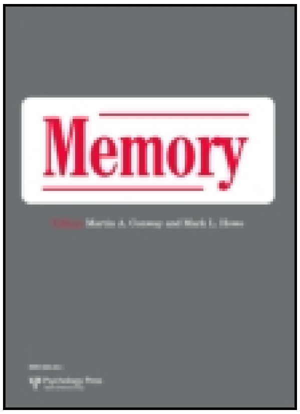

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Long-term memory, sleep, and the spacing effect

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Long-term memory, sleep, and the spacing effect

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Many studies have shown that memory is enhanced when study sessions are spaced apart rather than massed. This spacing effect has been shown to have a lasting benefit to long-term memory when the study phase session follows the encoding session by 24 hours. Using a spacing paradigm we examined the impact of sleep and spacing gaps on long-term declarative memory for Swahili–English word pairs by including four spacing delay gaps (massed, 12 hours same-day, 12 hours overnight, and 24 hours). Results showed that a 12-hour spacing gap that includes sleep promotes long-term memory retention similar to the 24-hour gap. The findings support the importance of sleep to the long-term benefit of the spacing effect.

Keywords: Memory; Spacing effect; Sleep.

The finding that memory is enhanced when study sessions are spaced apart rather than massed is widely documented as the spacing effect (e.g., Benjamin, 2011). This effect can be seen within a single session when to-be-remembered items are separated by interleaving items rather than being presented all at once (e.g., Glenberg, 1976). Additionally, the spacing effect has been shown to have a lasting benefit over many days when the second study session follows the initial session by 24 hours. This 1-day gap between learning and recall has repeatedly been shown to lead to better remembering than a gap less than 1 day when tested for recall following educationally meaningful delays (see Cepeda, Pashler, Vul, Wixted, & Rohourser, 2006, for a review).

For example, a study by Cepeda et al. (2009) found that participants who learned Swahili translations (word pairs) and then waited 24 hours before restudying the word pairs remembered more words at the cued recall 10 days later, compared to those who restudied right away. Thus we know that a short (∼15 minute) gap is less effective than a 24-hour gap. However, neither this study nor other studies in the literature have examined relearning gaps between 3 hours and less than a day (Cepeda et al., 2006), leaving open the question of whether partial-day intervals are sufficient to produce maximal spacing effect benefits for retention intervals about a week long. Thus we know little about the potential benefits from multi-hour within-day spacing or about the effects of sleep on spacing independent from temporal effects per se. A study with gaps of about 12 hours could function to clarify effects of time and sleep as contributors to the 1-day gap benefit; it would help to determine if time, sleep, or a combination of these factors contributes to spacing effect benefits.

One theory that explains the memorial benefit to spaced learning episodes is the contextual variability theory (Estes, 1955; Glenberg, 1979),

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which suggests that internal and external retrieval cues—such as current mood, objects in the environment, and other items that are being learned in the same study session—are associated with items as they are learned. These cues constantly fluctuate over time and will differ if studying takes place in multiple locations or different moods are induced. Temporal separation between learning episodes increases the likelihood that contextual cues associated with a given item will differ, as relatively closely spaced learning sessions will have more cues in common. To the degree that the cues associated with an item during learning match the cues available during test match, recall will increase. Empirical and modelling data predict the level of final test retention based on a complex function of learning episode gap and retention interval between the final learning episode and the test session, with longer learning episode gaps needed as retention interval increases (Cepeda, Vul, Rohrer, Wixted, & Pashler, 2008; Mozer, Pashler, Cepeda, Lindsey, & Vul, 2009). However, if too much time exists between learning episodes, and retention interval is relatively small, performance will decline because cues from the last learning episode contribute more heavily to the probability of successful retrieval.

Study-phase retrieval theory (Hintzman, Summers, & Block, 1975; Murray, 1983; Thios & D'Agostino, 1976), in contrast, states that a moderate level of retrieval difficulty during the restudy phase is required for the spacing benefit. If retrieval is immediate, as in massed conditions, participants will successfully retrieve the material, but the memory trace will not be strengthened due to degree of similarity between the first encoding session and subsequent recall session. In this case little effort is needed to retrieve the item from memory and as a result little reconsolidation of the memory trace will take place. As familiarity with the material declines, such as through spaced retrieval, greater strengthening occurs, because the memory trace requires modification as a result of retrieval difficulty. If retrieval does not occur because too much time has passed since the previous learning episode, no reconsolidation will take place and final test performance will decline. Both the contextual variability and study-phase retrieval theories emphasise the importance of the timing of the second session: if it is too soon or delayed too long, long-term memory will suffer.

As the 24-hour spacing gap includes a sleep episode, the 1-day spacing benefit may be due to an advantageous effect of sleep on memory (e.g., Aly & Moscovitch, 2010; Ekstrand, 1967; Saletin, Goldstein, & Walker, 2011). The exact mechanism by which sleep improves memory is debated (Walker & Stickgold, 2004). Wixted (2004), for example, suggested that the benefit of sleep is an increase in memory consolidation as a result of reduced interference because of the sleep episode. Wixted argues that forgetting is largely the result of proactive and retroactive interference and time spent awake is filled with a variety of activities and experiences that prohibit or delay memory consolidation. In this regard sleep is a period of time essentially free of those activities and experiences, allowing memory consolidation (e.g., Diekelmann & Born, 2010). However, the issue is more complicated than presence or absence of sleep. For example, it has been demonstrated that different aspects of sleep improve some types of memory: 3 hours of early sleep including significant periods of slow-wave-sleep improves verbal memory, while the same amount of sleep later in the night, including REM sleep, does not (e.g., Ekstrand, 1967; Fowler, Sullivan, & Ekstrand, 1973, Plihal & Born, 1997). Therefore verbal memory appears to be improved following a night's sleep due to the role of slow-wave-sleep in memory consolidation.

In summary, many studies have found a beneficial effect of sleep on memory (e.g., Ellenbogen, Hulbeter, Stickgold, Dinges, & Thompson-Schill, 2006; Payne et al., 2012; Takashima et al., 2006) and the results suggest that sleep may improve memory due to decreased interference or to some biological processes involved in memory consolidation during sleep. A critical difference between studies that examine the role of sleep on memory and spacing studies that examine the role of time on memory is the inclusion of an additional test presented at a later time in spacing studies to determine the impact of the spacing gap on long-term retention of those items. Therefore the extent to which sleep is a contributing factor of the long-term benefit associated with the spacing effect is not known.

The objective of the present study was to investigate the contribution of sleep during a spacing gap on long-term retention. Participants were trained to 100% performance at an initial encoding session on unrelated word pairs either in the morning or at night and then, in the same room, they restudied the word pairs either immediately (massed) or after a delay (either 12 or 24 hours). The 12-hour delay either included a night sleep (12 hours overnight) or did not (12 hours same day). In all groups a cued recall test was given approximately 10 days following the restudy session.

This spacing study involved four delay groups: massed, 12 hours same day, 12 hours overnight, and 24 hours. The two 12-hour delay groups held the absolute temporal delay constant and differed as to whether or not sleep occurred. This manipulation investigated whether the effect of absolute time between study sessions is critical for the spacing effect, independent from sleep-related effects, or if sleep plays an essential role in the spacing effect with a long gap and retention interval. Comparing the performance of the two 12-hour groups to the performance of massed and 24 hours spaced groups should determine the relative contribution of sleep to the long-term memory benefit of spacing. To the degree that cues differ after a sleep episode, contextual variability theory predicts increased retention in the 12 hours overnight and 24 hours conditions. To the degree that sleep increases retrieval difficulty, study-phase retrieval predicts the same pattern of increased retention as contextual variability.

METHOD

Participants

Participants were recruited from the participant pool at Santa Clara University and earned partial course credit for taking part. A total of 141 people participated (28% males) with an average age of 19.3 years ($SD = 1.1$). Participants were randomly assigned to one of four different conditions: massed (the study session occurred immediately following the training session), 12 hours spaced (the study session occurred 12 hours later, either same day or overnight), or 24 hours. There were 37 participants in the massed, 33 in the 12 hours same day, 36 in the 12 hours overnight and 35 in 24 hours conditions.

Materials and procedure

Participants learned 20 Swahili–English word pairs of varying parts of speech (similar to Cepeda et al., 2009, Experiment 1). For any given participant, encoding and restudy sessions were completed individually in the same room and on the same computer. The long-term memory test session was either completed online (using the Angel course management system) or in the lab. The 12 hours same day participants completed the encoding session at 9 am and restudy session at 9 pm. The 12 hours overnight participants completed the encoding session at 9 pm and had their restudy session at 9 am the next day. For the other groups encoding and restudy sessions were completed at convenient times on consecutive days (24 hours) or all at once (massed). Thus we have a group who learned and restudied the words in the morning and night (12 hours same day), in the night and the following morning (12 hours overnight), and at various times throughout one day (massed) or two (24 hours). Participants in the overnight conditions (12 and 24 hours) reported having had a regular night's sleep during the delay between the encoding and restudy sessions. Time of day of recall of the final long-term memory test (10 days later) was not controlled for any group, although most participants completed the tests between 9 am and 9 pm ($M = $2:45 pm, $SD = 5.5$ hours) and there was no difference in time of day by condition, thus any confounding effects associated with time of completion of the final test are constant across groups.

The encoding session first presented the 20 Swahili–English word pairs in random order. Word pairs appeared in black all-caps text on a grey background for 7 seconds. Immediately following the first presentation of the 20 word pairs, Swahili words were presented alone one at a time directly above a text field where participants could type the English translation. Word order was randomised (each Swahili word in the list of 20 was presented once without replacement). After entering a response, participants pressed the "Enter" key, received corrective feedback if needed, and then advanced to the next word in the list. The program cycled through all Swahili words until a participant correctly translated the Swahili word twice. After the second correct translation that Swahili word did not appear again in the encoding session. Thus only Swahili words that participants had not responded to correctly twice continued to be presented. The encoding session ended when all 20 Swahili words were correctly translated twice.

Participants completed the restudy session either immediately following the encoding session (massed condition) or 12 or 24 hours later (spaced conditions). The restudy session was a cued recall test with corrective feedback where the Swahili prompt was presented two times. Each Swahili word was displayed directly above a text field where participants could type a response. If the correct response was entered, ''Correct'' (in green text) flashed on the screen below the word pair and the word pair was displayed for 5 seconds. If participants skipped a word or entered an incorrect response, ''Wrong'' appeared briefly (in red text) followed by the correct word pair (displayed for 5 seconds). The restudy session presented the 20-word pair list twice, with the list randomised each time (i.e., all 20 word pairs were presented once, in random order, followed by a second presentation, again in randomised order).

The long-term memory test session was completed by some participants using Angel course management software (i.e., participants completed the final test from any computer); others completed the task in the lab approximately 10 days following the practice session. Because we found no difference in test performance between these two groups, this feature of the study will not be considered further. Each Swahili word was displayed directly above a text field in which participants could type a response (no feedback was provided). This session ended after the entire list was presented once.

RESULTS

Encoding phase

Because of the possible time of day confound in this study, with some participants learning the word pairs in the morning and others at night, we evaluated whether or not there were differences in the initial encoding session that may have affected restudy phase and later test phase performance. We found no difference in number of trials to reach criterion, $F(3, 137) = 2.1$, $p = .11$, with all participants requiring on average 82 trials to reach criterion (massed, $M = 78.9$, $SD = 22.4$, 12 hours same day, $M = 86.1$, $SD = 20.6$, 12 hours overnight, $M = 87.8$, $SD = 24.0$, 24 hours, $M = 76.0$, $SD = 25.5$). Like other studies (e.g., Payne et al., 2012), we did not find any differences in encoding phase performance based on when the learning occurred.

Restudy phase

Although our primary interest is in final test performance, we also expected to find that experimental condition would affect performance in the restudy phase of the experiment, as this component of the study is similar in design to many overnight studies (e.g., Cairney, Durrant, Musgrove, & Lewis, 2011; Payne et al., 2012). The key data from the restudy phase were the percentage of items recalled correctly to the Swahili word prompts. The restudy phase session involved two sequential presentations of the word list with feedback (corrective if they got it wrong) given after each response. In other words, the word list was presented once with feedback and then immediately presented a second time, also with feedback.

Although not of primary interest for the present study, we evaluated performance, measured as percent correct (number correct divided by 20), on the first presentation of the word list for the two 12-hour groups to determine whether performance differed when time was constant and found a significant recall advantage in the overnight condition, $t(67) = 2.97$, $p = .004$. If the 12-hour period included a night sleep participants remembered 85.5% of the words ($SD = 12.6\%$), while same day participants recalled only 73.5% of the words ($SD = 20.5\%$). This finding is similar to other sleep studies showing a memory benefit following a night's sleep. Whether or not this initial benefit to memory in the sleepers or the retrieval difficulty in the same day participants leads to long-term retention is the focus of the final analysis. No further analyses were conducted to compare the remaining groups because interpreting any differences at this stage of the study beyond the comparison of the two 12-hour groups is beyond the scope of the present study, as it does not address the trade-off between immediacy of presentation (in the massed condition) and sleep (in the overnight conditions) in a way that would allow for meaningful interpretation of the second session performance.

The critical issue for our purposes was performance in the second portion of the restudy session (i.e., the second presentation of the 20 word pairs). There we found no significant condition effect during the second restudy phase, $F(3, 137) = 1.60$, $p = .20$. In other words, performance was high ($M = 92.2\%$, $SD = 11.0$) and

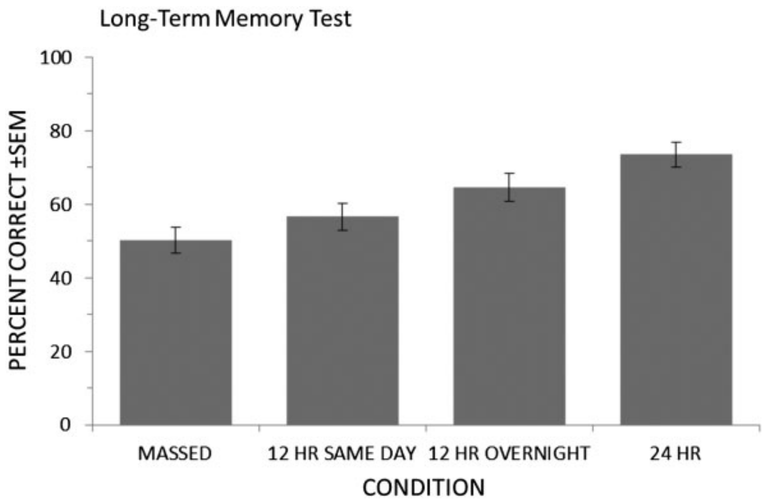

Figure 1. Overall percent correct (±*SEM*) for each delay shown for the long-term memory test.

equal during the second presentation of the Swahili word prompts in the restudy session.

Long-term memory test

Our primary goal was the effect of various spacing intervals and sleep on long-term memory performance. Thus we examined the effect of study episode spacing on long-term retention of word pairs (Figure 1). The percentage of correct responses in the (10-day-later) long-term memory test was analysed using a one-way ANOVA with condition (massed, 12 hours same day, 12 hours overnight, and 24 hours) as the between-participants factor. There was a significant effect of condition, $F(3,\ 137) = 7.5$, $p = .000$, $\eta_p^2 = 0.14$. Five a priori planned comparisons followed. First we compared performance between massed and 24 hours, showing a significant increase in performance of $M = 23.3\%$ for the 24 hours condition, $t(70) = 4.7$, $p = .000$. Second, we compared performance in the massed condition with each of the 12-hour conditions. There was no significant difference between the massed condition and the 12 hours same day condition, $t(68) = 1.3$, $p = .19$, but there was a significant difference of $M = 14.3\%$ between the massed condition and the 12 hours overnight condition, $t(37) = 2.8$, $p = .007$. Next we compared performance in the 24 hours spaced condition with each of the 12-hour conditions. There was a significant difference of $M = 16.3\%$ between the 24 hours spaced condition and the 12 hours same day, $t(66) = 3.2$, $p = .002$ condition, and there was no significant difference between the 24 hours spaced condition and the 12 hours overnight condition, $t(69) = 1.76$, $p = .08$. Overall, the analyses show we successfully replicated Cepeda et al. (2009) by finding a significant improvement in long-term memory following a study session spaced 24 hours compared to immediately after encoding. The 24 hours group performed better than the 12 hours same day group but not differently from the 12 hours overnight group, and both overnight groups remembered more words than those in the massed condition, suggesting that the sleep episode was beneficial to long-term memory. Interestingly, however, the 12 hours overnight condition advantage over 12 hours same day did not reach significance, $t(67) = 1.3$, $p = .19$, which suggests that sleep only partially accounts for the benefit of spacing and absolute delay may also be an important factor. Both sleep and time were needed to obtain a significant spacing effect; neither sleep nor time alone was sufficient to reach significance, while all conditions that combined sleep and time effects reached significance.

DISCUSSION

We found superior long-term memory performance when the gap between encoding and restudy sessions included a night's sleep, suggesting that the sleep episode contributes to the memorial benefit of the temporal separation of study sessions in spacing paradigms. Additionally, the differences in performance (possibly a function of retrieval difficulty) during the first presentation during the restudy phase between the 12 hours same day and 12 hours overnight participants did not result in superior long-term memory. Thus a combination of sleep and contextual variability factors from the passage of time appear to contribute to multi-day spacing effect benefits.

This study shows that an episode of sleep during the lag between encoding and restudying improves memory performance over a long-term delay. We evaluated the effect of massed, 12 hours same day, 12 hours overnight, and 24 hours spacing delays on memory and found that a sleep episode prior to the restudy session improved long-term recall. Similar to other studies reporting a stabilising effect of sleep on declarative memory (e.g., Payne et al., 2012) we extend those findings, demonstrating the benefit of a sleep episode prior to a restudy phase on long-term retention. Sleepers had superior long-term memory compared to those in the massed condition.

A unique contribution of this study was the long-term retention component following the second study session. We found that long-term memory performance was best when the gap in study sessions followed a night's sleep when compared to massing of encoding and restudy sessions. We examined memory performance at two intervals: once during the restudy phase (massed, 12 hours with or without a sleep episode, and 24 hours), and once 10 days later. Similar to the finding by Payne et al. (2012) of increased interference during the period of wakefulness, the 12-hours gap between encoding and first retrieval during the restudy phase had a negative impact on memory only when those 12 hours were spent awake. With delay constant (12 hours), retrieval in the restudy phase was more successful following a night's sleep, which could be explained by the role of sleep in memory consolidation. One interesting question, not addressed by our study, is what effect a nap would have on the same day deficit seen in the first retrieval in the restudy phase.

An alternative interpretation is that restudy-phase recall was better in the morning (overnight group) compared to at night (same day group), which might have to do with circadian rhythms and memory formation and retrieval. This conclusion seems unlikely given other studies have shown no time of day effect on memory (e.g., Payne et al., 2012) and we found no effect of time of day on initial encoding. Additionally, by the end of the restudy phase all participants remembered the same number of words. Therefore a time of day confound is not likely responsible for our findings that the overnight groups had superior memory for the non-related word pairs 10 days later.

Memory consolidation during sleep might have increased the benefit of the successful retrieval in the restudy session, which further strengthened the memory given that both overnight groups (12 and 24 hours) performed better than the massed condition at test, and the 12 hours same-day participants, who did not recall as many words during the restudy phase, did no better than the massed group at test. It could be argued that retrieval for the same day group was too difficult, resulting in poorer performance during the test. Another potential issue is that the second session provided two presentations, both with feedback, during the restudy session. This may have diminished some of the differences on the long-term memory test for the two 12-hour groups.

If memory consolidation is responsible for the benefit in spacing, then it follows that strengthening of the initial encoding session is essential to the spacing benefit and sleep may provide the mechanism for consolidation. However, Bjork and Allen (1970) varied interference during the delay by manipulating the difficulty of a task to be completed during the gap between encoding and retrieval of a memory. They used gaps of seconds (not hours, as in this study) and found that when the task between encoding and restudy was difficult, memory of the event was superior. They concluded that encoding during the restudy phase is critical to the spacing effect rather than consolidation following the encoding phase. One could consider the 12 hours conditions in our task as being an easy (overnight) and difficult (same day) manipulation during the gap between encoding and restudy. However, long-term memory recall was not different between participants in these two conditions, possibly due to two presentations of the words during the restudy phase with allowed participants in both conditions to relearn the words.

Similarly, in contrast to the memory consolidation account of sleep, Cairney et al. (2011) recently reported data suggesting that a night's sleep might lead to changing of contextual cues, resulting in contextual variability following a night's sleep. Therefore both time and sleep may cause contextual variability resulting in superior performance for overnight participants, especially those in the 24-hour group. A sleep episode, like temporal delay, may promote de-contextualisation or encoding variability that might then improve the recall of the remembered items (e.g., Glenberg, 1979). This interpretation suggests that sleep-related memory benefits may be due to an increase in retrieval difficulty during the restudy phase (Roediger & Karpicke, 2011). Rather than sleep leading to a decrease in interference or increase in memory consolidation, sleep might actually make the retrieval during restudy even harder, which results in a benefit to long-term memory. This interpretation of the role of sleep in memory formation is consistent with the findings of Bjork and Allen (1970) described above.

Our study shows that an episode of sleep during the lag between encoding and restudying improves memory performance over a long-term delay. Similar to other studies reporting a stabilising effect of sleep on declarative memory (e.g., Payne et al., 2012), we extend that finding to include memory 10 days later, thereby demonstrating the effect of a sleep episode on long-term retention. Future studies may be able to disentangle the role of sleep in memory consolidation and reduction in interference to long-term memory in spacing paradigms.

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