



Full Length Article

Napping after complex motor learning enhances juggling performance

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ARTICLE INFO

Article history:

Received 8 January 2016

Received in revised form

28 March 2016

Accepted 8 April 2016

Available online 20 April 2016

Keywords:

Motor learning

Motor skills

Memory consolidation

Nap

Sleep

ABSTRACT

The present study examined whether a nap after complex motor learning enhanced the following day's physical performance. Eighteen volunteers met the inclusion criteria and were assigned to either a nap ($n=9$; men=5; mean age=21.0 ± 1.5) or no-nap group ($n=9$; men=5; mean age=21.9 ± 0.3). Participants practiced juggling in the morning and were tested immediately afterwards. Participants of the nap group were given a 70-minute nap opportunity after juggling practice, while the no-nap group stayed awake. Juggling performance was then tested in the evening (retest-1) and the next morning (retest-2). Two-way analysis of variance (group: nap, no-nap × time: test, retest-1, retest-2) found there was a significant effect of test time and a significant group × time interaction. The juggling performance of both groups improved from test to retest-1, respectively. However, the juggling performance level of the nap group was higher than that of the no-nap group at the retest-1. As predicted, a nap promptly after learning motor skills was associated with subsequently improved performance. Moreover, the juggling performance of the nap group showed additional significant improvements in the retest-2. In the no-nap group, however, there were no significant improvements in the juggling performance after nocturnal sleep. These results demonstrate that the benefits of a nap following learning were further enhanced after nocturnal sleep. The present results may provide justification for introducing nap periods into daily athletic training as an active method to improve performance.

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1. Introduction

Sleep after learning has reportedly contributed to enhancing the consolidation of various memories in the two main memory systems, declarative and procedural memory [1–7]. This beneficial effect is expected to contribute to the improvement of skill-related performance, because the process of skill learning is related to procedural memory. A previous study has reported that the performance of sequential finger tapping improved when sleeping occurred after skill learning. Subsequent motor speed increased without a loss of accuracy [7]. Some additional findings about the details of this sleep-dependent learning have been demonstrated using the same task. The performance improvement occur not only after nocturnal sleep, but also after a daytime nap [8,9]. The

effect of sleep-dependence in the complex sequence task was greater than that in the easy sequence task [10]. Recent reports indicate that the performance of whole body movements, that are closest to a real sports performance, similarly improve after sleep [11,12]. The number of catches while three-ball juggling increased after a 2-hour nap.

Consequently, the effects of modest sleep intervention are expected to improve motor learning and sports training of athletes. However, it is still unknown if the benefits seen after a nap endures or further enhances the following day's performance after a full night's sleep. Regardless of whether napping after motor learning benefits performance, if the following day's performance does not maintain the improvement, there would be little practical benefit in napping if only a brief performance improvement is gained. The purpose of the present study is to determine if the benefits obtained by a nap after motor learning is further enhanced on the following day. We hypothesized that the following day's physical performance for those who took a nap after motor learning would be better on the following day than the performance of participants who did not nap.

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Peer review under responsibility of Brazilian Association of Sleep.

2. Methods

2.1. Subjects

The present study was approved by the ethics committee of the Waseda University. It was reviewed and carried out according to the Helsinki Declaration. Subjects with the following characteristics were included in the study: (1) 20–30 years old, (2) university or graduate students of the sport sciences, (3) three-ball cascade novices, and (4) ability to maintain a regular sleep-wake schedule (bedtime during 22:00–1:00 and rise time during 6:00–9:00). We excluded those who were: (1) smokers; (2) with a history of neurological, psychiatric or sleep disorders; (3) used hypnotics, psychotropic, or other medications; or (4) had exercise limitations as prescribed by their by medical doctor. Eighteen volunteers met the above inclusion criteria and were assigned to either the nap ($n=9$, men=5, mean age=21.0 ± 1.5) or no-nap group ($n=9$, men=5, mean age=21.9 ± 0.3).

2.2. Procedures

All subjects confirmed that they had abstained from caffeine, alcohol, and naps for 24 h before the start of the study. Subjects kept to their accustomed daily schedules, as indicated by entries in a sleep diary, which were confirmed by wearing a motion logging Actiwatch (model-AWL, Mini Mitter Co., Inc.) for a week prior to the experimental day. Subjects in the nap group came to the laboratory individually and attempted to nap for approximately 70 min (to allow an anticipated 60 min of sleep after 10 min to fall asleep) beginning at 14:00, in order to become familiar with the sleep environment before the experimental day (adaptation). One week after the adaptation visit, each subject's experimental day began at our laboratory at 10:00 (Fig. 1). The subject watched the instructional DVD, then practiced three-ball cascade juggling for 15 min before the practice test session. Testing consisted of five trials lasting for 3 min each, during which subjects continued juggling for as long as possible. All practice and test trials were video recorded. Subsequently, each subject in the nap group took a nap for around 70 min starting at 14:00, whereas the no-nap group subjects remained awake reading books or watching videos on TV. At 17:30, 7 h after the juggling test, each subject's juggling performance was re-evaluated (retest session-1). The next morning, subjects again performed the three-ball cascade at 10:30 (retest session-2).

We used the 70-minute nap protocol in order to increase the likelihood of obtaining NREM sleep, particularly slow wave sleep (SWS), which has been shown to have the greatest relevance for juggling performance improvements in a previous study [12]. To get sufficient SWS, in cases of subjects who require a long time before SWS, the time in bed was, if necessary, extended by up to 10 min. Actigraphic recordings of nocturnal sleep on the nights

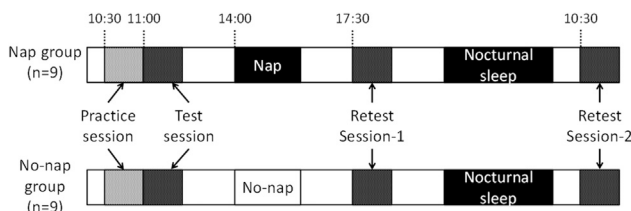


Fig. 1. Experimental design practice session: subjects practiced three-ball cascade juggling after watching an instructional DVD. Test session: juggling performance was evaluated in five 3 min trials, during which subjects continued juggling for as long as possible. After the test session, subjects in the nap group took a 70-minute nap starting at 14:00, while the control subjects stayed awake. Retest-1 session: juggling performance re-tested at 17:30. Retest-2 session: juggling performance re-tested at 10:30 the following morning.

immediately before and after the experiment were recorded in order to measure sleep quality (sleep onset and offset, total sleep, wake and sleep times as well as sleep efficiency and latency). Actiwatch produces results that are highly correlated with polysomnography [13].

2.3. Measurements

Three-ball cascade juggling was selected because it requires training and engagement of complex motor skill activities that are similar to a real sports performance. Training for juggling was done systematically by having the subjects follow video recorded instructions presented in a commercially prepared training DVD (NARANJA, Inc. JAPAN). The standard for evaluating subjects' practice was the number of ball catches after a subject threw a ball from one hand and caught it with the other. One cycle of juggling consists of a series of three ball throws and catches, which was counted as a three-time catch and explained as follows. The first ball is thrown from the right to the left hand (the first catch), and the second ball from the left to the right hand (the second catch) before the first ball reaches the left hand. Then, the third ball is thrown from the right to the left hand (the third catch), starting before the first ball comes back to the right hand. If the subject fails to catch the third ball, the catch number is recorded as two. We counted the number of catches for each subject in 3-min long trials. The methods for learning the three-ball cascade were defined based on a previous study [12].

Electroencephalograms (EEG) were recorded from 4 scalp sites (Fz, Oz, C₃, C₄, referenced to linked mastoids A2 and A1), which were placed in accordance with the International 10–20 system [14]), recorded using a Polymate recording system (AP1000, TEAC), and filtered with a time constant of 0.3 s. Horizontal and vertical electrooculograms (EOG) were recorded from the outer canthi of both eyes, and from above and below the left eye, with time constants of 0.03 s. The electromyogram (EMG) was recorded from electrodes taped to the skin above the mentalis muscles, using a time constant of 0.03 s. Electrode impedances were initially below 5 kΩ at bedtime, and the sampling rate was 500 Hz for each channel. A high-cut filter of 30 Hz was used for all channels.

Subjective fatigue, concentration, and sleepiness were measured using 100 mm visual analog scales. In the subjective fatigue scale, a 0 score indicated “vigorous,” and 100 indicated “tired.” In the subjective concentration scale, a 0 score indicated “distracted” and 100 indicated “concentrated.” In the sleepiness scale, 0 indicated “alert” and 100 indicated “sleepy.”

2.4. Statistical analysis

Juggling performance was quantified as the mean number of successful catches that were made during the five 3 min test trials. Analyses used a two-way analysis of variance (ANOVA) (group: nap, no-nap × time: test, retest-1, retest-2), with Bonferroni post-hoc testing of significance differences.

Polysomnography was scored using standardized criteria and analyzed using 30 s epochs (Rechtschaffen & Kales, 1968 [15] and the supplements and amendments to these criteria developed by the Sleep Computing Committee of the Japanese Society of Sleep Research [16]). Scored sleep stages were NREM stages 1–4, REM sleep stages, awake, and movement time. SWS consisted of both stage 3 and stage 4 NREM sleep. Total bed time, total sleep time, sleep efficiency, sleep latency, number of awakenings, and durations were calculated for each stage.

Using the Actiware version 5.0 software, the following nocturnal sleep variables were calculated from the Actiwatch data for the nights preceding and following the experimental day: sleep onset, sleep offset, total bed time, wake time, total sleep time,

sleep efficiency, and sleep latency. Unpaired *t*-tests were carried out to compare these variables between the groups.

The subjective ratings of fatigue, concentration, and sleepiness were analyzed using a two-way ANOVA (group: nap, no-nap \times time: test, retest-1, retest-2), with Bonferroni post-hoc testing when a potentially significant difference was obtained.

All analyses were conducted using software (SPSS, v 11.5; SPSS Inc., Chicago, IL, USA). Statistical significance was indicated by a *p* value of less than 0.05.

3. Results

Fig. 2 presents the comparisons of the juggling performances between groups. In the initial (training) test session, the mean number of three-ball cascade juggling catches in the nap group was 4.4 ± 1.7 (mean \pm SD), which was not significantly different from the no-nap group mean of 3.4 ± 2.2 . In the retest-1 after the nap, the mean number of juggled catches for the nap group increased significantly to 7.7 ± 3.2 , whereas the no-nap group did not, averaging 4.6 ± 3.2 . Over the additional 12 h that included nocturnal sleep following retest-1, the mean number of catches for the nap group demonstrated an additional significant increase to 13.8 ± 6.4 , whereas, again, the no-nap group did not, and averaged 7.1 ± 5.1 . There was a significant main effect of test time ($F_{2,32}=31.25$, $p\eta^2=0.66$, $p < 0.001$), and significant group \times time interaction ($F_{2,32}=5.89$, $p\eta^2=0.27$, $p=0.024$). The results of the post-hoc analysis showed that the mean number of juggled catches in the nap group increased from test to retest-1 ($p < 0.001$), and retest-2 ($p < 0.001$), and from retest-1 to retest-2 ($p < 0.001$), respectively. In the no-nap group, the mean number of juggled catches significantly increased from test to retest-1 ($p=0.027$) and retest-2, respectively, but did not show any significant increase from retest-1 to retest-2 ($p=0.061$). The nap group had a significantly greater mean number of juggled catches in the retest-1 ($p=0.049$) and retest-2 compared to the no-nap group ($p=0.027$).

Based on the results of the sleep variables obtained from the 70-minute nap, participants of the nap group slept 65.8 ± 7.6 (mean \pm standard deviation) minutes, with a good sleep efficiency of $91.9 \pm 5.0\%$ and sleep latency of 6.1 ± 2.8 min, respectively. Thus, all nap group subjects obtained a substantial amount of sleep with good quality indicators under laboratory conditions. The duration of sleep in stages 1, 2, slow wave (stages 3 and 4), and REM were 9.6 ± 3.0 , 28.2 ± 5.4 , 15.9 ± 10.2 and 11.7 ± 7.8 min, respectively (Table 1).

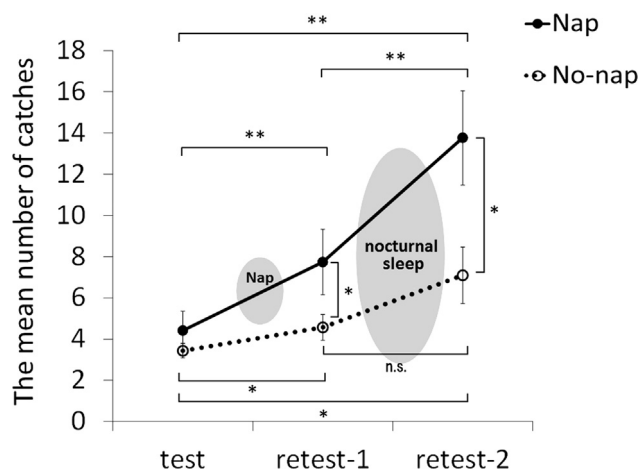


Fig. 2. Comparison between the nap and no-nap groups of the mean number of catches while juggling. The solid line identifies the nap group, while the dotted line identifies the no-nap group. Error bar shows the standard error. ** $p < 0.001$. * $p < 0.05$. n.s. not significant.

In the nap group, results from nocturnal sleep, including qualities inferred from actigraphy on the night prior to the experimental day including the bed, rise, and total sleep times were $23:31 \pm 70.0$, $7:00 \pm 57.0$, 370.2 ± 76.2 min and sleep efficiency was $82.9 \pm 3.9\%$. In the no-nap group, bed, rise, total rise times were $23:50 \pm 46.0$, $7:02 \pm 46.0$, 367.3 ± 57.9 , respectively, and sleep efficiency, respectively. There were no significant differences in each variable between groups. The results of the sleep variables on the night following the experimental day in the nap group showed the bed, rise, and total sleep times were $23:46 \pm 49.0$, $7:22 \pm 51.0$, 374.1 ± 56.7 min, respectively, and sleep efficiency was $82.9 \pm 4.9\%$. In the no-nap group, sleep variables on the experimental following night including the bed, rise, and total sleep times were $0:08 \pm 42.0$, $7:26 \pm 31.0$, 377.7 ± 72.6 min, respectively, and sleep efficiency of $83.5 \pm 5.2\%$. There were no significant differences between the groups for all sleep variables (Table 2).

In the assessment of subjective fatigue, there was no significant main effect of test time ($F_{2,32}=0.55$, $p\eta^2=0.03$, $p=0.581$) and no significant group \times time interaction ($F_{2,32}=1.24$, $p\eta^2=0.07$, $p=0.304$). Similarly, subjective concentration showed no significant main effect of test time ($F_{2,32}=1.57$, $p\eta^2=0.09$, $p=0.223$), and no significant group \times time interaction ($F_{2,32}=2.01$, $p\eta^2=0.11$, $p=0.150$). In subjective sleepiness, there was no significant effect of test time ($F_{2,32}=0.43$, $p\eta^2=0.03$, $p=0.657$), but there was a significant group \times time interaction ($F_{2,32}=5.16$). There were also no significant differences between groups during the test ($p=0.120$), retest-1 ($p=0.050$), or retest-2 ($p=0.168$), respectively. The subjective sleepiness in the nap group significantly decreased from test to retest-1 ($p=0.017$), and increased from retest-1 to retest-2 ($p=0.020$). In the no-nap group, there were no significant differences in the subjective ratings of sleepiness between the test to retest-1 ($p=0.139$) and retest-1 to retest-2 ($p=0.209$) (Fig. 3).

4. Discussion

Juggling performance improved significantly for the group that took a nap between the test and retest-1 performances, but an improvement was also found in the no-nap group that remained awake between performance tests. The improvement in the no-nap group between the test and retest-1 performances is not consistent with our previous study [12]. A possible reason for this inconsistency is a difference in the subjects. Subjects in the present study included men and women whereas the previous study included only women. There are thought to be sex differences in motor performance.

In the present study, there were significant differences in the

Table 1

Polysomnographic sleep variables from the nap that followed motor learning. NREM, non-rapid eye movement sleep; REM, rapid eye movement sleep; SD, standard deviation.

| | Mean | SD |
|-----------------------------|------|------|
| Total bed time (min) | 71.5 | 6.2 |
| Total sleep time (min) | 65.8 | 7.6 |
| Sleep efficiency (%) | 91.9 | 5.0 |
| Sleep latency (min) | 6.1 | 2.8 |
| Number of waking episodes | 0.7 | 1.1 |
| Duration in NREM sleep | | |
| Stage 1 (min) | 9.6 | 3 |
| Stage 2 (min) | 28.2 | 5.4 |
| Stage 3 (min) | 15.9 | 10.2 |
| Stage 4 (min) | 2.9 | 4 |
| Duration in REM sleep (min) | 11.7 | 7.8 |

Table 2
Actigraphic sleep measurements of the nights prior to and following the experimental day.

| | Previous day night | | | Experimental day night | | |
|------------------------------|--------------------|-------|-------|------------------------|-------|-------|
| | Mean ± SD | d | P | Mean ± SD | d | P |
| Bed time (h:min) | | | | | | |
| Nap | 23:31 ± 70.0 | -0.33 | 0.499 | 23:46 ± 49.0 | -0.48 | 0.319 |
| No-nap | 23:50 ± 46.0 | | | 0:08 ± 42.0 | | |
| Rise time (h:min) | | | | | | |
| Nap | 7:00 ± 57.0 | -0.04 | 0.929 | 7:22 ± 51.0 | -0.11 | 0.826 |
| No-nap | 7:02 ± 57.0 | | | 7:26 ± 31.0 | | |
| Time in bed (min) | | | | | | |
| Nap | 444.1 ± 76.9 | -0.11 | 0.824 | 449.1 ± 44.6 | -0.06 | 0.904 |
| No-nap | 451.3 ± 56.7 | | | 452.2 ± 61.3 | | |
| Total sleep time (min) | | | | | | |
| Nap | 370.2 ± 76.2 | 0.04 | 0.929 | 374.1 ± 56.7 | -0.05 | 0.923 |
| No-nap | 367.3 ± 57.9 | | | 377.7 ± 72.6 | | |
| Sleep onset latency (min) | | | | | | |
| Nap | 14.9 ± 5.6 | -0.07 | 0.882 | 12.3 ± 7.3 | -0.19 | 0.698 |
| No-nap | 15.4 ± 9.5 | | | 13.4 ± 4.2 | | |
| Wake after sleep onset (min) | | | | | | |
| Nap | 73.8 ± 5.6 | -0.64 | 0.192 | 75.0 ± 17.5 | 0.24 | 0.687 |
| No-nap | 84.0 ± 17.4 | | | 71.8 ± 15.8 | | |
| Sleep efficiency (%) | | | | | | |
| Nap | 82.9 ± 3.9 | 0.44 | 0.374 | 82.9 ± 4.9 | -0.11 | 0.821 |
| No-nap | 81.2 ± 4.4 | | | 83.5 ± 5.2 | | |

number of juggled catches in retest-1. These results suggest that although both the nap and no-nap groups improved in juggling performance over time [17,18], performance improvement was enhanced by taking a nap shortly after practice. This indicates that napping facilitates motor learning and improves performance.

Although there were no differences in the subjective ratings of fatigue or concentration between groups, which could be expected to reflect the benefits of the nap, the changes in juggling performance appear to have been facilitated by sleep. The subjective rating of sleepiness in the nap group after the nap was lower than in the no-nap group. However, the subjective rating of sleepiness in both groups showed no differences between test and retest-1, and juggling performance improved. Thus, it can be concluded that changes in juggling performance were attributable to the nap.

The most profound finding in the present study was that juggling performance for the nap group showed a further second significant improvement the following morning after nocturnal sleep between retest-1 and retest-2. In contrast, juggling performance for the no-nap group was not statistically improved the following morning. Furthermore, the differences in performance levels between groups were greater in retest-2. Previous studies that used discrimination [8] and a finger-tapping task [19] reported improvements in performance after 60–120 min of napping, and improved further the following day after nocturnal sleep. Our improved juggling performance the following morning is consistent with these studies.

In the earlier visual learning study just described, the no-nap group did not significantly demonstrate improved performance the day following nocturnal sleep. That result is consistent with our present study. However, another previous study using a finger-

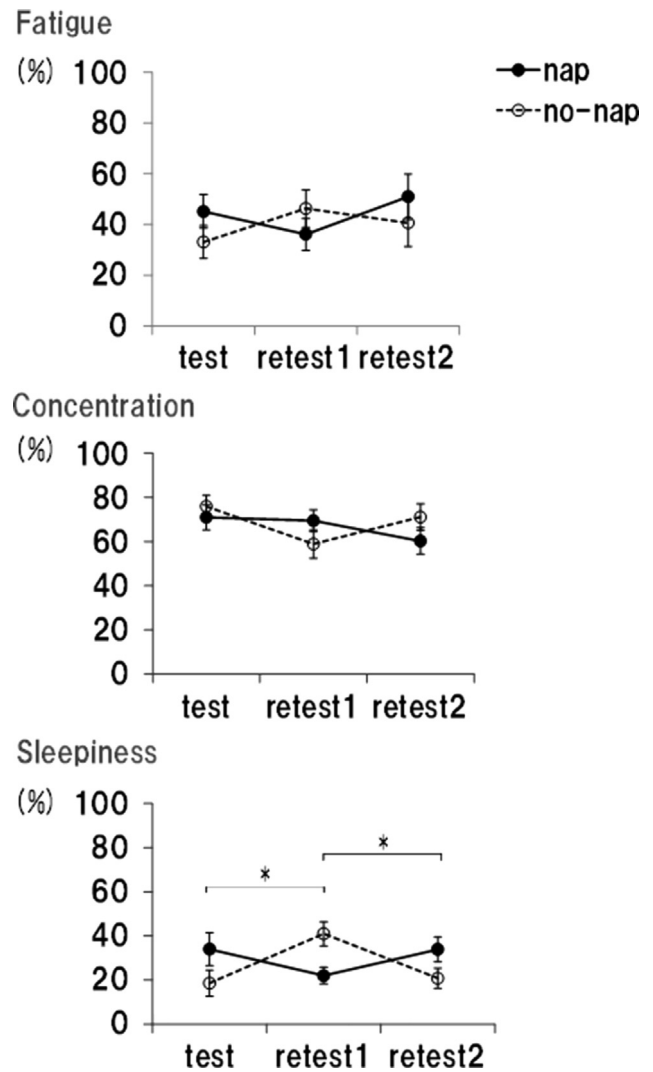


Fig. 3. The assessment of subjective fatigue, concentration, and sleepiness. The black bars indicate the nap group, while the white bars identify the no-nap group. Error bar, standard deviation. **p* < 0.05 in the nap group.

tapping task reported that both their nap and no-nap groups improved their performances the following day. That difference from the present results could be attributable to differences in task difficulty. Three-ball cascade juggling, which is similar to real sports learning, is a more complex procedure with multiple memory and learning requirements, which may not duplicate those required for the finger-tapping task. Indeed, acquisition of the three-ball cascade requires three learning processes [20,21]. Therefore, participants could not completely master the juggling skill in the allotted few initial training and practice sessions. In other words, all subjects remained in the learning stages of juggling.

It could also be that the 15 min of retest-1 may have played a role as an enhanced training session. Given the performance improvement after the nap that was evident in retest-1, the nap subjects had already become experts at the task, and so they essentially continued their learning from a much more expert level for 15 min during retest-1, while the no-nap subjects could only continue from their still disorganized and inefficient level. Thus, the additional benefits of nap sleep could not be obtained by nocturnal sleep for the no-nap group, whereas the already improved juggling performance was further enhanced by nocturnal sleep in the nap group.

Regardless of cause, although the present nap and no-nap groups experienced the same practice and test periods and obtained similar nocturnal sleep time (and similar sleep quality), only the nap group improved their juggling performance the following morning. These results indicate that the beneficial effect of the nap immediately after practice was itself further enhanced by nocturnal sleep. Therefore, sleep right after learning or motor skills practice can have important benefits for improving performance. These results suggest that a nap right after initial motor skill acquisition results not only in improvement of the skill itself (possibly, by enhancing the consolidation processes) but also establishes a brain state that facilitates functions of the subsequent natural sleep period and enable the further improvement of performance. We still do not know whether the nap and following night's sleep are quantitatively or qualitatively different, but such differences should be carefully examined in future studies.

Some limitations of the present study should be discussed. First, although we were able to determine that the effect of the nap on performance after juggling learning was further enhanced the following day, in future work, all-night polysomnograms should be recorded in order to allow inspection of the expressed sleep EEG qualities to assess their possible relationships with improved performance. For example, a previous study found that slow oscillation, delta wave, and sigma wave EEG spectral power increased significantly during SWS after juggling learning compared to a baseline nap (no learning day) [12]. However, we did not conduct baseline polysomnography in the present study to reduce the experimental burden on the subjects. Thus, we could not determine the relationship between SWS and juggling performance.

Second, there might be sampling bias because of our small sample size. Moreover, all subjects were recruited from students of sport sciences. Because juggling is a complex motor skill, the subjects' prior motor performance level might have affected the results. To reduce such differences between subjects, we recruited a homogeneous group. However, this did not guarantee equal ability in juggling performance learning.

5. Conclusion

Our results indicate the advantageous effects of a nap can be further enhanced following nocturnal sleep and are evident in the following day's performance. Furthermore, sleep right after learning or motor skills practice can have important benefits for improving performance. The present results may provide more convincing justification for introducing nap periods into daily athletic training as an active method to improve performance, not just as a passive opportunity for recovery from fatigue.

Conflicts of interest

Nothing to disclose.

Acknowledgments

This work was aided by the Japan Society for the Promotion of Science (JSPS) through the Grant-in-Aid for JSPS Fellows. The authors thank Dr. Thomas Maloney for kind and detailed editing of the manuscript.

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