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Short communication

The role of sleep and practice in implicit and explicit motor learning

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ABSTRACT

Sleep is hypothesized to play a functional role in the consolidation of memory, with more robust findings for implicit, than explicit memory. Previous studies have observed improvements on an explicit motor task after a sleep period. We examined the role of massed practice and sleep on implicit and explicit learning within a motor task. Controlling for non-sleep factors (e.g. massed practice, circadian confounds) eliminated both explicit and implicit learning effects that have been attributed to sleep.

Performance improvements following an inter-session sleep episode have been interpreted as sleep having a necessary role in consolidation [1], although some argue against the sleep–memory consolidation hypothesis [2]. Evidence of sleep benefits for explicit [3] and implicit [4] memory has been found, though enhancements in implicit memory are typically larger and more robust [5]. One explicit memory task frequently used to study the benefits of sleep is sequential motor learning. In this motor task, participants repeatedly enter a specific number sequence (e.g. 4-1-3-2-4) during training and then are tested 12 or 24 h later for speed and accuracy. Participants allowed to sleep between training and testing have shown improved performance, compared to awake controls [6].

Recently, several studies have shed light on uncontrolled factors present in many sequential motor learning study designs. Factors, such as averaging artifacts, time-of-day confounds, and fatigue [7], may account for the observed benefits independent of sleep-related processes. Importantly, studies that controlled for these factors reported the elimination of sleep effects [7–9]. Furthermore, morning performance has been shown to be significantly better than evening performance on simple motor tasks [7], indicating that time-of-day confounds inherent in nocturnal sleep studies may produce an illusory sleep effect. Consistent with this observation, training and testing at the same time of day eliminates between session benefits [7,8]. Lastly, massing effects, due to long training blocks, create a false measurement of learning when fatigue has dissipated by the subsequent session [9]. Accordingly, inserting rest breaks while maintaining the same global time-on-task eliminates observed sleep enhancement [9].

These results contrast with sleep improvements on implicit memory tasks that have been observed even while controlling for these factors. For example, studies implementing a napping paradigm, which controls for circadian factors by testing nappers and non-nappers at the same time of day, show sleep-specific improvements on implicit memory tasks [4,10–12]. Thus, while an emerging literature suggests that careful controls must be used to study and interpret the role of sleep on explicit motor memory, there is strong evidence supporting the benefit of sleep in consolidating implicit visual memories.

The present study compares implicit and explicit motor learning in a pursuit motor task. Two other studies have shown sleep-specific improvements on this task using a sleep deprivation paradigm that controls for time-of-day confounds by having all participants test simultaneously; one group sleeps overnight while the control group remains awake [13,14]. In the pursuit motor task, the participant controls a cursor and follows a target moving along a specified path. Performance is measured by how closely the participant is able to follow the target, either in terms of distance to the target or the proportion of time spent within a specified range of the target. Unlike motor sequence learning, pursuit motor learning necessitates the integration of visual information with motor planning. In traditional pursuit motor learning, the target's path is explicitly circular. However, Maquet et al. [13] have used a non-repeating target trajectory, where the path was determined by a

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combination of several sine waves of different fixed frequencies. They found that learning in this more implicit, procedural version of the task was better in people who had a full night's sleep compared with those who spent the night awake. Unlike learning on an explicit motor sequence task, implicit learning on a pursuit motor task may depend on sleep for performance enhancement. We note, however, that fatigue effects due to massed practice have not been investigated in this motor task, and therefore, could confound a true sleep effect.

The current study attempts to reconcile the findings of negative fatigue results [9] with positive sleep results [13] by investigating explicit and implicit motor learning in a single task. To do this, we manipulated three factors. First, we varied target patterns between an explicit, repeating pattern and an implicit, non-repeating pattern. Second, to examine fatigue, we tested a massed condition (based on Maquet et al. [13]) and a spaced condition (based on Rickard et al. [9]). Lastly, we compared napping to a quiet rest control group [11,15] to eliminate circadian confounds and the possible negative effects of sleep deprivation, waking interference, on-task fatigue, or uncontrolled forms of inhibition in the non-sleep group.

We hypothesized that the explicit, repeating target pattern would show a between session benefit driven by fatigue in the first session rather than sleep. Second, we hypothesized that spacing practice in the explicit pattern condition would eliminate both massed practice fatigue and the between session performance increases previously ascribed to sleep-dependent processes. Third, we hypothesized that improvements in the implicit, non-repeating target pattern would be sleep-dependent, not observed in the quiet rest group, and independent of both massed and spaced learning.

Results were obtained from a cohort of 81 participants. Forty-seven participants (28 and 19 in the napping and quiet rest conditions, respectively) received massed block training. Thirty-four participants received spaced training (19 and 15 in the napping and quiet rest conditions, respectively). Participants were 18–35 years of age with no personal history of neurological, psychological, or other chronic illness. Participants provided informed consent to participate in the experiment, which was approved by the Institutional Review Board of the University of California at San Diego. Ensuring that participants were well rested and had typical sleep histories, participants completed sleep diaries and were monitored by actigraphy for 5–7 days before testing to assess sleep–wake activity. Participants were required to sleep an average of 6 h per night for the 5 days leading up to the experiment and at least 6.5 h the night before the experimental day. They were also restricted from consuming caffeine and alcohol 24 h before and during the experimental day. While this is a light requirement on sufficient sleep and the caffeine restrictions may have resulted in withdrawal for some participants, any effects due to these restrictions would increase apparent sleep benefits. Typical caffeine consumption for these participants was reported to be between 1 and 2 caffeinated drinks per day.

All participants performed two sessions of the pursuit motor task, once in the morning and then again in the afternoon (Fig. 1). At 09:00, participants completed a training session of the pursuit motor task that consisted of following the motion of a circular red target on a computer screen with a cursor controlled by a mouse operated by the participant's non-dominant hand. Participants returned at 13:00, at which time they were randomly assigned to a nap or a quiet rest group. Those assigned to the nap received a polysomnographically recorded (PSG) nap of up to 90 min of sleep or 2 h in bed. The mean sleep time of all participants was 59.9 min. Data were excluded from further analysis if their total sleep time was less than 20 min. Those in the quiet rest condition listened to instrumental music with PSG monitoring for 90 min. Participants in the quiet rest condition were monitored for sleep and alerted if the first signs of stage one sleep were observed.

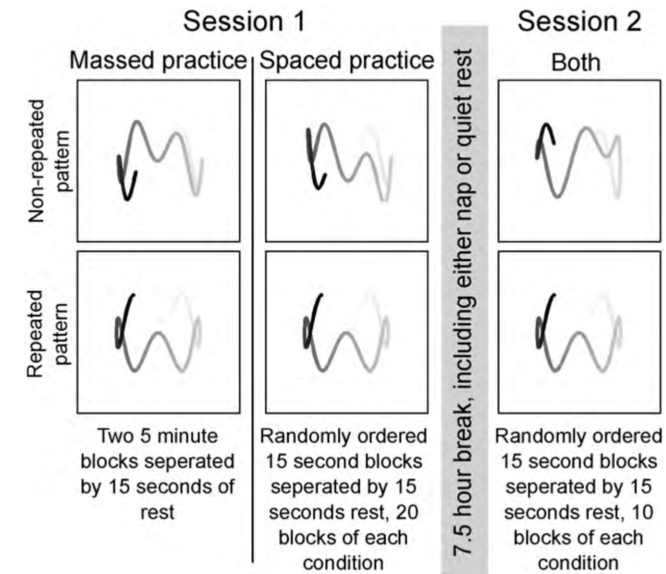

Fig. 1. The experimental paradigm with examples of the movement patterns used in the experiment. The "tracers" or "tails" in the figure are for illustrative purposes only; during the experiment the screen was blank, with the exception of a single dot target and the cursor.

At 16:30, participants returned for session two of the pursuit motor task.

The massed training condition consisted of two 5-min blocks of the task. In one block, the target followed a non-repeating trajectory. In the other, the target trajectory followed a repeating pattern. In the second session, participants performed the rotary pursuit task in 15 s blocks. The order of blocks for both sessions was counterbalanced between participants and each block was separated by 15 s of rest. These block durations replicate those used by Maquet et al. [13], where sleep effects were found in a similar non-repeating pursuit motor task. The spaced training condition was identical to the massed training condition with the exception that in the first session, twenty 15 s blocks of non-repeated and pattern trajectories were interleaved with 15 s of rest. Rickard et al. [9] found that spacing practice in 15 s blocks as opposed to 30 s blocks eliminated both fatigue in the first session and between session improvements.

During the task, the target's path was determined independently for horizontal and vertical directions using sine functions of different periods. The repeated and non-repeated pattern conditions were created by using paths which either repeated both within and between blocks or did not repeat during the entire experiment, and were therefore unpredictable. In both conditions, horizontal movement was determined by a single sine function with a 3/15 Hz period. Vertical movement was more complex and guided by the product of three sine functions of different periods. In non-repeated patterns, the periods were randomly chosen from a list of potential patterns for which the combined vertical and horizontal movement of the target would never repeat. In the repeated pattern condition, the global movement was determined by the product of sine functions with 3/15, 6/15 and 9/15 Hz periods. Given these parameters, the target movement pattern repeated every 5 s. For all conditions, the target started in the center of the screen at the beginning of every block. Target position was indicated with a 10-pixel diameter red circle, and the position of the mouse cursor was indicated by crosshairs. The target position ranged in the center 400×400 pixel area of a 640×480 pixel resolution display.

The position of the mouse cursor was sampled at approximately the screen refresh rate (60 Hz). The mean of the Euclidian distance from the cursor to the target was computed and recorded every 200 ms. We obtained identical results analyzing our data using the