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Continuous Re-Exposure to Environmental Sound Cues During Sleep Does Not Improve Memory for Semantically Unrelated Word Pairs

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Abstract

Two recent studies illustrated that cues present during encoding can enhance recall if re-presented during sleep. This suggests an academic strategy. Such effects have only been demonstrated with spatial learning and cue presentation was isolated to slow wave sleep (SWS). The goal of this study was to examine whether sounds enhance sleep-dependent consolidation of a semantic task if the sounds are re-presented continuously during sleep. Participants encoded a list of word pairs in the evening and recall was probed following an interval with overnight sleep. Participants encoded the pairs with the sound of “the ocean” from a sound machine. The first group slept with this sound; the second group slept with a different sound (“rain”); and the third group slept with no sound. Sleeping with sound had no impact on subsequent recall. Although a null result, this work provides an important test of the implications of context effects on sleep-dependent memory consolidation.

Keywords

sleep; context; consolidation; learning

Memory can be influenced by environmental cues. Often taken for granted is the fact that recall is impaired by changes in the testing environment relative to the learning episode (Abernathy, 1940; Standing, Bobbitt, Boisvert, Dayholos, & Gagnon, 2008). Likewise, if material is learned with music, recall is enhanced if this music is present at recall relative to an environment with different music or without music (Smith, 1985). These environmental contexts are thought to trigger memories through associations formed during encoding (Henke, Weber, Kneifel, Wieser, & Buck, 1999).

Although context effects have been repeatedly demonstrated (reviewed in Smith & Vela, 2001), recent studies have illustrated that environmental cues can also enhance the consolidation of memories over sleep. Rasch, Büchel, Gais, and Born (2007) presented the scent of a rose while participants performed a spatial learning task. The odor was presented

again during SWS in a semicontinuous fashion (30 seconds on, 30 seconds off). Participants who slept with the odor recalled 12% more pairs than those that had no experimental odor present during sleep.

More recently, Rudoy, Voss, Westerberg, and Paller, (2009) used discrete sounds to boost memory consolidation. Participants memorized the location of objects on a screen. Each object was presented with a related sound cue (e.g., “meow” for cat). During the SWS portion of a subsequent nap, a subset of the sounds was replayed. Recall of locations of the objects whose sounds were re-presented during the nap was greater than recall for items for which the sound was not re-presented.

Motivating this study was the question of whether such environmental effects can be used academically to enhance learning. This research was directly motivated by a group of educators and students who proposed that these results suggest a simple strategy to enhance academic performance: Study with music followed by sleep with the music will enhance subsequent test performance. Unrecognized by these individuals were the technical limitations associated with yoking cues to certain physiological sleep states. Whether the environmental context can reactivate memories if presented throughout sleep has not been examined. Although Rasch et al. (2007) posited that cues might be habituated if present during the whole sleep bout, continuous environmental cues from the learning environment (e.g., lighting, room arrangement, background sounds) have been shown to enhance performance even if present continuously during a recall episode (Abernathy, 1940; Standing et al., 2008; Weir & May, 1988). Moreover, contextual reactivation has only been demonstrated to enhance spatial learning tasks. Whether semantic learning—known to benefit from sleep (Ellenbogen, Hulbert, Jiang, & Stickgold, 2009) and more typical of academic learning—is similarly enhanced by re-presentation of environmental cues during sleep, has not been examined.

To directly assess whether continuous environmental cues from the learning environment can enhance consolidation for semantic memories, we presented sounds from a sound machine during encoding and subsequent sleep. Sound machines were selected (over, for instance, music), given that they are widely available, inexpensive (\$15 or \$3 for a smart phone application) and, therefore, practical for students preparing for exams. We examined the hypothesis that environmental cues from the learning environment can enhance consolidation of word pair learning relative to conditions in which the context is not re-presented during sleep.

METHODS

Participants

Participants were 77 (48 female and 29 male) students ranging in age from 18 to 28 yrs (mean = 20.8 yrs; $SD = 2.2$ yrs). All participants reported no history of sleep or neurological disorders and were not taking medications that affect sleep. Procedures were approved by the local ethical review board.

Participants were separated into five groups (Table 1). To confirm that sleep-dependent performance changes are present on this task, two groups performed the experiment over three sessions. The AM-PM-AM group ($n = 12$) performed the first session in the morning (between 8:00 a.m. and 9:30 a.m.), and the second and third sessions took place 12 and 24 hours following the first session, respectively. The PM-AM-PM group ($n = 14$) started the experiment in the evening, the second session started 12 hours later following overnight sleep, and the third session started 24 hours after the first session.

To assess whether oversleep changes are enhanced by contextual sound cues, three groups performed the experiment over two sessions with sound manipulations. All of these groups performed the first session in the evening (between 8:00 p.m. and 9:30 p.m.) and the sound of “the ocean” was presented at low levels during encoding for all participants. The second session took place 12 hours later. The two-session groups differed with respect to the sound present during overnight sleep. Participants in the Ocean- Ocean group ($n = 18$) slept with “the ocean” sound during the entire overnight interval. The Ocean- Rain group ($n = 14$) slept with a different sound (“rain”). The Ocean- Quiet group ($n = 19$) slept without experimental sounds.

Task and Procedure

For each participant, word lists were generated by randomly selecting 64 words from a list of 168 single-syllable, high-frequency, concrete nouns (see Appendix). Words were randomly paired to create 32 semantically unrelated word pairs (e.g., cat–coach). During the encode phase, word pairs were presented with one word centered on each half of a computer monitor. Each pair was displayed for 4 seconds. Participants were instructed to pay attention to the word pairs presented on the screen, because they would be asked to recall them later. To facilitate learning, participants were instructed as follows: “To remember the pairs, it is helpful to think of associations between the pairs. For example, if the words were frame–shoe, you might imagine a framed painting of a shoe.” All groups performed the encode phase with the “ocean” selection from a sound machine (HoMedics, model SS-2000) continuously playing at audible levels (30 dB).

The immediate recall phase began shortly after encoding. To equate to delayed recall conditions, no sound was presented during immediate recall. During immediate recall, participants were presented with a single word from the pairs presented during the encode phase and were asked to type the corresponding word. Feedback (“correct!”) was provided if the appropriate response was entered. If answered incorrectly, the correct answer was displayed for 3 seconds. Participants practiced recalling the list of pairs in a randomized order until performance at the end of the list was more than 62% or until they reached a maximum of five repetitions of the list. Delayed recall was identical to immediate recall, except that participants only went through the list once and no feedback was provided.

Following the first session, the Ocean–Ocean and the Ocean–Rain group participants took the sound machine home with instructions on the use of the machine, including that the sound should be turned on at bedtime and should be turned off when they wake. Participants in the AM-PM-AM group, who performed the first session in the morning, were asked to

return to the laboratory following a 12-hour daytime interval in which they were instructed to refrain from napping.

In the second session, after completing the sleep diary, all groups performed the delayed recall phase of the task. The sound machine was not used during this phase for any groups and the testing room was essentially silent. Following delayed recall of list 1, participants in the three-session groups repeated the encode and immediate recall phases with a new word list. Both groups returned to the lab 12 hours later for the delayed recall phase of list 2.

Sleep Assessments

After the sleep interval, participants completed a sleep diary, which probed subjective estimates of bedtime, waketime, and wake after sleep onset (Smith, Nowakowski, Soeffing, Orff, & Perlis, 2003). Sleep diaries have been shown to have high levels of agreement with polysomnography (Rogers, Caruso, & Aldrich, 1993). In the final session, participants completed the Pittsburgh Sleep Quality Index (Buysse, Reynolds, Monk, Berman, & Kupfer, 1989).

RESULTS

Immediate Recall of Word Pairs

It is important to first assess whether accuracy prior to the intersession interval differed across groups. Accuracy (percent correct) at the end of the immediate recall phase (last 30 pairs) provides an estimate of learning prior to the intersession interval. Most participants reached the performance criterion in two to three presentations of the list (mean = 2.9). However, some participants did not reach criterion after five presentations (approximately three per group) or met the criterion in the middle of a list, but the criterion test was only performed after each full presentation of the list resulting in more than 62%. Nonetheless, the average recall at the end of the immediate recall phase (last 30 pairs) was 61.8% ($SD = 1.2\%$) and did not differ across groups ($F(4,72) = .05, p = .99$; Figure 1). Participants in the three-session groups performed better at the end of immediate recall of the second list relative to the first list ($F(1,24) = 6.02, p = .02$; group $\times$ session: $F(1,24) = .11, p = .75$).

Performance Changes Over Sleep Versus Wake

To validate the claim that performance on this task is modulated by sleep, we probed learning following 12 hours with sleep relative to 12 hours spent awake in the three-session groups. Participants performed significantly better following the interval with sleep relative to the interval awake (Figure 1). In a two-way ANOVA comparing delayed recall accuracy across groups (AM-PM-AM vs. PM-AM-PM) and intersession interval types (sleep vs. wake), the main effect of interval type was significant ($F(1,24) = 17.1, p < .004$). The main effect of group was not significant ($F(1,24) = 2.0, p = .17$; group $\times$ interval type: $F(1,24) = 1.7, p = .21$).

To account for variability in initial learning, we also compared the change in recall across sessions. Specifically, accuracy for delayed recall was subtracted from accuracy at the end (last 30 pairs) of immediate recall in the prior session. The change in recall was significantly

different for the wake-sleep intervals ($F[1,24] = 18.8, p < .001$). The main effect of group was significant ($F[1,24] = 9.1, p = .006$), driven by a significantly greater decrement in recall between the second and third sessions for the PM-AM-PM group (interaction: $F[1,24] = 6.0, p = .02$; Figure 2).

Influence of Continuous Contextual Sound Cues on Sleep-Dependent Consolidation

A goal of this study was to investigate whether continuous sound can provide an environmental contextual cue to enhance sleep-dependent consolidation. As depicted in Figure 2B, there was no significant difference in the change in recall across sessions based on the presence or type of sound in the overnight interval ($F[2,48] = 0.13, p = .88$). Power estimations revealed that based on our study design and the number of participants, we exclude medium effect sizes of $F = .17$ ($p = .05$) with a probability of more than 80% in our study.

Subjective Sleep Reports

The lack of environmental benefits for the Ocean- Ocean condition may reflect that the experimental sounds may have disrupted sleep. However, there was no difference in total sleep time ($F[4, 69] = .79, p = .54$), number of awakenings ($F[4, 69] = .99, p = .42$), or subjective sleep quality ($F[4, 69] = 1.2, p = .32$) across groups. Average sleep time was 6.7 hours ($SD = 1.4$), 6.2 hours ($SD = 1.0$) and 6.6 hours ($SD = 1.6$) for the Ocean–Ocean, Ocean–Rain, and Ocean–Quiet groups respectively.

DISCUSSION

The growing literature illustrating cognitive changes following sleep suggests a strategy for improving academic performance: Sleep following learning will enhance recall relative to when learning and recall are separated by wake. Environmental cues present at learning have also been shown to enhance recall if re-presented at recall (Abernathy, 1940; Smith, 1985; Standing et al., 2008). Prominent recent reports suggest that sleep-dependent memory processes can similarly be enhanced with environmental cues (Rasch et al., 2007; Rudoy et al., 2009). These cues are thought to prime the related memory during sleep or contextual reactivation of the memory (Chun & Jiang, 2003; Chun & Phelps, 1999; Henke et al., 1999).

The purpose of this study is to investigate whether a similar context effect may benefit academic performance. For this reason, we examined whether continuous sound, re-presented throughout the overnight sleep interval, can similarly enhance sleep-dependent changes in memory. The sound machines used here are widely available, inexpensive, and easy to use. Moreover, as we were particularly interested in the formation of new memories, we used a semantically unrelated word pair learning task. This task is representative of many academic learning objectives (i.e., learning a new language). Although we failed to find context-dependent enhancement of sleep-dependent memory consolidation, the present results provide an important test of the simple interpretation of past results for educators and suggest important avenues for future research.

Sleep-Dependent Consolidation of Semantically Unrelated Word Pair Learning

The three-session groups were included to examine whether sleep-dependent processes act on semantically unrelated word pair learning. Participants remembered more word pairs following a 12-hour interval with sleep relative to a 12-hour interval awake. We consider three accounts for better performance following sleep relative to wake. First, performance may have been better in the morning session because of circadian influences on attention (Valdez, Ramirez, Garcia, Talamantes, & Cortez, 2010) or arousal (Silver & Lesauter, 2008). This explanation seems unlikely given that there was no difference in immediate recall in the first session when performed in the morning (AM-PM-AM) relative to the evening (PM-AM-PM).

Alternatively, performance changes following sleep may illustrate active processing of the memory over sleep, or sleep-dependent memory consolidation. Memory consolidation is often marked by performance increases following sleep (Stickgold, 2005). Using the paired-associates task, Tucker et al. (2006) reported that recall improved by 45% following a nap interval and only 28% following an equivalent wake interval. However, given that feedback is provided throughout the task in the present experiment and in prior studies of associative word pair learning (Plihal & Born, 1999; Tucker et al., 2006), subsequent improvements may reflect additional learning from feedback over this phase in addition to or rather than consolidation. As such, one cannot reliably determine whether enhancement following the break reflects learning from feedback or sleep-dependent memory consolidation. It is likely that feedback from associated word pair learning is more effective because it raises the activation strength of existing memories, whereas feedback in the unrelated task relies on establishing new memories.

A third account for the relative improvement following sleep is that sleep may protect memories from interference. In fact, delayed recall following sleep did not significantly differ from immediate recall in the prior session (PM-AM-PM group: $t(11) = .39, p = .70$; AM-PM-AM group: $t(13) = .26, p = .80$). Without *polysomnography* (a montage of physiological measures during sleep), which can be used to associate specific sleep states with performance changes (Stickgold, 2005), we cannot rule out this alternative.

Neuroimaging (Henke et al., 1999) and human lesion studies (Chun & Phelps, 1999) support an active role of the hippocampus in forming novel associations, and sleep-dependent processing is thought to be greatest for hippocampal-dependent tasks (Marshall & Born, 2007; Spencer, Sunm, & Ivry, 2006), suggesting that nonassociative learning should be strengthened by sleep. However, in this study, the “sleep” interval contained both sleep (approximately 6 hrs) and wake (approximately 6 hrs). As such, we hypothesize that decay over wake and consolidation oversleep resulted in a net maintenance of performance. Admittedly, however, this is speculative and requires further investigation.

Context Effects on Sleep-Dependent Processing of Semantically Unrelated Word Pair Learning

Although we found better recall following an interval with sleep, the benefit of the sleep interval was not enhanced by the presence of environmental cues from the learning context.

Sleep diaries suggest that the sound did not disturb or alter sleep: Subjective reports of sleep quantity and quality did not differ across groups. Although these results may seem at odds with previous studies (Rasch et al., 2007; Rudoy et al., 2009), we posit that the null result may reflect one or more restriction of this effect that may limit the translation of such research to academic settings.

First, it is possible that the sounds we selected may have triggered other memories related to the sounds rather than the encoding event. For instance, the sound of “the ocean” may have activated memories of a summer vacation instead of the encoding event or in addition to the encoding event. As such, cue-associated memory reactivation may have been for the memory of the vacation rather than encoding. Although we cannot rule out this account, we consider this unlikely. For one, the sounds produced by the sound machine are digital sounding, which means the sounds are only vaguely similar to any sounds in nature. Additionally, environmental cues shown to enhance recall in other studies are not necessarily novel (e.g., Mozart and jazz music; Smith, 1985) and room color (Weir & May, 1988). Cues shown to enhance sleep-dependent memory consolidation are likewise commonplace: The odor used by Rasch et al. (2007) was that of a rose, and sounds used by Rudoy et al. (2009) included the whistle of a teakettle and a meow of a cat. As such, we do not believe the lack of novelty for the environmental cues used here was a limitation.

Second, it may be easy to overlook another difference between these earlier studies on enhancement of sleep-dependent consolidation through environmental cues and our present translational test. Specifically, participants slept in their own beds rather than in a laboratory. As such, we may expect sleep to have been greater in quantity and quality than in previous studies, thereby allowing significantly more memory processing even for those without the re-presentation of environmental cues. Although we cannot rule out this possibility, it is perhaps unlikely given that performance was less than 70% after sleep, suggesting room for further improvement.

Third, the lack of environmental cueing effect from the re-presentation of the sound during sleep may lend further to the hypothesis presented previously; that is, sleep may not play an active role in memory processing for nonassociative learning, rather, sleep may have served to passively protect performance from interference. As such, the null result for the sound conditions may be indication of absent sleep-dependent consolidation for this task. Likewise, our task may not be amenable to contextual effects. Studies assessing contextual enhancement of sleep-dependent consolidation used an object location task (similar to a memory game; Rasch et al., 2007; Rudoy et al., 2009). Although a wealth of tasks has been shown to benefit from context effects, the benefit is likely task dependent. A meta-analysis of these studies suggests that context effects are greatest for tasks that do not require associative processing during encoding (i.e., “encoding orientation”; Smith & Vela, 2001). Instructing participants to create associations for the semantically unrelated pairs may have minimized the integration of the environmental context into the memory. Although much is known of the limitations on the tasks and cues amenable for enhancing recall, whether these same features are necessary for enhancing consolidation during sleep is a subject for future research.

Fourth, re-presentation of environmental cues may work in a task-specific way. Previous studies of such enhancement effects have only used a spatial learning task. Although sleep-dependent changes in word pair learning have been demonstrated repeatedly (Ellenbogen et al., 2009; Plihal & Born, 1997; Plihal & Born, 1999; Tucker & Fishbein, 2008) using similar procedures as that used here (Ellenbogen et al., 2009), environmental cues may act differently on spatial and semantic learning tasks. However, given that both tasks are expected to draw on hippocampal resources for encoding, this seems unlikely.

Finally, the lengthy presence of the environmental cue during sleep may have allowed the participants to habituate to the sounds prior to SWS. Rasch et al. (2007) re-presented the odor selectively only during SWS and in 30-second on-and-off bouts to prevent habituation. Likewise, Rudoy et al. (2009) presented brief (200–500 ms) sounds once every 5 seconds during SWS. By presenting the sound throughout the night in this study, participants may have habituated to this sound prior to SWS, thereby prohibiting the usefulness of the cue. A study specifically contrasting continuous and discrete sounds is necessary to determine whether habituation prevents oversleep context effects given that habituation has not been shown to limit context effects on recall.

CONCLUSIONS

In summary, this study adds two valuable contributions to education psychology. First, it provides the first demonstration of improved recall of semantically unrelated memories following sleep. Although it remains unclear as to whether this benefit of sleep reflects memory enhancement or protection (or both), initial performance measures rule out the possibility of circadian accounts. Given that this task more accurately captures most academic learning, this is a significant point of insight. Second, by testing the effects of a widely available sound as an environmental cue, we provide the first test of how context effects on consolidation may be used more broadly. The null result in this respect suggests that educators should take caution in promoting environmental cues as a means to enhance learning until more research is available.

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Appendix

APPENDIX

Single-word nouns used to form word pairs.

AGE	GLOVE	AIR	GLUE
ARM	GOLD	ART	GRASS
AUNT	HAIR	BAG	HAND
BALL	HAT	BAND	HIP
BANK	HOLE	BAR	HOOK
BATH	HORN	BAY	HOUSE

BEACH	ICE	BEAR	INK
BED	JAM	BELL	JOB
BELT	JOKE	BIKE	KID
BILL	KING	BIRD	LAKE
BLOCK	LAMP	BOAT	LEAF
BODY	LEG	BONE	LID
BOOK	LOCK	BOOT	MAN
BOWL	MAP	BOX	MEAT
BOY	MILK	BREAD	MOON
BRICK	MOUSE	BUS	MOUTH
BUSH	MUD	CAKE	NAIL
CAP	NECK	CAR	NOSE
CARD	NUT	CAST	PAGE
CAT	PARK	CHAIN	PEN
CHAIR	PET	CHEEK	PIG
CHEST	PILL	CHILD	POLE
CHIN	POOL	CHIP	PRIZE
CLOCK	RAIL	CLOUD	RAIN
CLUB	RING	COACH	ROAD
COAL	ROCK	COAST	ROPE
COAT	SACK	COIN	SALT
COW	SAND	CROP	SCALE
CROWN	SEA	CUP	SEAT
DAD	SEED	DAY	SHIP
DESK	SHIRT	DIRT	SKIRT
DISH	SKY	DOG	SNAKE
DOOR	SNOW	DRUM	SONG
DUST	STAIR	EAR	STICK
EGG	SUN	EYE	TEA
FACE	TAIL	FAN	STOVE
FARM	TENT	FIRE	TOE
FISH	TOWN	FLAG	TOY
FLOOR	TRAIN	FLY	TREE
FOOT	VAN	FORK	WALL
FRUIT	WING	GIFT	WOOD
GIRL	YARD	GLASS	ZOO

REFERENCES

- Abernathy EM. The effect of changed environmental conditions upon the results of college examinations. *Journal of Psychology*. 1940; 10:293–301.
- Buyse DJ, Reynolds CF III, Monk TH, Berman SR, Kupfer DJ. The Pittsburgh Sleep Quality Index: A new instrument for psychiatric practice and research. *Psychiatry Research*. 1989; 28(2):193–213. [PubMed: 2748771]

- Chun MM, Jiang Y. Implicit, long-term spatial contextual memory. *Journal of Experimental Psychology. Learning, Memory, and Cognition*. 2003; 29(2):224–234.
- Chun MM, Phelps EA. Memory deficits for implicit contextual information in amnesic subjects with hippocampal damage. *Nature Neuroscience*. 1999; 2(9):844–847. [PubMed: 10461225]
- Ellenbogen JM, Hulbert JC, Jiang Y, Stickgold R. The sleeping brain's influence on verbal memory: Boosting resistance to interference. *PloS One*. 2009; 4(1):e4117. [PubMed: 19127287]
- Henke K, Weber B, Kneifel S, Wieser HG, Buck A. Human hippocampus associates information in memory. *Proceedings of the National Academy of Sciences of the United States of America*. 1999; 96(10):5884–5889. [PubMed: 10318979]
- Marshall L, Born J. The contribution of sleep to hippocampus-dependent memory consolidation. *Trends in Cognitive Sciences*. 2007; 11(10):442–450. [PubMed: 17905642]
- Plihal W, Born J. Effects of early and late nocturnal sleep on declarative and procedural memory. *Journal of Cognitive Neuroscience*. 1997; 9(4):534–547. [PubMed: 23968216]
- Plihal W, Born J. Memory consolidation in human sleep depends on inhibition of glucocorticoid release. *Neuroreport*. 1999; 10(13):2741–2747. [PubMed: 10511433]
- Rasch B, Büche C, Gais S, Born J. Odor cues during slow-wave sleep prompt declarative memory consolidation. *Science*. 2007; 315(5817):1426–1429. [PubMed: 17347444]
- Rogers AE, Caruso CC, Aldrich MS. Reliability of sleep diaries for assessment of sleep/wake patterns. *Nursing Research*. 1993; 42(6):368–372. [PubMed: 8247821]
- Rudoy JD, Voss JL, Westerberg CE, Paller KA. Strengthening individual memories by reactivating them during sleep. *Science*. 2009; 326(5956):1079. [PubMed: 19965421]
- Silver R, Lesauter J. Circadian and homeostatic factors in arousal. *Annals of the New York Academy of Sciences*. 2008; 1129:263–274. [PubMed: 18591487]
- Smith, LJ.; Nowakowski, S.; Soeffing, JP.; Orff, HJ.; Perlis, ML. The measurement of sleep.. In: Perlis, ML.; Lichstein, KL., editors. *Treating sleep disorders: Principles and practice of behavioral sleep medicine*. John Wiley & Sons; New York, NY: 2003. p. 29-73.
- Smith SM. Background music and context-dependent memory. *American Journal of Psychology*. 1985; 98:591–603.
- Smith SM, Vela E. Environmental context-dependent memory: A review and meta-analysis. *Psychonomic Bulletin & Review*. 2001; 8(2):203–220. [PubMed: 11495110]
- Spencer RM, Sunm M, Ivry RB. Sleep-dependent consolidation of contextual learning. *Current Biology: CB*. 2006; 16(10):1001–1005. [PubMed: 16713957]
- Standing LG, Bobbitt KE, Boisvert KL, Dayholos KN, Gagnon AM. People, clothing, music, and arousal as contextual retrieval cues in verbal memory. *Perceptual and Motor Skills*. 2008; 107(2): 523–534. [PubMed: 19093614]
- Stickgold R. Sleep-dependent memory consolidation. *Nature*. 2005; 437(7063):1272–1278. [PubMed: 16251952]
- Tucker MA, Fishbein W. Enhancement of declarative memory performance following a daytime nap is contingent on strength of initial task acquisition. *Sleep*. 2008; 31(2):197–203. [PubMed: 18274266]
- Tucker MA, Hirota Y, Wamsley EJ, Lau H, Chaklader A, Fishbein W. A daytime nap containing solely non-REM sleep enhances declarative but not procedural memory. *Neurobiology of Learning and Memory*. 2006; 86(2):241–247. [PubMed: 16647282]
- Valdez P, Ramirez C, Garcia A, Talamantes J, Cortez J. Circadian and homeostatic variation in sustained attention. *Chronobiology International*. 2010; 27(2):393–416. [PubMed: 20370477]
- Weir W, May RB. Environmental context and student performance. *Canadian Journal of Education*. 1988; 13:505–510.

FIGURE 1.

Recall across groups. Dotted lines reflect intersession intervals. Error bars reflect standard error.

FIGURE 2.

Intersession change in recall (delayed recall accuracy minus accuracy at the end of immediate recall). Error bars reflect standard error.

TABLE 1

Experimental Conditions for Each Group

Group	Session 1	Session 2	Session 3
PM-AM-PM	8 p.m.: encode list 1 with “ocean” immediate recall list 1 (no sound) (sleep: no sound)	8 a.m.: delay recall list 1 (no sound) encode list 2 with “ocean” immediate recall list 2 (no sound)	8 p.m.: delay recall list 2 (no sound)
AM-PM-AM	8 a.m.: encode list 1 with “ocean” immediate recall list 1 (no sound)	8 p.m.: delay recall list 1 (no sound) encode list 2 with “ocean” immediate recall list 2 (no sound) (sleep: no sound)	8 a.m.: delay recall list 2 (no sound)
Ocean-Ocean	8 p.m.: encode list 1 with “ocean” immediate recall list 1 (no sound) (sleep: “ocean”)	8 a.m.: delay recall list 1 (no sound)	
Ocean-Rain	8 p.m.: encode list 1 with “ocean” immediate recall list 1 (no sound) (sleep: “rain”)	8 a.m.: delay recall list 1 (no sound)	
Ocean-Quiet	8 p.m.: encode list 1 with “ocean” immediate recall list 1 (no sound) (sleep: no sound)	8 a.m.: delay recall list 1 (no sound)	