Motriz, Rio Claro, v. 28, 2022, e10220017221 *DOI: http://dx.doi.org/10.1590/S1980-657420220017221*

Neural Control of Movement

The role of nocturnal sleep on the retention, adaptability, and relearning rate of a motor skill

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Abstract - Aim: The influence of sleep on the adaptability and relearning rate during learning of complex motor skills is still unknown, limiting the comprehension of the sleep role in motor memory consolidation. Thus, we aimed to investigate the nocturnal sleep influence on retention, adaptability, and relearning rate of the dart-throwing task. **Methods:** Sixty healthy adults were divided into two groups: SLEEP and WAKE. Both groups practiced an under-arm dart-throwing task. However, WAKE practiced in the morning and performed a retention phase in the evening, and SLEEP practiced in the evening and performed a retention phase in the morning of the next day. The practice and retention phases were separated by 12 h in both groups. There were analyses regarding retention (retention test), adaptability (delayed transfer test), and relearning rate (savings). **Results:** Both groups improved their performance across the acquisition phase and maintained it in the retention test. The groups did not demonstrate adaptability and did not demonstrate a significant difference in relearning rate. **Conclusion:** We conclude that nocturnal sleep did not modulate the consolidation of motor memories related to ballistic discrete motor skills.

Keywords: sleep, consolidation, motor memory, discrete motor skill, motor learning.

Introduction

Motor learning is a set of processes associated with practice or experience leading to relatively permanent changes in the capability for skilled movement[1]. During motor skill acquisition, practice-dependent behavioral improvements are derived from changes in functional networks in the Central Nervous System (CNS), which are recognized as motor memories[2,3].

Motor memory creation is a time-dependent process, mainly composed of three phases: encoding, consolidation, and retrieval[3,4]. Encoding is the initial phase when the memory engram creation occurs[5]; for motor memories, the encoding mainly happens during practice[3]. Consolidation is the post-practice phase when the memory becomes more robust and stable with less susceptibility to interference[4,6]. Then, savings of the improvement achieved during practice (retrieval) is consolidation-dependent[2,7,8]. Therefore, the relative permanence of the improved performance which characterizes motor learning is mainly developed during the consolidation phase[3,8].

It has been suggested that motor memory consolidation occurs during wakefulness periods that are temporally close to practice and during sleep[8,9]. In this way, it is supposed that sleep has a critical role in motor memory consolidation and consequently in motor learning[10-13].

Several behavior-based studies identified that nocturnal sleep stabilizes[14] or even enhances[15-17] motor performance after practice. Interestingly, some findings demonstrated that whole-body and complex motor skills are more susceptible to consolidation sleep-dependent mechanisms[14,18] than less complex motor skills, such as finger sequences[19] or continuous motor tracking tasks[20]. In fact, there is a call to action in the Motor learning area to use complex motor skills as the to-be-learn motor task in the experiments. Given that, the principles created by simple task studies are not generalized to complex motor skills[21], such as sports skills and activities of daily living.

Only one study with complex motor skills (dance routine implanted on a video game - PlayStation 2, Game Dance Stage) verified whether the nocturnal sleep influences the adaptability of the improved performance to a new variety of performance contexts characteristics[22]. In this case, the nocturnal sleep did not impact the performance of a new sequence of a dance routine. However, in this study, Genzel et al.[28] did not verify the effect of sleep on the adaptability of the motor task practiced; instead, they investigated whether sleep influences the transfer to a new motor skill (a new dance routine). Therefore, the effects of sleep on the adaptability of a motor task previously practiced still is unknown.

Also, an interesting aspect that is still unfilled in this literature is whether sleep can impact a subsequent practice. It has been postulated that reacquiring a skill that has already been learned once before (but then apparently forgotten or partly remained) is typically faster than learning it the first time, being this phenomenon called savings[2]. Also, to the best of our knowledge, no studies have directly tested the influence of nocturnal sleep on savings.

Regarding Christina[23], there is an improvement in the inference about motor memory construct underlying learning and retention as more than less performance information is known[23]. Therefore, including savings and transfer measures can benefit motor learning inferences (for a review about transfer, savings, and retention in motor learning inference, see Christina and colleagues[23-25]).

In this way, we aimed to investigate the influence of nocturnal sleep on complex motor skill learning. More specifically, we assess the impact of the nocturnal sleep on 1- retention, 2 - adaptability through a transfer test, and 3 - relearning (savings). Based on previous studies, we hypothesized that a nocturnal sleep would enhance the persistence and adaptability of the improved performance, and it would induce a faster relearning rate.

Methods

The ethics board from the State University of Piaui approved this study (protocol number. 30227720.0.0000.5209). All participants signed the consent term before participation. There were no monetary or other types of compensation to participate in this study. All experiment was conducted following Helsinki Declaration.

Participants

We recruited 60 participants from the local university community, aged 18-39 years old (M = 25.35; SD = 5.65), 31 men and 29 women. The inclusion criteria were: 1 - Visual, neuromotor, and cognitive conditions for understanding and executing the proposed tasks; 2 - Right-handed regarding the Edinburgh Handedness Inventory[26]. The exclusion criteria were: 1 - Osteoarticular diseases or disfunction which unviable the performance of the proposed activities; 2- Do not use a corrective lens in case the participant has unsatisfactory visual acuity; 3 - Previous experience in the dart-throwing task. 4 - The participants were oriented to have good nocturnal sleep one day before and during the experiment. They needed to have 7-9 h of nocturnal sleep and subjectively perceive the nights of sleep as satisfactory to recover for the next day. There was no participant removed concerning this last criterion.

Instruments and tasks

The participants practiced an underarm dart-throwing task used in previous motor learning studies (i.e., Al-Abood et al.[27]). The task goal was to score as many points as possible by throwing darts (Winmax® WMG50374) with the dominant arm towards a target dartboard. The target was placed on the floor 3 m away from a throwing line. The darts had 30 g and a length of 15 cm. The target contained ten concentric circles, with the middle circle having a diameter of 2.25 cm, with each other circle increasing by 2.25 cm in radius. We determined 10 points to trials that hit the bullseye with each concentric circle radiating out from the decreasing by one point. Hence, the outermost circle was awarded only one point. If the dart hit the outside of the target, it was attributed 0 points.

Design and procedures

After the participants signed the informed consent, they were randomly allocated into two groups: the Sleep Group (SLEEP) (n = 30), which had a nocturnal sleep between the acquisition phase and the retention phase, and the Wakefulness group (WAKE) (n = 30) that completed the acquisition phase and retention test in the same day.

To characterize the chronic sleep condition of the participants, firstly, they answered the Pittsburgh Sleep Quality Index (PSQI). After, they received instructions about the motor task. Regarding the task's goal, the participants received the following verbal instruction: “try to throw the dart as accurately as possible into the center of the target”. Also, they received visual instruction concerning the movement parameters through a video of a skilled person performing the task.

After the instructions, the participants performed 3 trials to familiarize themselves with the task. Following, they completed a pre-test composed of 5 trials. The acquisition phase was composed of 115 trials organized in 23 blocks. The participants rested 1 minute among the blocks of practice to avoid deleterious effects from fatigue. After practice, the participants performed a post-test with similar conditions to the pre-test. After 12 h from the post-test began the retention phase, the participants performed a retention test identical to the pre-test and post-test. Then, the participants performed a delayed transfer test at a distance of 4 m to the target, composed of 1 block of 5 trials. Finally, the target was reallocated to 3 m away from the participants; then, the participants performed 24 blocks of 5 trials interspersed with 1 minute of rest to assess the relearning rate (savings).

The unique aspect that differentiated the SLEEP and WAKE was the time of day that the acquisition phase and the retention test were allocated. The WAKE performed the acquisition phase between 7:00 and 8:00 am, and the retention test was performed at night on the same day, between 7:00 and 8:00 pm. SLEEP had the acquisition phase between 8:00 and 9:00 pm, and the retention test was performed between 8:00 and 9:00 am on the following day. The participants were oriented to wake up 1 h before the tests in the morning. The general experimental design can be checked in Figure 1.

Measures

We assessed the motor performance of the participants through Root Mean Square Error (RMSE), being the total amount of "spread" of the movements about the target, so it represents an overall measure of how successful the performer was in achieving the target[1], through the equation:

$$RMSE = \sqrt{\sum (x_i - T)^2/n}$$

where x_i = score on trial i, T = score maximum of the target, n = number of trials.

Statistical analysis

We used STATISTICA 11.0 (StatSoft Inc., Tulsa, OK, USA) and Microsoft Excel 365 software for statistical analyses adopting a 5% significance level. We evaluated the normality and homogeneity of the data with the Shapiro Wilks and Levene tests, respectively. We compared TSQI (sum of the components) between the groups using the Student's t-test.

We performed an ANOVA two-way - 2 groups (SLEEP, WAKE) x 4 times (pre-test, post-test, retention test, and transfer test) with RMSE to verify whether sleep influenced motor improvement, retention, and adaptability. Tukey test was used for post hoc analyses. We evaluated the savings by computing the number of blocks of trials required for the participants to reach the mean performance achieved in the post-test during the savings phase. Next, we compared the number of blocks between SLEEP and WAKE through a Student's t-test.

Lastly, we addressed whether the chronic quality sleep identified by TSQI influences the consolidation process of the SLEEP, comparing the RMSE in the retention test between individuals with poor and good sleep quality through a Student's t-test.

Result

Regarding the PSQI, there was no significant difference between SLEEP and WAKE for the sum of the components ($p = 0.12$; SLEEP M = 4.76, SD = 2.56; WAKE M = 5.96, SD = 3.40). In the SLEEP, 11 participants had poor sleep quality, while 19 had good sleep quality; for WAKE, 14 participants had poor sleep quality, and 16 participants had regular sleep quality.

Analyzing the RMSE in comparing the pre-test, post-test, retention test, and transfer test (Figure 2), the two-way ANOVA did not demonstrate interaction effects and statistical significance in the Group factor. However, the Time factor was statistically significant ($F_{1,58} = 4.79$, $p < 0.01$, $\eta^2 = 0.07$). The Tukey post hoc test revealed that the post-test ($p = 0.01$) and the retention test ($p < 0.05$) differed significantly from the pre-test. There

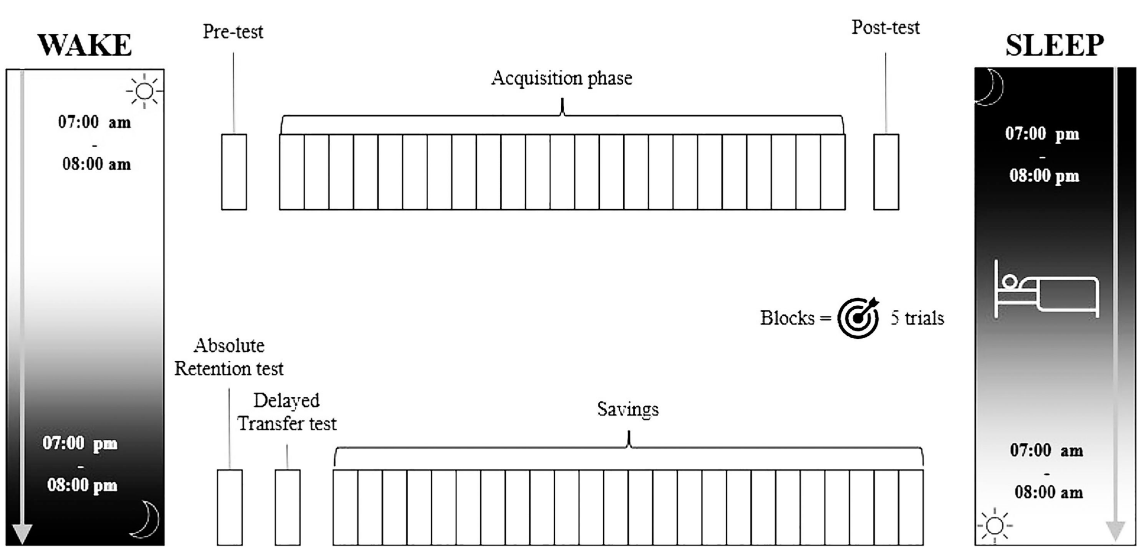

Figure 1 - Experimental design timeline.

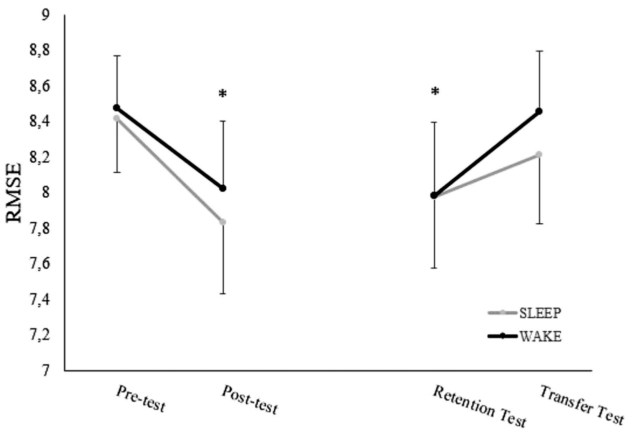

Figure 2 - Performance on the underarm dart-throwing task as assessed by root means square (RMSE) across practice, retention, and transfer period. Data are presented as mean and 95% confidence interval by each group. * = significant difference in Time factor in comparison to pre-test.

was no significant difference between the pre-test and transfer test (p = 0.91), indicating that groups did not demonstrate adaptability independently of the nocturnal sleep occurrence. Thus, our findings indicated that SLEEP and WAKE improved their performance, maintained it in the 12 h-retention test, and did not demonstrate adaptability in the delayed transfer test, without difference between them.

Lastly, our savings analysis through the students' t-test revealed no significant difference between SLEEP and WAKE regarding the relearning rate (p = 0.88, SLEEP: M = 3.56, SD = 4.76, WAKE: M = 3.40, SD = 3.71) (Figure 3). These findings indicate that nocturnal sleep did not impact the relearning rate (savings) of a motor skill previously practiced.

Finally, there was no significant difference for RMSE in the retention test between SLEEP participants classified with good and poor sleep quality in PSQI (p = 0.12; poor: M = 7.85, SD = 1.23, good: M = 8.04, SD = 1.08), which suggests that the chronic quality sleep did not influence the consolidation process of the SLEEP.

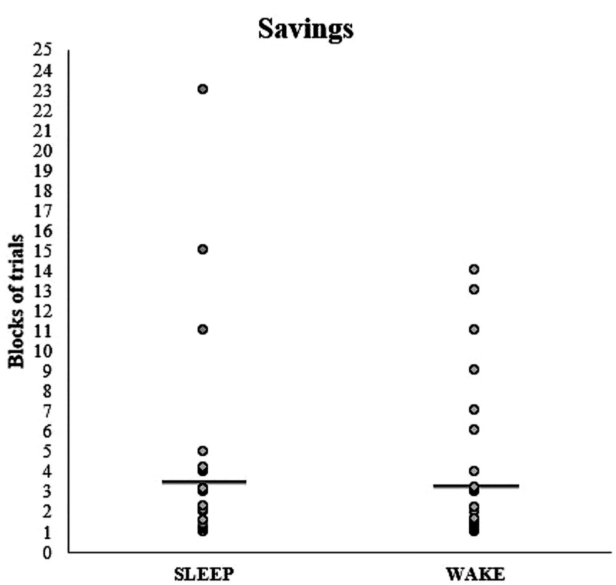

Figure 3 - Number of blocks during the relearning phase needed to achieve the post-test mean performance for each participant. Data show the mean (solid line) and individual data (dots).

Discussion

We investigated whether nocturnal sleep influences the learning of a complex discrete motor skill. We adopted an experimental design that allowed us to infer the nocturnal sleep role in the retention, adaptability, and relearning rate. Our findings revealed that nocturnal sleep did not influence the retention, adaptability, and relearning rate. The SLEEP and WAKE groups demonstrated motor learning with the same behavior, which did not corroborate previous studies.

Given that motor learning is a process composed of improvement (gains in motor performance derived from practice), consistency (performance becomes increasingly more consistent), persistence (relatively permanent improvement in performance), and adaptability (the improved performance is adaptable to a variety of performance context characteristics)[28]. Our study was the first that includes a complete inference about the essential characteristics of the performance across the motor learning processes in the experimental design. Previous studies did not include transfer tests and savings analyses in their experiments, which may induce an incomplete assessment of motor memory creation[25,29].

Even with the lack of inference about adaptability and savings in previous studies, the influence of sleep on motor memory consolidation and motor learning is consistently confirmed[10,12,13]. The difference between our findings with the previous studies can be related to the fact that the influence of sleep on motor memory consolidation is task characteristic-dependent[10].

It has been supposed that tasks with a strong cognitive component tend to be supported by sleep-dependent processing[30], which may explain why complex and whole-body motor tasks are more influenced by sleep-dependent offline processes, given their higher cognitive demand[12]. It has been suggested that some neuronal circuits involved in motor learning are consolidated in the wakefulness period while others are sleep-dependents[4,5,8].

One aspect that maybe be related to the difference between our findings and the previous results in the literature is the task characteristics. In our study, we assessed the role of nocturnal sleep in the learning of a discrete motor task. In contrast, previous studies used bimanual arm movements[31], shooter video game task[32], bimanual finger tapping tasks[15], unrestricted reaching task with the non-dominant hand involving horizontal displacement[16,33], dance choreography in a videogame apparatus[22], finger tapping task, pursuit tracking task, and countermovement jump (60% of individual maximum)[14], and a locomotor task under dual-task requirement[17]. Analyzing all these studies, just one did not report the difference between wakefulness and nocturnal sleep in the retention test[14]. This study used a countermovement jump task (60% of individual maximum), a discrete task as the underarm dart-throwing task. Nocturnal sleep improved motor consolidation for all motor tasks (serial or continuous), inducing a better retention test.

Classical studies already had signalized that discrete motor skills demonstrate less retention than continuous motor skills[34,35]. Two hypotheses have been used to explain this phenomenon[1]: 1 - Discrete motor skills have more cognitive demands that are less robust to the forgotten than motor components, 2 - The practice of discrete motor skills typically consists of a single adjustment or action, receiving less amount of motor practice than continuous tasks, for example.

However, a third hypothesis can be created based on our and previous findings. We suppose that the consolidation of discrete motor skills is less susceptible to sleep-dependent processes, allowing less robustness against forgetfulness for this type of motor memory. In this way, neurocognitive findings have indicated parallel neural networks to process and store movement components and goal components of the motor skill to be learned[6,36,37]. Additionally, the goal component is processed and stored during sleep, while the movement component is wakefulness-dependent[4,6].

The primary mechanism to improve the motor performance of discrete motor skills (such as countermovement jump and dart-throwing tasks) is to enhance the movement component (parameterization of force and speed) because the goal component remains the same among the trials (jump in a specific height or throw it into the center of the target). This task-specific demand could induce a lower effect from the sleep-dependent consolidation processes for discrete motor skills, which explains our results compared to previous studies.

Further investigations can address the effect of the nocturnal sleep on the consolidation of different complex motor tasks (serial, discrete and continuous tasks) to verify whether the characteristics of the task influence the sleep-dependent consolidation participation. These further studies should include transfer tests and saving analyses to verify the motor memory creation process, as we did in this study.

In our study, we controlled the amount of sleep in the SLEEP group (7-9 h), the chronic quality of the sleep through the Pittsburgh Sleep Quality Index (PSQI), and the time to wake up before the retention test (1 h). However, we did not control the sleep quality between the acquisition phase and retention test for SLEEP. It can be interpreted as a limitation because sleep quality influences the potential of motor memory consolidation[17,38].

We adopted a "varied time design" (AM-PM versus PM-AM) to study the role of sleep on motor memory consolidation. It has been well documented that the circadian cycle is a covariable in this design[39]. However, other designs also have their limitations. For example, using nap as an independent variable with two groups practicing at the same period can avoid the influence of the circadian cycle[39]. However, nap design does not engage the same nocturnal sleep mechanisms[10]. Also, we have the "deprivation design"[39,40], which both groups practiced in the evening and tested on the following day. Though, one group remains without sleep. In this case, we could control the circadian cycle effects, but we have the detrimental somnolence effect on the retention test for the experimental group[10,39]. Further studies may include different experimental designs (varied time, nap, and deprivation) to provide a complementary comprehension of the sleep role in learning complex motor skills.

Conclusion

Our results suggest that nocturnal sleep does not influence the learning of a discrete motor skill. Specifically, nocturnal sleep does not affect the retention, adaptability, and relearning rate of a discrete motor skill. We believe that the consolidation process of discrete motor skills is mainly based on wakefulness-dependent consolidation processes, given the low demand for movement components of discrete motor skills compared to serial or continuous motor tasks.

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Manuscript received on October 29, 2021
Manuscript accepted on May 5, 2022