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Article

Benefits of daytime naps on consecutive days for motor adaptation learning

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Abstract: Daytime napping offers benefits for motor memory learning and is used as a habitual countermeasure to improve daytime functioning. A single nap has been shown to ameliorate motor memory learning, although the effect of consecutive napping on motor memory consolidation remains unclear. This study aimed to explore the effect of daytime napping over multiple days on motor memory learning. Twenty university students were divided into a napping group and no-nap (awake) group. The napping group performed motor adaption tasks before and after napping for three consecutive days, whereas the no-nap group performed the task on a similar time schedule as the napping group. A subsequent retest was conducted one week after the end of the intervention. In the napping group, there were no significant consolidation effects over the three consecutive nap intervention periods, however, the speed to complete the retention task was significantly faster than that of the awake group. No significant difference was confirmed for trajectory length to complete the task. Thus, consecutive napping may facilitate motor learning and motor memory consolidation long-term.

Keywords: nap, sleep, motor adaptation, learning, consolidation

1. Introduction

Sleep has been considered a crucial post-practice activity for the evolution of memory. Numerous studies have demonstrated the beneficial role of sleep in memory consolidation, under the process that the newly learned information may be organized and reactivated offline, such that initially labile memory traces become more robust and fixed [1,2]. Among different arrays of memory systems, declarative memory was positively associated with sleep-dependent consolidation [3]. Subsequently, this concept has extended to other forms of memory, such as the procedural memory domain. In early studies, sleep-dependent memory processing was observed in the domains of declarative and procedural memory [4,5]. Accumulating evidence has indicated that motor memory consolidation refers to the “off-line” state in sleep, wherein memory traces are presumably consolidated in a different manner than on-line [6].

Procedural memory is defined as a collection of abilities to acquire various skills, which do not involve direct recall of previous episodes [7]. Motor learning includes both simple and complex motor skill behaviors from daily activities such as household chores to techniques involving sports and music. Nevertheless, motor memory processing may depend on the nature of the motor learning demands. Adaptation to visuomotor rotations is one of the most widely studied paradigms of motor learning skills, in which individuals have to adapt to sensorimotor perturbations (motor adaptation, MA) [8]. MA represents the capacity to modify motor behavior in response to changes in the environment [9]. Plihal and Born have initially demonstrated that sleep following an initial session of MA increased performance in a subsequent retest by employing a mirror tracing task [4]. Hereafter, more studies have replicated the beneficial effect of sleep on MA with different variations of tasks and situations [10-15]. In the recently employed gross MA task, it has been reported that sleep has a facilitative effect on skill acquisition and consolidation [12,16]. However, a recent meta-analysis questioned the previous findings that sleep facilitates MA leaning [17]. Debas et al. reported that sleep had no effect on MA performance, although sleep significantly improved motor sequence learning (MSL) performance [18]. A greater effect on MA consolidation is induced by practice and not by sleep [19]. However, whether MA consolidation depends on the manner of sleep remains controversial.

Daytime napping is regarded as a healthy habit by reducing sleepiness resulting in refreshment in the afternoon, as well as an effective countermeasure to sleep deprivation [20]. While napping has a prominent benefit on motor learning tasks, the beneficial effect was demonstrated predominantly in an MSL task [21,22]. In contrast to an MSL task, a few studies have explored the association between MA consolidation and napping. Backhaus et al. have found no significant differences in the changes of MA performance between the three groups (awake, short nap, and long nap groups), in retesting the following day [11]. In addition, Hoedlmoser et al. have demonstrated the inverse effect of napping on MA consolidation, provided the decreased performance after taking a nap [22]. However, the previous study investigating the association between motor leaning and napping examined the effect of napping on a single occasion. Napping not only helped reduce daytime sleepiness but also played an essential role in recovering from a chronic loss of sleep, resulting in an extension of overall sleep time [1]. Sleep extension has been shown to improve visuospatial processing [21,23] and sports performance requiring motor procedural learning [24-26]. The improvement in performance due to extended sleep may be the result of eliminating "sleep debt," considered as chronic sleep loss [27]. Although consecutive napping may be useful for reducing cognitive deficit due to sleep deprivation, no studies have examined motor memory consolidation through consecutive habitual napping.

Therefore, this study aimed to explore motor learning employed when performing MA tasks by analyzing three-day consecutive daytime napping. To examine the effect of consecutive napping opportunity on MA consolidation, the retest was performed one week after the end of the three-day napping intervention. Polysomnography was recorded to score the sleep stages and examine the association between the magnitude of consolidation and sleep architecture. We hypothesized that there would be a significant consolidation effect in consecutive napping opportunity; this would confirm that the habit of napping is practical for overcoming sleep deprivation. Our findings provide experimental evidence for the effects of consecutive napping habits on motor memory function.

2. Materials and Methods

2.1. Participants

Altogether, 20 male university students aged between 18 and 30 years were assigned to either the napping group (n = 10, mean age: 23.1 ± 1.3 years) or awake group (n = 10, mean age: 22.2 ± 3.5 years). The inclusion criteria were no prior history of drug or alcohol abuse, neurological, psychiatric or sleep disorders and had maintained a regular sleep schedule 1 week prior to the experiment. The participants were also required to abstain from caffeine and alcohol throughout the study duration and refrain from non-experimentally measured naps, confirmed by a post-experimental questionnaire. The examiner directly confirmed all conditions above by careful interview.

The sample size was calculated using G * Power 3.1.9.6 with an effect size determined by $\eta_p^2 = 0.06$, and the values for α and power were set at 0.05 and 0.80 for MA performance, respectively [28]. The required sample size was eight for each group to evaluate MA performance, plus two participants were required (i.e., 20 participants in total).

Based on the Pittsburgh Sleep Quality Index, the participants were observed to have good sleeping habits (4.7 ± 1.9). The Academic Research Ethical Review Committee of Waseda University approved all activities (IRB #2019-193), and all participants provided informed consent. The study was conducted in accordance with the 1975 Declaration of Helsinki, as revised in 2013.

2.2. Experimental designs: napping and awake groups

The experimental procedure is illustrated in Figure 1. The experiment comprised a five-day schedule: Day 1 (D1), Day 2 (D2), Day 3 (D3), Day 4 (D4), and Day 11 as a retention test (RT). Both groups performed the first task at 13:00 (pre-nap), and the second task at 15:00 pm (post-nap) with a 2-h interval. The nap group performed the experimental task in the laboratory, whereas the no-nap group performed the task while remaining awake at a similar time in their home environment. Because the home environment was used, the no-nap group was instructed by the experimenter (YM) through an online videoconference system via smartphone.

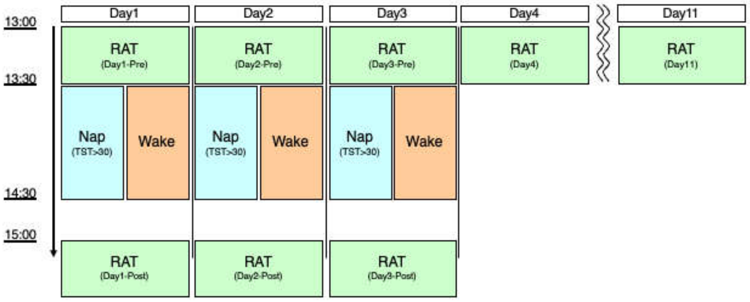

Figure 1. Schematic diagram of the experimental protocol.
Abbreviations: RAT, rotation adaptation task; TST, total sleep time

For the napping group, the experiment on D1, D2, and D3 started at 13:00 in the laboratory. The participants performed the pre-nap experimental tasks. After the completion of the pre-nap task, they answered the Karolinska Sleepiness Scale to assess subjective sleepiness. Subsequently, electrodes were attached on the scalp of the participants in the napping group to record sleep EEG during the nap. For the awake group, the experiment was conducted in the home environment. Similarly, beyond the experimentally recorded midday nap, those in the napping group were also instructed not to nap before or after the noon sleep session. The D4 and RT (D11) sessions were conducted once at 13:00.

After completing the task, the nap group entered a quiet, air-conditioned, dark room in the laboratory after being attached to the EEG for sleep measurement. Participants in the nap group sat deeply in a soft beanbag chair (Yogibo MAX, Webshark Inc., Osaka, Japan) and were requested to take a nap after the lights were turned off at 13:30. Then, they were woken up by an examiner (YM) at 14:30. Considering the decreased vigilance after wakeup (conceptualized as ‘sleep inertia’), post nap tasks were conducted at 15:00, approximately 30 minutes after awakening. On the other hand, participants were instructed not to nap during the equivalent period (13:00-15:30), instead they were allowed to do passive activities (e.g., use computers or smartphones, watch television, play videogames, read, listen to music). The activities of participants during this period were monitored and confirmed online by the experimenter.

Both groups performed the experimental task at the following 8 points: D1-pre, D1-post, D2-pre, D2-post, D3-pre, D3-post, D4, and RT (D11), with "pre" indicating the task before the equivalent timing of napping, and "post" indicating the time after napping. To monitor nocturnal sleep during the experiment, the participants wore an activity meter (MTN-220, Acos. Ltd., Nagano, Japan) during nighttime sleep for the entire experimental period.

2.3. Sleep measurements at night

In the napping group, the participants were requested to wear a Fitbit Charge 3 activity monitor (Fitbit Inc., San Francisco, CA, USA) on their non-dominant wrist for 24 h/day during the intervention period, except during water-related activities, to assess nighttime sleep during the experiment period. The validity of the Fitbit Charge series in examining sleep against the standard of polysomnography has been demonstrated in recent validating studies [29,30]. For more detailed information on how the Fitbit computes sleep-related measures, see http://help.fitbit.com. Fitbit devices generated sleep variables, including total sleep period time and sleep efficiency (i.e., the ratio of total sleep time over time in bed).

2.4. Rotation adaptation task

To investigate motor memory consolidation associated with consecutive napping, a rotation adaptation task (RAT) was adopted in the experiment task (Figure 2). The task consisted of eight white, circular target objects and one green, circular cursor object, placed on the circumference at equal angles (45° intervals). The cursor was placed at the center of the circle and could be moved. When the task started, one of the targets turned red, and the participant was asked to move the cursor to reach the red target (one trial). The cursor moved in the direction of a certain additional angle from the direction the participant moved it, with six additional angles: ±30°, ±60°, and ±90°. The additional angle was randomly determined for each trial and displayed on the screen during each trial. The participants were asked to instantly recognize the additional angle displayed on the screen for each trial and adapt to the rotational effect of the additional angle to precisely bring the cursor to the target. After the cursor reached the target, the next trial started after a 1-s interval.

The experimental tasks were performed on the screen of a laptop computer with a 15.6-inch (192 × 1080) display. A trackball mouse (KT-2337/72337 JP, Kensington, San Mateo, CA, USA) was used as the input interface to control the cursor. The participants were instructed to sit in a comfortable chair with the laptop PC placed on the desk in front of them. With the orientation of the trackball mouse and forearm aligned to face the front, the participants operated the trackball using the index and middle fingers. The distance between the center of the circle which corresponds to the initial position and the center of each target was 400 px. The size of the target itself was 40 px in diameter, and the cursor itself was 20 px in diameter.

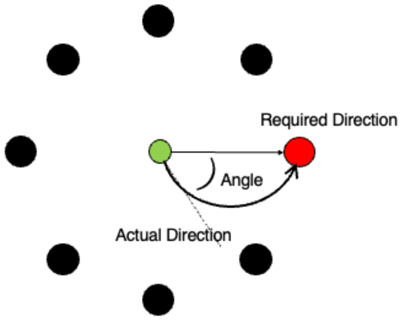

Figure 2. Schematic diagram of the rotation adaptation task (RAT).

2.5. PSG recording and sleep stage scoring

Polysomnography recording was performed in accordance with standardized techniques [30], using digital EEG, electromyography (EMG), and electrooculography (EOG) signals acquired with a Polymate mini AP108 (Miyuki Giken Ltd., Tokyo, Japan). The sampling rate was at 256 Hz, and the high- and low-pass filters were 0.3 Hz and 35 Hz, respectively. A referenced PSG electrode montage was utilized, including EEG sites C4 and O2, EOG referenced to A1 and A2, left and right outer canthi. Each sleep epoch of the PSG record was scored every 20 s by a clinical professional technologist blinded to the interventions according to the American Academy of Sleep Medicine manual scoring rules [31]. Sleep stages were classified into four sleep stages: (1) awake (2) rapid eye movement (REM) sleep, (3) light non-REM (NREM) sleep (stages N1 and N2), and (4) deep NREM sleep (N3).

2.6. RAT data analyses

The RAT analysis results consisted of three items: the time required for the cursor to reach the target (required time), the length of the trajectory required for the cursor to reach the target (trajectory length), and the value obtained by multiplying the above two items (synthetic index: required time × trajectory length). The required time indicated the smoothness of the cursor movement, and the trajectory length showed the distance loss when moving the cursor, implying the accuracy of the task. The synthetic indicator indicated the combined results of the time required and the trajectory length. The analysis trajectory length L was calculated using the following formula:

$$L = \sum_{k=1}^{n} \sqrt{(x_k - x_{k-1})^2 + (y_k - y_{k-1})^2} - 400$$

where "n" indicated the number of frames from the start of the cursor movement until it reached the target, "x" the x-coordinate of the cursor, and "y" the y-coordinate of the cursor. To evaluate the loss from the shortest distance, the actual trajectory length minus 400 (px) was used as the trajectory length for analysis. Additionally, the trajectory length was adopted for analysis because it reflected the angle error more properly. The exclusion criteria were as follows: more than +2 standard deviations [SD] ± 90° in the D1-

pre and D1-post for the time required, and more than 2512 pixels for the trajectory length of one circumference of the target.

2.7. Statistical analysis

The Shapiro-Wilk test showed that all data were normally distributed; thus, no transformation was required. For each of the 12 items, a two-way repeated measures analysis of variance (ANOVA) was conducted by group (napping and awake groups) × measurement point (D1-pre, D1-post, D2-pre, D2-post, D3-pre, D3-post and D4). The Greenhouse–Geisser correction was conducted to the evaluate degrees of freedom as necessary. When the Mauchly–Test was significant, we adapted values with the Greenhouse–Geisser correction. To account for multiple comparisons, the ANOVA p-values were controlled using the false discovery rate (FDR) method [31]. When significant interaction effects were noted with the two-way ANOVA, analyses were broken down into paired *t*-tests as the post-hoc test. Statistical comparisons of RT between the groups were independently performed using paired Student's *t*-tests. Effect sizes (Cohen's d) were calculated from *t*-statistics to reduce the probability of type II error [32]. All analyses were performed using SPSS version 27 (IBM Corporation; Armonk, NY, USA).

3. Results

3.1. Sleep variables at night during the experiment

Nighttime sleep variables measured using the Fitbit activity monitor during the RAT experiment period (DAY 1 to DAY 3) were calculated for the napping group. The sleep duration was 371.0 min (*SD* 83.0 min) and sleep efficiency was 66.0% (*SD* 16.7%). Regarding nighttime sleep measurements during the entire experimental period from DAY 1 to DAY 11, the data of four participants were excluded due to poor recording. The mean sleep duration was 365.0 min (*SD* 95.0min) and sleep efficiency was 67.7% (*SD* 11.7%). These data indicate that there was no significant sleep deprivation over the duration of the experiment.

3.2. Nap propensities

Table 1 summarizes the sleep variables during napping of each experimental day. No significant differences were obtained in each variable among days. The duration and quality of napping on each experiment day were shown to be equivalent.

Table 1. Sleep parameters during napping on each experimental day

	TIB (min)	TST (min)	SE (%)	SL (min)	Wake (min)	N1 (min)	N2 (min)	N3 (min)
DAY 1	50.7 (4.3)	39.8 (5.0)	78.4 (1.6)	4.9 (1.7)	10.9 (3.6)	14.0 (7.1)	18.2 (9.1)	7.6(9.2)
DAY 2	49.7 (2.8)	39.4 (7.6)	79.1 (1.3)	4.1 (1.5)	10.2 (6.3)	11.6 (3.7)	18.5 (10.6)	9.4 (9.4)
DAY 3	52.7 (3.0)	37.5 (12.1)	70.9 (1.3)	4.0 (1.6)	15.3 (11.3)	12.4 (8.6)	15.5 (9.1)	9.5 (8.7)

Average	51.0 (2.2)	38.9 (5.0)	76.2 (0.8)	4.3 (1.1)	12.7 (3.6)	12.7(3.6)	17.4 (5.8)	8.8 (7.6)

*A*bbreviations: TIB, total time in bed; TST, total time of sleep; SE, sleep efficiency; SL, latency to sleep onset; N1, NREM sleep stage 1; N2, NREM sleep stage 2; N3, NREM sleep stage 3. Sleepiness Scale values are shown as means (standard deviations).

No statistical differences were obtained through the three-day experiment.

3.3. Subjective sleepiness

The changes in subjective sleepiness in the napping group are shown in Table 2. Sleepiness after napping was significantly reduced compared with sleepiness before napping on each experimental day. The mean value of sleep quality evaluated using the visual analog scale during the nap was better than that during the median point, indicating that the subjective napping was comfortable.

Table 2. Changes in subjective sleepiness before and after napping

	KSS (pre nap)	KSS (post nap)	Degree of improvement in KSS	VAS
DAY 1	5.3 (1.1)	3.7 (1.4)	1.7 (1.6)	4.9 (1.7)
DAY 2	5.3 (1.3)	3.7 (1.5)	1.7 (1.3)	4.1 (1.5)
DAY 3	4.7 (1.5)	3.4 (2.0)	1.2 (1.3)	4.0 (1.6)
Average	5.1 (0.9)	3.6 (1.2)	1.5 (0.8)	4.3 (1.1)

Abbreviations: KSS, Karolinska Sleepiness Scale; VAS, Visual Analog Scale (for self-rated sleep quality, 0 — poor, 10 — good). Values are shown as means (standard deviations).

3.4. Required time

The results of total angle time required at each measurement point for the napping and awake groups are shown in Figure 3.

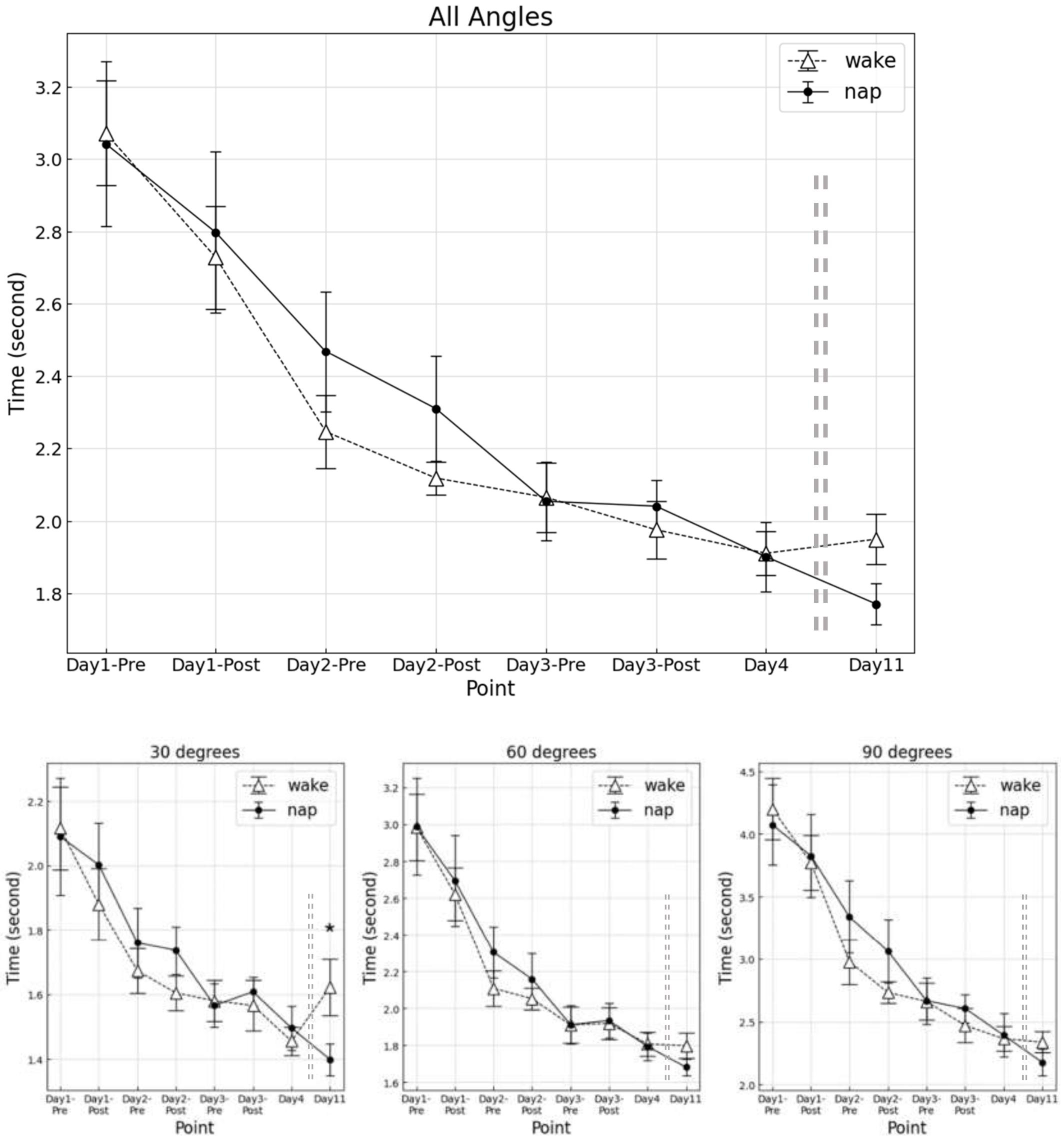

Figure 3. Time required at each measurement point. Upper, averaged angle; Lower left, 30°; middle, 60°; right, 90°. * $p < 0.05$

For overall angles combined, the main effect of group was not significant (F (1,16) = 0.120, p = 0.734, $\eta_p^2 = 0.001$). However, a significant main effect by measurement point was obtained (F (2.46, 39.40) = 50.62, $p < 0.001$,$\eta_p^2 = 0.766$). Divided by each angle, the main effect by measurement point was significant for each angle (30° F (2.28 , 36.55) = 19.68, $p < 0.001$, $\eta_p^2 = 0.557$; 60° F (2.34, 37.51) = 36.41, $p < 0.001$, $\eta_p^2 = 0.701$; 90° F (3.40, 54.43) = 50.36, $p < 0.001$, $\eta_p^2 = 0.756$). No significant interaction between the groups and measurement point (F (2.46, 39.40) = 1.130, p = 0.342, $\eta_p^2 = 0.068$) was observed.

Although post-hoc analysis revealed no significant differences among measurement points, the speed of the final RT for 30° was significantly faster in the napping group compared to the awake group (p = 0.034, Cohen's d = 0.853).

3.5. Trajectory length

The results of the trajectory length at each measurement point for the napping and awake groups are shown in Figure 4.

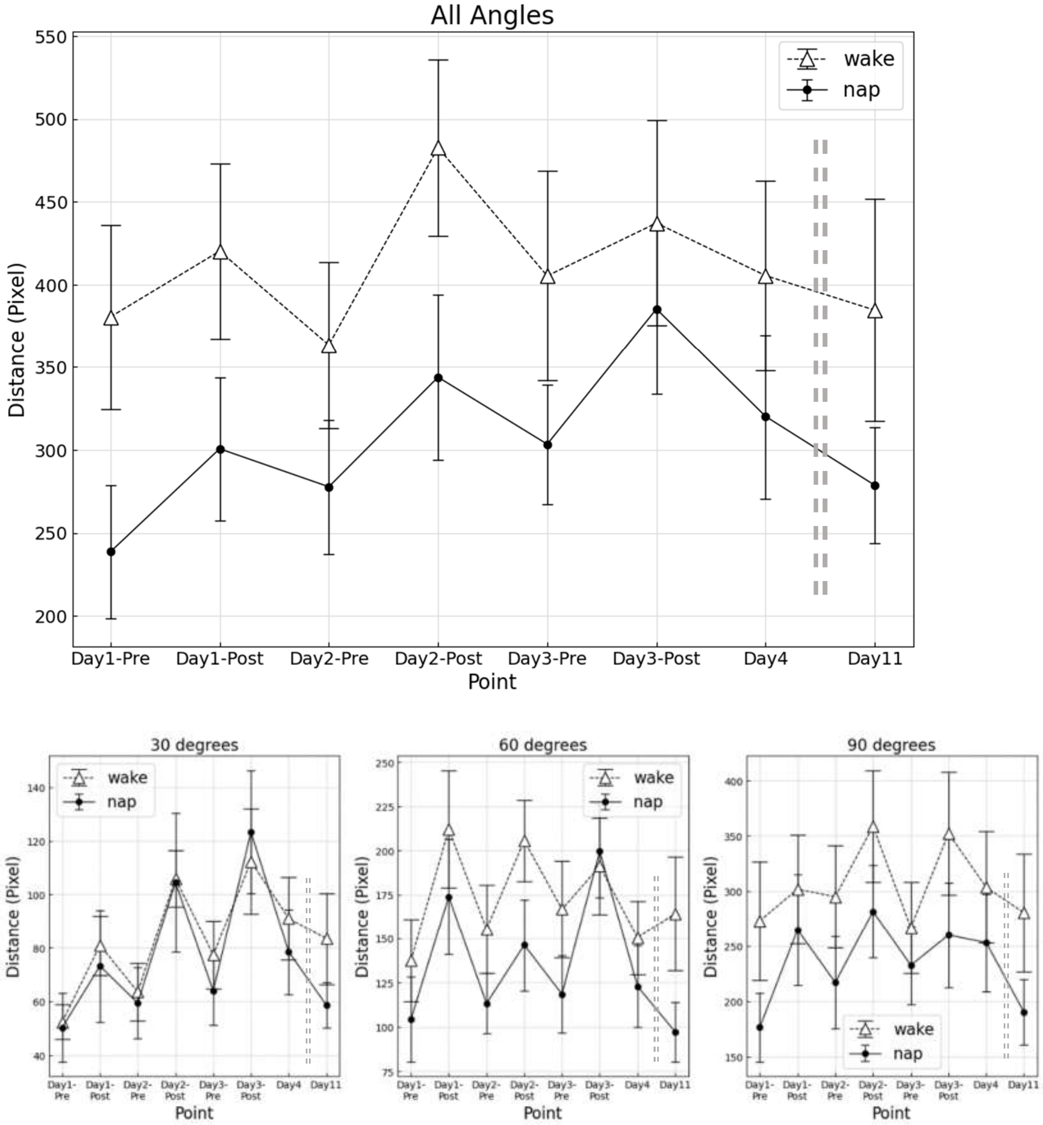

Figure 4. Trajectory length at each measurement point. Upper, averaged angle; Lower left, 30°; middle, 60°; right, 90°

For overall angles combined, neither the main effect of group (F (1,16) = 2.650, p = 0.123, $\eta_p^2 = 0.066$), nor the main effect by measurement point (F (2.51, 40.21) = 2.570, p = 0.077, $\eta_p^2 = 0.137$) was found to be significant. No significant interaction was observed between group and measurement point (F (2.51, 40.21) = 0.44, p = 0.689, $\eta_p^2 = 0.024$).

When divided by angles, the main effect by measurement point was significant for each angle (30° F (3.12, 49.91) = 6.46, p = 0.001, $\eta_p^2 = 0.282$; 60° F (3.02, 48.38) = 4.11, p = 0.011, $\eta_p^2 = 0.210$; 90° F (7,112) = 2.27, p = 0.034, $\eta_p^2 = 0.124$). Post-hoc analysis showed no significant differences among measurement points. The final RT was not significantly different between the two groups for each angle.

3.6. Synthetic index (required time × trajectory length)

The results of the synthetic index at each measurement point for the napping and awake groups are shown in Figure 5.

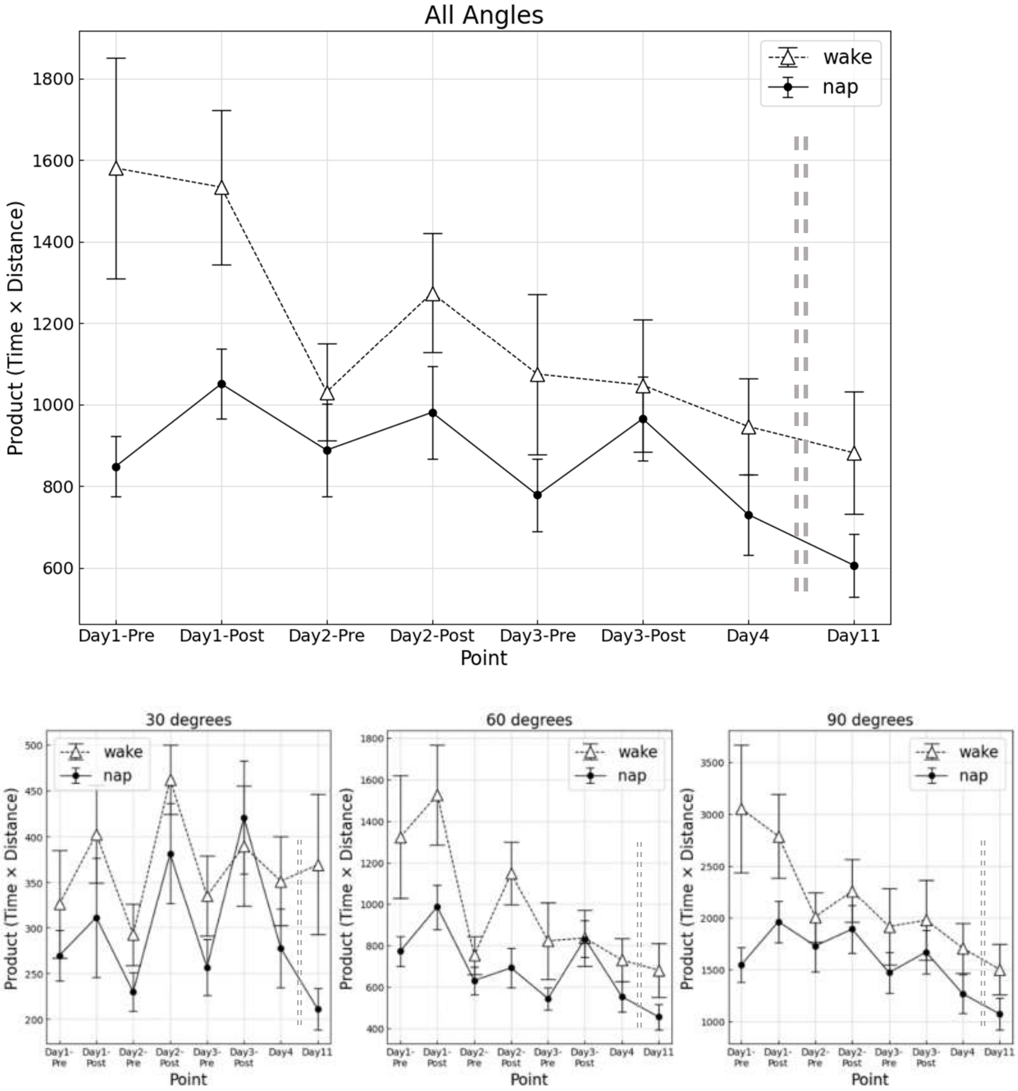

Figure 5. Trajectory length at each measurement point. Upper, averaged angle; Lower left, 30°; middle, 60°; right, 90°

For overall angles combined, a significant main effect of group was obtained ($F(1,16) = 4.993$, $p = 0.040$, $\eta_p^2 = 0.098$), as well as a significant main effect by measurement point ($F(2.89,46.20) = 6.01$, $p = 0.002$, $\eta_p^2 = 0.264$) . No significant interaction was observed between group and measurement point ($F (2.89, 46.20) = 1.75$, $p = 0.172$, $\eta_p^2 = 0.100$). In the RT trial, the napping group had a shorter required time than the awake group ($p = 0.241$, $d = 0.130$), although no significant difference was observed.

Divided by each angle, a significant main effect of group was obtained in the 60° angle trial (30° $F (1,16) = 3.196$, $p = 0.090$, $\eta_p^2 = 0.066$; 60° $F (1,16) = 7.471$, $p = 0.015$, $\eta_p^2 = 0.097$; 90° $F (1,16) = 3.700$, $p = 0.072$, $\eta_p^2 = 0.104$). The significant main effects of group by measurement were acquired in all angle deviations (30° F (3.28, 52.54) = 3.71, $p = 0.014$, $\eta_p^2 = 0.042$; 60° F (3.10, 49.63) = 7.09 , $p < 0.001$, $\eta_p^2 = 0.072$; 90° F (3.27, 52.26) = 5.46, $p = 0.002$, $\eta_p^2 = 0.091$). No significant interactions were observed between group and measurement point for each angle (30°F (3.28, 52.54) = 0.75, $p = 0.538$, $\eta_p^2 = 0.042$; 60°F (3.10, 49.63) = 1.60 , $p = 0.201$, $\eta_p^2 =0.072$; 90°F (3.27, 52.26) = 1.41, $p = 0.247$, $\eta2 = 0.091$).

Post-hoc analysis showed no significant differences among measurement points. The final RT also revealed no significant difference between the two groups for each angle.

4. Discussion

In the current study, we analyzed the effects of three-day consecutive daytime napping on MA learning and subsequent consolidation of motor memory by combining behavioral data with contemporaneous EEG recordings. Variables including speed, accuracy, and combined speed–accuracy index showed significant main effects in the napping group compared with the awake group. Notably, the speed of the 30° angle in the final retest session was significantly faster in the napping group compared with the awake group. Thus, the current results suggest that consecutive napping during MA learning enhances motor memory consolidation.

While motor learning tasks have a distinct nap benefit [33-36], evidence that napping has an incremental effect on MA consolidation has been limited. The first formative study by Plihal and Born revealed that the MA facilitation after sleep was specific to the latter part of night sleep, consisting of a higher proportion of REM sleep [4]. A facilitative effect of nocturnal sleep that includes sufficient REM sleep on subsequent MA consolidation has been consistently reproduced [10,13,14,37,38]. Considering that napping contains less REM sleep than nocturnal sleep, daytime napping is unlikely to enhance MA learning. Meanwhile, several studies have reported that even whole night sleep provided no overnight improvement of MA compared with the wake control group [11,39-41]. Whether sleep facilitates MA consolidation remains under debate; however, consecutive napping may be beneficial for MA consolidation because of a lower capacity to maintain the memory trace for MA during wakefulness, requiring a subsequent time window for the stabilization of the acquired MA skill [10,13,14,37,38]. Although the effects of consecutive naps on memory consolidation may not be obvious during the intervention period, significant facilitation of MA occurred after the retest session one week later.

While the effect of napping on MA consolidation appears inconsistent, consecutive daily napping is considered a practical strategy to increase sleep duration, which may be equivalent to extended sleep [24]. Although the participants of both the napping and awake groups reported that they kept a regular sufficient sleep duration, a past study demonstrated that even habitual 6-h sleep, which is considered a normal sleep duration, produced cognitive performance deficits equivalent to up to 2 nights of total sleep deprivation [42]. Poor quantity and quality of sleep induced by slow-wave sleep deprivation have been shown to impair the sleep-related consolidation of a visuomotor adaptation task [43]. Regarding compensation of sleep loss, a previous study has demonstrated that sleep duration was considerably unaffected by whether the sleep was placed nocturnally or split between nocturnal anchor sleep periods and daytime naps [44,45]. According to the notion that daytime napping has the potential to work as a supplement against unperceived sleep loss, consecutive napping has a similar effect to that of sleep extension on procedural motor learning.

In this experiment setting, speed benefited more from napping opportunity than trajectory length, resulting in a significant enhancement effect on RT in the relatively easy condition of 30°. The present results are unlikely to be consistent with previous research

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which differentiated the effects of training in speed and accuracy components of motor tasks, with speed benefiting most from training [46]. One possibility as to why speed was significantly enhanced is that the participants may have prioritized only speed for the cursor movement, making trajectory length a secondary consideration. The participants were requested to "move the cursor to the target as fast and as straight as possible," implying that the participants prioritized speed since it was written at the beginning of the warning. In addition, however, the facilitating effect on the retest was observed in the relatively easy 30° rather than the more difficult 60° and 90° conditions, suggesting that task difficulties in MA learning are related to gaze control. A past study demonstrated that gaze control during a visuo-adaptation task was modified more in the 30° condition compared to the 75° condition [47], implying that sleep-dependent learning of gaze control would be exhibited in an easier task such as the 30°condition.

In terms of trajectory length, the awake group required an overall longer trajectory length compared with the napping group. The trajectory length of the awake group was generally higher than that of the napping group, which may be partly due to the experimental environment. The experiment in the awake group was not conducted at home, possibly resulting in distraction from the experiment. Considering that the internet-based experiment has recently become a well-validated alternative to traditional laboratory-based assessment, recent studies have indicated the inconsistency of negligible differences between the domestic and laboratory settings [48-50]. Here, considering the similar tendency of the synthetic index, the awake group may have been less focused on the experiment than the napping group.

Neural networks have been implicated in sleep-dependent learning of MA. In contrast to MSL tasks involving greater contributions from a cortico-striatal system, MA tasks primarily recruit a network of cortico-cerebellar structures instead [17]. A previous neuroimaging study has revealed no significant difference of cerebral activities in the overnight intervention group compared with the wake control group [18]. Albouy et al. have demonstrated that sleep deprivation after an initial adaptation session impaired learning, with increased activation in cerebello-cortical networks afterwards [10]. This result suggests that the process of MA consolidation predominantly occurs in earlier learning stages within the brain system related to motor coordination. Thus, daily napping after MA learning may help memory consolidation further after a certain amount of time scale involving the neural networks of the cortices and cerebellum.

Converging evidence has demonstrated that MSL consolidation was robustly associated with sleep spindle, regarded as a hallmark of NREM sleep [35,51]. Sleep-dependent memory consolidation of MA was shown to be related to increased regional slow wave activity during NREM sleep in the task-relevant region [13]. Aside from slow wave sleep, fast spindle activity was associated with MA in a mirror tracing task [52]. This inconsistency is in line with our findings that revealed no association between sleep architecture and the extent of MA learning. While REM sleep density may be involved in MA learning [53], the effect of sleep propensity on memory consolidation remains unclear, and further studies are needed to explore the role of subsequent sleep of MA learning, including temporal protection against relevance.

Nevertheless, the present study has several limitations. First, the sample size was insufficient to demonstrate the incremental effect of napping. Second, the duration of the napping intervention was limited to 3 days, which is relatively inadequate to confirm the effect of napping on motor learning. By extending the intervention period, the effect on motor learning could be verified. Third, the environment of the experiment was different in different groups. Since the experiments in the napping group were conducted in the laboratory, while those of the awake group were conducted in a place other than the laboratory, the degree of concentration during the experiments differed, which may have affected the results of the trajectory length. The adequacy of the results of the motor adaptation learning should be tested in a similar experimental environment. Lastly, only the required time was displayed on the screen, resulting in attenuated results of the trajectory length. However, our results suggest that consecutive napping has benefits on MA consolidation, specifically observed in speed. Additionally, one of the important implications of the current study is it shows that that even if we do not extend our nocturnal sleep, getting enough sleep through daytime napping can be effective in facilitating motor memory learning such as playing sports or instruments. Further research is warranted to elucidate the neural mechanism between MA learning and sleep propensities.

5. Conclusions

Multi-day naps promote MA learning. While no significant interaction was observed between napping and speed, the napping group demonstrated a significantly faster speed than the awake group in the subsequent RT. Neither a significant interaction nor main effects were confirmed for trajectory length or the combined index. Accuracy and combined speed–accuracy index were not significantly higher. These results suggest that consecutive napping may help in MA consolidation representing the improved speed, which presumably stabilizes memory tracing after MA learning. Further research is warranted to elucidate the causal relationship between napping and MA consolidation. This will provide practical support in daily life activities, such as sports activities that require MA ability.

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