore,

sleep-related prospective memory benefits were pronounced during the semantic categorization task. Differential engagement of monitoring could not explain the sleep-related benefit or prospective remembering in the other delay conditions. Collectively, these results have practical and theoretical implications for prospective memory and sleep research.

Sleep and Memory

The present experiment aimed to legislate between three views (self-reminder view, interference view, and binding view) of prospective memory performance across sleep and wake delays. By embedding the prospective memory cue in several ongoing task contexts in the present experiment and not specifically linking the prospective memory intention to any given context, a test of the structure (i.e., mental representation) of the prospective memory intention following sleep and wake delays was possible. Indeed, the ability to compare prospective memory performance across contexts was a primary advantage of using a prospective memory paradigm to examine the structural effect of sleep on a memory and legislate between the self-reminder, interference, and binding views.

The self-reminder view argued that prospective remembering should improve over longer delays if the cumulative effect of self-reminders leads to greater attention being devoted to the prospective memory task (Hicks et al., 2000). According to this view, because more conscious self-reminders should occur while awake than while asleep, there should be an increase in prospective remembering in the wake delay condition relative to the sleep delay condition that is paralleled by an increase in cost. The results of the present experiment failed to support the self-reminder view because

cost did not differ between delay groups (perhaps because focal cues were used) and prospective memory performance was better following sleep than wake.

The second hypothesis tested was Jenkins and Dallenbach's (1924) view that sleep improves memory by protecting it against retroactive interference. According to the interference view, prospective memory performance should be better in the sleep delay condition than the wake delay condition, irrespective of the context in which the prospective memory cue appeared. One initial result supported this prediction. Not only did more participants remember to perform the prospective memory action at least once after a sleep delay than an equally long wake delay, but the proportion of participants that *ever* remembered to perform the prospective memory task did not decline from a 20-min short delay to a 12-hr delay that included nighttime sleep. The practical implication is that delayed intentions (such as remembering to call your mother on her birthday) are best encoded in the evening and executed following a full night's sleep. However, not all results were consistent with the interference view's predictions. Specifically, the finding that the power of sleep in boosting prospective remembering was largely due to performance during the semantic categorization task (Figure 1) suggests that the interference view does not capture the complexity of sleep's effect on memory.

The binding view, which is a variant of consolidation theory, suggests that sleep increases associative binding. According to this view, "the brain is functionally organized to preferentially activate weak associative links that may aid in the strengthening of... [the] labile memory trace" (Mogras et al., 2008, p. 430; also see Stickgold et al., 1999). The binding view therefore predicted that sleep's benefit on prospective memory would be largely, if not solely, localized to the ongoing task context in which a weak association

was formed. Because the semantic categorization task immediately preceded prospective memory encoding during the first experimental session, but was never explicitly linked to the prospective memory intention, the association between the semantic categorization task and prospective memory task could be expected to be present but weak (during encoding) in the wake conditions (Drosopoulos, Windau, et al., 2007). Interestingly, prospective remembering during the semantic categorization task was so high in the sleep delay condition that there was no decline in performance relative to the short (approximately 20-min) delay conditions. This result did not obtain during the living/nonliving or lexical decision tasks (i.e., only a delay main effect obtained), thereby disfavoring simple interference explanations of sleep benefits. However, the finding was consistent with the idea that sleep primarily benefits memory through a binding process that strengthens weak associations. Because of the temporal proximity of the semantic categorization task to prospective memory encoding, this association was selectively strengthened during sleep (Drosopoulos, Windau, et al.), thereby leading to a substantial increase in prospective remembering in that context. In a sense, sleep gave the intention a context in which it could be executed.

Theoretical Implications for Prospective Memory

The results of the present experiment have further implications for how individuals remember to perform intended actions using real-world-relevant retention intervals. Whereas monitoring theory predicts that monitoring (which produces cost) must precede a target cue for an intention to be retrieved, the multiprocess theory argues that spontaneous retrieval processes may support prospective remembering even when an individual is devoting no attention toward monitoring for cues (i.e., in the absence of pre-

target cost). The results of the pre- and post-target cost analyses demonstrated that cost was absent preceding the first target cue in each ongoing task. This finding cannot be explained by insufficient power to detect cost (cf. Smith et al., 2007) because significant cost was observed *following* the first target cue (in each ongoing task). Furthermore, there was no correlation between cost preceding target events and the likelihood of pressing Q in response to that target event. Again, the failure to find a correlation between prospective memory performance and cost preceding target events cannot be explained by insufficient power because highly reliable correlations obtained between prospective memory performance and cost *following* target cues. These results collectively suggest that monitoring processes are not always required for prospective memory retrieval (especially not for focally processed cues, McDaniel & Einstein, 2007). The present results thus converge on the conclusion that, in the absence of monitoring for prospective memory cues, focal processing of cues may spontaneously trigger retrieval of intentions. Furthermore, the finding that the sleep benefit during the semantic categorization task was not due to monitoring suggests that, during sleep, the association between the semantic categorization context and the prospective memory intention was selectively enhanced, thereby leading to greater focal processing of the prospective memory cue during semantic categorization (see also the encoding specificity hypothesis, Tulving, 1983). The probability of spontaneously retrieving an intention therefore not only depends upon encoding and retrieval conditions, but also depends upon off-line consolidation processing during sleep.

Conclusions and Future Directions

The results of the present research demonstrated that many factors determine whether a memory is retrieved. Simple explanations for prospective memory retrieval (e.g., monitoring theory, Guynn, 2003; Smith, 2003) and sleep-related memory benefits (Jenkins & Dallenbach, 1924) are simply not adequate. More adequately complex explanations for prospective memory retrieval and sleep-dependent memory benefits are offered by the multiprocess theory (McDaniel & Einstein, 2007) and consolidation theories (Brankack et al., 2009; Charlton & Andras, 2009; Rasch et al., 2007), respectively.

The benefits of sleep to memory are likely to be complex and to interact with many factors. Therefore, the best theory of sleep and memory will surely incorporate both understanding of the physiological processes occurring during sleep and the behavioral literature on memory retrieval processes. By doing so we may understand what and how information is consolidated as well as how and when sleep-dependent consolidation translates to greater remembering.

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