Consolidation of complex motor skill learning: evidence for a delayed offline process

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Abstract
Following initial acquisition, studies across domains have shown that memories stabilize through consolidation processes, requiring a post-acquisition temporal interval to allow their occurrence. In procedural skill memories, consolidation not only stabilizes the memory, but also simultaneously enhances it by accumulating additional gains in performance. In addition, explicit skill tasks were previously shown to consolidate through sleep, whereas implicit tasks were consolidated following a time interval which did not include a period of sleep. Although previous research has been instrumental in utilizing simple motor tasks designed to model skill learning, whether and how skill consolidation processes operate in complex real-life environments remains to be determined. Here, we tested consolidation in a complex motor skill, used to train execution of fine-motor movements. Since the complex task was explicit, we hypothesized that consolidation will be evident immediately following sleep, as in simple explicit motor skills. However, results show that even though participants were aware of the goal of the complex skill task, consolidation was evident only 24 hr following skill acquisition, and not following a shorter 12 hr interval, even when the latter included sleep. An additional experiment verified that without a temporal interval longer than 12hr, the same skill training does not undergo complete consolidation. These results suggest that task complexity is a crucial characteristic determining the proper terms allowing full consolidation. Due to the enhanced ecological validity of this study, revealing the differences between complex and simple motor skills could enable the facilitation of advanced rehabilitation methods following neurological injuries.

Statement of Significance
In the research of skill learning and its consolidation, previous studies have focused on simple motor tasks, leaving a gap in knowledge regarding complex skill learning in real-life environments, and the existence and characteristics of its consolidation processes. Here, we tested complex motor skill consolidation, requiring execution of fine-motor movements. In a set of studies, we showed that complex skill consolidation required a delayed 24 hr post-acquisition phase, and was not evident following shorter intervals, even if they included sleep. The identification of an extended consolidation process in complex skills is highly relevant for clinical translation, allowing advanced neurological rehabilitation, as well as facilitation of complex learning in healthy populations.

Key Words: skill learning; sleep; procedural memory; consolidation; fine-motor; offline gains
Introduction

Upon learning new information, the brain encodes that information in the form of a new memory, establishing the required mechanistic molecular- and systems-level adaptations. Therefore, following the initial encoding stage, the memory undergoes a process of consolidation [1], during which new protein-synthesis forms and stabilizes the new memory ensemble [2, 3]. As a consequence, consolidation promotes the memory to a stable state, reducing its susceptibility to interference [1, 4].

Being vastly studied across different memory domains, consolidation received extensive attention in the field of procedural memory, due to the interesting phenomenon of “offline gains” [5–11]. Offline gains are improvements in performance evident following a consolidation interval which does not include any further practice. That is, in procedural memories, participants achieve a certain level of performance at the end of the initial acquisition session, but when tested again following consolidation, additional offline improvements in performance are evident.

Offline gains in performance can be either sleep-dependent, evident immediately following sleep, or time-dependent, evident following the passage of a time interval which does not contain sleep [12]. In motor skill learning, this dissociation is based on differences in task properties. Some experiments have shown that explicit motor skill memories, in which participants are fully aware of the goal of the task, required between-session sleep to fully consolidate, whereas implicit motor skill memories required passage of time per se to consolidate, even when this time interval does not include sleep [13].

In daily life, the human brain is required to learn and consolidate motor skills with varying difficulties, at times even demanding complex motor skill learning. Such complex motor learning could be based on different neural mechanisms relative to simple motor learning, possibly requiring the recruitment of attentional, spatial, and perceptual systems along with the known mechanisms engaged in simple motor skill learning [14, 15], or modified motor sequence learning tasks [16–18]. Such variations of sequence learning included longer sequences (nine or eight elements instead of the common five-element sequence) or bimanual tapping. Studies testing explicit sequence learning reported offline gains in performance, independent of the length of the sequence, with a higher rate of offline gains following bimanual tapping of the longer sequence [16, 18]. In addition, a study testing consolidation of implicit sequence skills in either unimanual or bimanual tapping reported no sequence-specific offline gains, but rather general motor skill over-night improvements [17]. However, complex skills in daily life might be composed of different properties than finger-tapping tasks, possibly engaging different neural mechanisms. Since this study focused on complex skill learning, we sought to use a new task which requires fine-motor movements and resembles daily-life complex skills. Hence, as a step towards revealing the mechanisms underlying complex skill learning, this study tested the existence of an offline consolidation process following acquisition of a complex fine-motor skill, and whether such a process is sleep-dependent.

To examine complex motor skill learning, naïve participants learned a complex skill requiring fine-motor movements (originally used to train dental-medicine students). They were retested twice, following 12 and 24 hr from acquisition, whereas only one of the two intervals included nocturnal sleep. Since participants were aware of the goal of the task, as in simple explicit motor tasks, we hypothesized that consolidation of the complex skill will be sleep-dependent, showing improved performance when retested following sleep.

Methods

Participants

Forty-seven naïve healthy participants aged 18–30 (23 females, mean age 23.7 years, SD = 3.8 years) gave their written informed consent to participate in the study, which was approved by the Tel Aviv University Institutional Ethics Committee. All procedures were in accordance with approved guidelines. Participants were right-handed, declared no prior medical history of psychological or neurological problems, and no addiction to drugs or alcohol. To assure the novelty of the task for the participants, all of them were not dental-medicine students and declared no relevant background. In addition, participants reported at least 7 hr of sleep the night before each experimental session and rated their wakefulness to be high (score less than 3 in the Stanford Sleepiness Scale [19], see Supplementary Table S1, ensuring high wakefulness). Participants were instructed not to consume alcohol, caffeine or drugs for 12 hr prior to and between the experimental sessions.

Task

The task was developed by a cooperation between investigators from the school of dental medicine, faculty of engineering, and occupational therapy in Tel Aviv University, aimed to provide complex motor skill training for dental-medicine students. The portable tool is composed of two jaws, gingival tissue and a rubber cover which simulates the mouth of the patient. Replaceable plastic teeth are assembled on the jaws. Two specific teeth produced by a 3D printer (Objet 3D printer, Stratasys Ltd., Minnesota US, Utilize Polyjet jetting technology) were each designed with five holes in different directions. The tool was attached to a table with a compatible stand (Figure 1A).

During each trial of the task, participants were instructed to insert 10 metal pins into the specific holes in the plastic teeth (Figure 1B), using a tweezer held by their dominant right hand. The number of trials differed between sessions according to the experimental design (see below). The end-point measure was the total time (seconds) to complete the insertion of all 10 pins into all holes of both plastic teeth. This measure combines both speed and accuracy since it quantifies the time to complete correct and accurate insertions of each pin. Performance was not videotaped and was carefully monitored visually by the experimenter. To assure consistency, all 47 participants were instructed and evaluated by the same experimenter.

To measure their initial ability for fine-motor skills, participants performed the O’Connor tweezer dexterity task at the beginning of the study, before acquiring the complex motor skill. Two participants did not participate in performing this task. This fine-motor skill test has previously been shown to be valid and reliable in the field of occupational therapy [20, 21]. The O’Connor task consisted of a board with 100 holes and pins. Participants were requested to insert all 100 pins using tweezers held by their right, dominant hand. The end-point measure was the total time to complete the insertion of all pins.
Experimental design

The study had a within-participant design across two separate experiments. In both experiments, participants first practiced the complex skill task with five trials, each trial lasting 2–4 min, and a 30 s break between the trials. After the initial training, two trials of the same task, spaced by a 30 s break, were performed, defined as Test1.

Based on the commonly used experimental design aimed to test consolidation processes during sleep/wake periods [22–24], participants in Experiment 1 were divided into two groups. The Wake-Sleep group (n = 16) performed the initial acquisition of the skill and Test1 at 10:00 am. Following 12 hr in which they were instructed to remain awake, participants repeated the test at 10:00 pm (Retest2). At 10:00 am on the next day, following additional 12 hr in which all participants reported at least 7 hr of sleep, participants were retested again (Retest3, Figure 2).

The Sleep-Wake group (n = 15) performed the initial acquisition of the skill and Test1 at 10:00 pm. Following 12 hr in which all participants reported at least 7 hr of sleep, participants repeated the test at 10:00 am on the next day (Retest2). At 10:00 pm, following additional 12 hr in which they were instructed to remain awake, participants were retested again (Retest3, Figure 2).

To test whether the improvement in Experiment 1 was due to a delayed offline process, we performed a further control experiment. In experiment 2, the Single-Day group (n = 16) acquired the complex motor skill and was tested and retested following short intervals during a single day.
Data analysis

In both experiments, to assess within-session learning in the initial acquisition session, we performed a repeated-measures ANOVA with five time points of the initial training trials. In Experiment 1, this model included group as a between-participant factor as well.

Test and retest performance were quantified as the average time to complete the task in both sequential trials. To test for gains in performance, in Experiment 1, a repeated-measures ANOVA was performed, with three time points (Test1, Retest2, and Retest3). Thereafter, to evaluate the effect of sleep or wake periods on learning, Experiment 1 consisted of a First offline interval (Test1 to Retest2), which did not include sleep in the Wake-Sleep group, and did include sleep in the Sleep-Wake group. Similarly, the Second offline interval (Retest2 to Retest3) included sleep in the Sleep-Wake group and did not include sleep in the Sleep-Wake group. A (2x2) repeated-measures ANOVA was performed, with group as between-participant factor, and interval (First offline interval or Second offline interval) as the within-participant factor.

In experiment 2, to test performance following the acquisition of the complex skill, a repeated-measures ANOVA was performed, with four time points (Test1, Retests 2-4). In addition, as performed in Experiment 1, repeated measures ANOVA with interval (first, second, and third) as within-participant factor tested the offline gains in performance following skill acquisition.

To verify the relation between performance in the complex skill task, and commonly used tasks demanding fine-motor abilities (O’Connor test [20, 21]), we calculated Pearson’s correlation between initial performance in both tasks, across all participants.

Statistical differences were calculated at α < 0.05. When applicable, the sphericity assumption was tested, and Greenhouse-Geisser corrections were applied when this assumption was not met.

Results

Experiment 1

In the current study, we tested the existence of an offline consolidation process following initial acquisition of a complex motor skill, and whether such process is sleep-dependent. We first confirmed that participants improved their performance within the initial training trials. A repeated-measures ANOVA with group as between-participant factor revealed a significant effect of trials for both groups (F_{4,116} = 30.05, p < 0.001) with no significant interaction (F_{4,116} = 2.19, p = 0.1) indicating similar within-session improvements in the training trials (Supplementary Figure S1A).

Similarly, performance at Test1 was comparable across both groups (univariate ANOVA: F_{1,116} = 3.08, p = 0.09).

We next measured the offline learning gains in performance, to assess offline consolidation improvements in the complex motor skill. A repeated-measures ANOVA testing performance in all three tests (Test1, Retest2, and Retest3) showed offline gains in performance following the acquisition of the complex skill (F_{2,60} = 19.51, p < 0.001). Post hoc analysis verified that performance in Retest3 was significantly better than performance in Test1 and in Retest2 (p < 0.01, Bonferroni corrected, Figure 3A).

This result provides evidence for the existence of an offline consolidation process following acquisition of a complex motor skill.

Importantly, to test whether offline consolidation of the complex motor skill memory is sleep-dependent, we compared the improvements between test and retests, i.e. offline gains, either following an interval which included sleep or an interval which did not include sleep. Hence, the First offline interval (Test1 to Retest2) did not include sleep in the Wake-Sleep group and did include sleep in the Sleep-Wake group. The Second offline interval (Retest2 to Retest3) included sleep in the Wake-Sleep group and did not include sleep in the Sleep-Wake group (see Methods and Figure 2). In a (2x2) repeated-measures ANOVA, with group as between-participant factor, and interval (first or second) as within-participant factor, we found a significant differences.
A repeated-measures ANOVA with four time points showed that session, three retests were conducted, spaced by 4 hr each. Pearson's correlation between initial performance in both tasks, of occupational therapy (O'Connor test). Tasks requiring fine-motor abilities commonly used in the field a delayed offline consolidation process in complex skill learning. The improvements in performance in Experiment 1 could not be practice does not improve complex skill performance, if the practice is performed within a temporal interval of up to 12 hr. Thus, could it be that these offline gains did not stem from a delayed consolidation, where participants were aware of the goal of the task, consolidation is often sleep-dependent. However, results here suggest that the mechanisms in complex motor skill learning operate differently, since participants in the current study were aware of the goal of the task, but consolidation was not immediately enhanced following sleep. Although sleep might have contributed to consolidation-dependent offline learning gains were evident only following a sufficient period of time (24 hr). This difference might stem from the complexity of the task, which could possibly determine the amount of time required for consolidation, resulting in delayed expression of offline gains. Of note, the current study did not include sleep deprivation conditions, testing longer time intervals without sleep. It would be of interest to test in future studies the impact of conditions such as a period of 24 hr which does not include sleep.

**Experiment 2**

Could it be that these offline gains did not stem from a delayed offline process, but rather from additional practice per se, performed in Retest2? To verify this issue, we conducted an additional experiment, in which participants performed the same amount of practice as in experiment 1, followed by an additional retest (Retest4). However, the performance of the task was limited to a 12 hr period between the initial acquisition of the skill and the last retest at the same day (see Methods and Figure 2). As in Experiment 1, the initial acquisition of the skill in Experiment 2 had a typical learning curve (Supplementary Figure S1B), with a significant effect of trials ($F_{1,29} = 15.66, p < 0.001$).

Following Test1, performed at the end of the initial acquisition session, three retests were conducted, spaced by 4 hr each. A repeated-measures ANOVA with four time points showed that time did not have a significant effect on performance ($F_{3,89} = 0.19, p = 0.91$, Figure 4A). Furthermore, a repeated-measures ANOVA with interval (first, second, and third) as within-participants factor found no significant effect of interval order ($F_{2,30} = 0.34, p = 0.71$, Figure 4B). Together, these results indicate that additional practice does not improve complex skill performance, if the practice is performed within a temporal interval of up to 12 hr. Thus, the improvements in performance in Experiment 1 could not be attributed to additional practice per se, supporting the concept of a delayed offline consolidation process in complex skill learning.

To test the relation between the complex skill task, and tasks requiring fine-motor abilities commonly used in the field of occupational therapy (O'Connor test [21]), we calculated Pearson's correlation between initial performance in both tasks, across participants. Initial performance showed a significant correlation with performance in the O'Connor test ($r = 0.62, p < 0.001$, Figure 5).

**Discussion**

Previous studies have contributed to the research of consolidation processes in skill learning by exploring simple motor tasks. However, the existence and characteristics of motor skill consolidation processes in complex real-life environments remained unexplored. Findings of the current study indicate that offline consolidation gains were evident only 24 hr following skill acquisition, and not following a shorter 12 hr interval, even when the latter included sleep. A further control experiment verified that additional practice, performed up to 12 hr following training, does not improve performance. Thus, this set of results supports the concept of a delayed consolidation process in complex skill learning.

Previous work has shown that in explicit motor skill learning, the specificity of the results was tested using a Pearson correlation, which showed that initial performance in the complex motor task was highly correlated with a validated complex motor task, the O'Connor tweezer dexterity task. This strong correlation suggests that the results presented here would be valid for other complex motor skills as well, and it would be of interest to test additional daily life tasks in future research.

Previous research has found performance enhancement over shorter periods, if those included sleep. Interestingly, these tasks were restricted to regularities such as a repeated sequence of movements, or a response to a repeated pattern of visual stimuli.
In contrast, performance of the complex skill tested here was self-controlled by the participant, resembling daily-life skills and assuring high ecological validity of the conclusions. Consequently, this may explain why consolidation mechanisms in such complex tasks could require a longer offline interval following skill acquisition and may not be completed following shorter intervals (regardless of whether those shorter intervals include sleep). Future studies would be required to test whether the length of time required for efficient consolidation and the involvement of sleep covary with the degree of regularities induced during task performance. In addition, it would be of interest to dissociate in future studies between the effects of nocturnal and diurnal sleep [27, 28]. Neuroimaging studies, as well as noninvasive brain stimulation studies, have shown that the motor cortex and its interconnected network are involved in simple motor skill acquisition [15, 29] and in its consolidation process [5, 8, 30–32]. However, since the current study showed that complex skill learning may differ from common skill learning, originating from a delayed consolidation process, the underlying neural mechanisms could differ as well, raising the necessity of neuroimaging or neuromodulation studies testing the mechanisms underlying complex skill learning.

Expanding the knowledge of motor skill learning to incorporate complex learning tasks may contribute to a more complete understanding of neural mechanisms underlying ecological daily-life memory consolidation processes. Furthermore, this knowledge could enhance rehabilitation following neurological injuries at advanced stages, requiring the facilitation of complex skill learning.

Supplementary Material
Supplementary material is available at SLEEP online.

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