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THE TIME COURSE OF OFF-LINE FOR CONSOLIDATION IN IMPLICIT MOTOR SEQUENCE LEARNING IN YOUNG ADULTS

Abstract: Implicit skills learning such as riding a bicycle and playing a musical instrument play a central role in daily life. Such skills are learned gradually and are retained throughout life. The learning of motor skill occurs with practice, but skill can also increase between sessions, a process termed ‘‘off-line learning’’. In this research, Participants were tested on an implicit version of the Alternating Serial Reaction Time Task and re-tested 6, 24 or 72 h later. ANOVA revealed significant off-line motor skill improvement participants responding faster at the beginning of Session 2 than at the end of Session 1. The elapsed time between the two sessions influenced the improvement of motor skill improvements as well. Thus, participants' response speed improved more after the 24-, 72hr than after the 6-hr. The subsequent paired-samples t-tests conducted separately for all delay groups revealed that the off-line improvement of motor skill was significant in all groups ($p < .05$), and in all groups the 6, 24, 72-hr delay led to off-line enhancement ($p < .05$).This demonstrates that implicitly acquired skills can increase between sessions and the process occurs over hours. These findings are consistent with theoretical accounts of procedural skill learning such as the procedural reinstatement theory as well as with previous studies of retention of other motor skills.

Key Words: ASRT, Implicit sequence learning, Memory consolidation, Time course

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Introduction

Skill learning can be differentiated by phases (rapid and slower), modalities, and whether or not it is conscious (implicit and explicit) (1, 2). Implicit learning can be examined by exposing people to subtle regularities (3) and is said to occur if individuals improve in the speed and/or accuracy of their responses to predictable events and yet are unable to describe such regularities (4). Implicit skill learning occurs when information is acquired from an environment of complex stimuli without conscious access either to what was learned or to the fact that learning occurred (3, 1). In everyday life, this learning mechanism is crucial for adapting to the environment and evaluates events unconsciously (1). This ubiquitous process plays a role in skills ranging from language acquisition (5) to social intuition (6), which involve extracting predictable words from speech streams and non-verbal cues from social interactions, respectively (7).

Motor learning depends on practice, in the so-called "online" periods, but also continues to develop over time after practice has ended, during the so-called "off-line" periods (8). The "off-line" process known as memory consolidation, and the behavioral outcomes of this process are observable when skills are recalled at a later time (9-12). These "offline" processes improve your game and your understanding of this essay, and more generally, enhance adaptive behavior. A memory passes through at least three key milestones in its development: initially it is encoded, then it is consolidated, and finally it is retrieved (9, 12).

This notion has been solidified, in recent decades, by numerous studies which clearly indicated that a learning experience-dependent phase of protein synthesis constitutes a critical step in the establishment of long-term memory at the cellular level (13-15). The leading paradigm in cellular and molecular studies of memory consolidation is the interference paradigm whereby a post-training manipulation (pharmacological, electrophysiological or behavioral) is used to define the time-window of the various sub-processes of consolidation (13, 15). Recent studies, however, suggest the notion that in terms of behavior, two different measures may reflect consolidation processes sub serving the evolution of long-lasting procedural memory: the time-dependent transformation of the effects of training into a robust form which cannot be interfered with by subsequent experience (13,16), but also the evolution of delayed gains in performance. Although the time-windows at which these two measures of consolidation may somewhat differ, there are clear indications that interference does interact with the evolution of delayed gains in performance (11, 13, 16, 17).

During consolidation a memory can undergo both quantitative and qualitative changes. A memory may be enhanced, demonstrated by a quantitative increase in performance, or it may be stabilized, demonstrated by becoming quantitatively less susceptible to interference (10, 18-20). A memory can also undergo qualitative changes: there can be a shift in the strategy used to solve a problem or the emergence of awareness for what had earlier been learned (18, 21). Although there is a rich diversity in the behavioral expression of consolidation, each of these examples may rely upon the same underlying computation. Consolidation is measured as a change in performance between testing and retesting. Contrasting final performance at retesting against an initial baseline provides a direct measure of "offline" performance changes that occur during consolidation (10, 18, 20). Consolidation-based enhancement has been observed in perceptual skills (22, 23), in motor skills (12, 13, 24), and in the behaviors of trained musicians (25) and novices (9) practicing motor tasks relevant to music performance. Despite extensive evidence supporting memory consolidation hypotheses, there remain a number of inconsistencies regarding the behavioral effects of these phenomena. For example, performance enhancements have been found to develop across sleep and waking hours for certain types of procedural tasks (20, 22, 26). Significant enhancements in motor skill performance also have been observed only moments after skill practice ends, prior to extended periods of consolidation (8). Hotermans and colleagues (2006) reported in their study a significant "boost" in motor sequence performance when practice resumed following a rest interval of either 5 or 30 min (8). An assessment performed in closer proximity to the practice bout (immediate retention test) may not reflect the efficacy of consolidation processes that evolve over the 4–6 h post-practice and over a night's sleep. Although there is no current consensus on the best timing for administering a delayed retention assessment, the typically used 24 h retention assessment seems to be more pragmatic for experimental purposes and meets the criteria from an understanding of consolidation processes presented here. In real-world settings such as sports and therapy, this window is often more than 24 h and reflects a cumulative effect of practice (27).

Studies on the time course of skill consolidation indicate that there is a "critical period" after the learning phase, which is necessary for the stabilization of memory traces (1). This time period depends on the task demand, and it varies from 1 to 2 hr (18), to 5 hr (28), or 6 hr (12). Using the serial reaction time (SRT) task, which is a widely known sequence learning paradigm, one study found that the off-line enhancement increased with the length of delay (29). In this SRT study, no enhancement was found 1 hr after the learning phase, but significant enhancement was observed after 4 hr, which further increased after 12 hr. These results suggest that off-line learning may be a dynamic process. However, this study examined only a shorter stretch of time, so the question can be raised, what happens in skill consolidation after more than 12 hr (1). In other study, Individuals who perform a simple motor tracking task, the rotary pursuit task, show improved performance after a brief interval of only 15 min between testing and re-testing, an effect termed "reminiscence" (29,30).

Despite the results of previous studies that found greater improvement after longer off-line periods (more after 12 hr compared with 4 hr), it is less plausible that this is true for 6-, 24-, and 72-hr delays as well. Therefore, we aim to determine a time point in a longer stretch of time at which improvement can still be observed in implicit skill learning consolidation.

Methods

Participants: All subjects signed informed consent. Sixty young healthy right-handed (mean age=23.53 years, SD=3.02; 60 female) took part in the experiment. They were randomly assigned to the 6-, 24-hr, or 72-hr delay group. The age and education of participants were controlled. Participants did not suffer from any developmental, psychiatric, or neurological disorders did not have sleeping disorders, and all reported having 7–8 hr of sleep a day. All participants provided signed informed consent agreements and received no financial compensation for their participation.

Procedure: There were two sessions in the experiment to examine the off-line changes of implicit skill learning: a learning phase (Session 1) and a testing phase (Session 2) separated by a 6-, 24-, or 72hr interval off-line period (see Figure 1). Previous studies with similar tasks and experimental designs showed no time of day effect either on general RTs or on learning measures (1, 20, 29, 31); the time of testing was however controlled in our study.

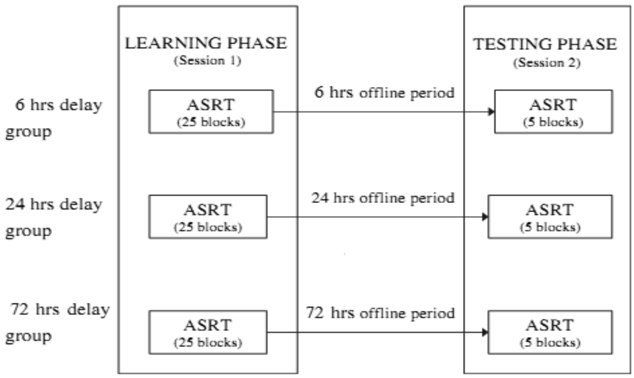

Figure 1. The design of the experiment.

Alternating Serial Reaction Time Task (ASRTT): The ASRTT was performed on an iMac computer with a 40 inch monitor. The stimuli, apparatus and procedure were similar to those used previously (1, 31). Participants were instructed to place their middle and index fingers of each hand on the keys marked ‘z’, ‘x’, ‘.’, and ‘/’, respectively. The keys corresponded to four equally spaced circles on the computer screen. See Figure 2 for a graphical representation of the task. On each trial, one circle became black and remained so until the participant pressed the key corresponding to this target. After a delay of 120 milliseconds, the next target appeared. Participants completed eight epochs of five blocks. Each block consisted of 10 random trials followed by 80 learning trials. These 80 trials consisted of 10 repetitions of an eight-element sequence, in which random trials alternated with pattern trials (e.g.1r2r3r4r where 1–4 refer to the spatial position, left to right, and r refers to a randomly selected position). Participants took a brief break after each block and a longer break halfway through the session, between epochs 4 and 5. The data from the first 10 random trials of each block were not analyzed (1, 4, 31).

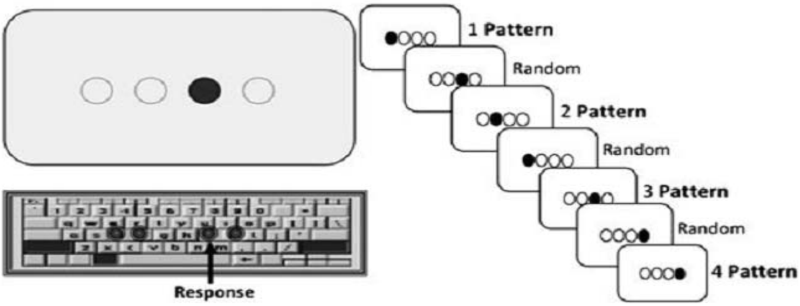

Figure2 . Graphical representation of the ASRTT where the pattern is 1r2r3r4r

Six patterns were counterbalanced across participants (1r2r3r4r, 1r2r4r3r, 1r3r2r4r, 1r3r4r2r, 1r4r2r3r and 1r4r3r2r). Since the repeating pattern forms a continuous sequence, these six patterns include all permutations of the four alternating events. The computer was programmed to guide participants to an accuracy level of about 92% via an end□of□block visual display. If accuracy for a block was above 93%, the computer displayed 'focus more on speed', and if accuracy was below 91%, the computer displayed 'focus more on accuracy' (1, 4, 31).

During Session 1 (learning phase), the ASRT task consisted of 25 blocks, with 85 stimuli in each block. For practice purposes, the locations of the first five stimuli of each stimulus block were always random. These were followed by the eight-element sequence (e.g., 1R2R3R4R) repeating 10 times (1, 4). Following the design of Howard and Howard (1997), stimuli were presented 120 ms after the response to the previous stimulus. Between stimulus blocks, the subjects received feedback about their overall RT and accuracy presented on the screen, and then they had a rest period of between 10 and 20 s before starting the next stimulus block. Session 2 (testing phase) consisted of only five stimulus blocks of the same type as in Session 1 (1, 31). The computer program selected a different ASRT sequence for each subject based on a permutation rule such that each of the six unique permutations of the four repeating events occurred with equal probability (1, 31). The repeating sequence was identical between Session 1 and Session 2 for each participant.

To explore how much explicit knowledge subjects acquired about Alternating Serial Reaction task, we administered a short questionnaire (1, 32) after the testing phase. None of the participants reported noticing the sequences in Alternating Serial Reaction Task (4, 32).

Statistical analysis: To facilitate data processing, stimulus blocks were organized into larger clusters (called epochs); where the first epoch contained blocks 1–5, the second epoch blocks 6–10, etc. (1,4). Consequently, Session 1 consisted of 5 epochs, whereas Session 2 consisted of 1 epoch (1). The median RTs were averaged across blocks to obtain a mean of the median RT for each epoch (4).

The data were analyzed with repeated measure ANOVA with epochs (5 epochs in Session 1) as within-subject factor and delay type (4, 24, 72hr) as between subject factors in learning phase and ANOVA with session (last epoch of Session 1 versus the first epoch of Session 2) as within-subject factor and delay type (4, 24, 72hr) as between subject factors in testing phase. Significant main effects and interactions were analyzed using pair wise comparisons, with Bonferroni adjustment for multiple comparisons.

Results

In learning phase, a 5 (epochs) ×3 (4, 24, 72hr delay) ANOVA on the combined Session1 data revealed a significant main effect of epoch for RT, $F(4, 228)=263.59$, $p=.0001$, such that people became faster over all with practice, reflecting motor skill learning but neither the main effect of delay type, $F(2, 57)= 0.134$, $P=.87$, nor the delay type×epoch interaction, $F(8, 228)=1.20$, $p=.29$, reached significant and There was no significant difference in skill level at the end of session 1 across groups ($P > 0.1$).

In testing phase, the amount of off-line learning, defined as a change in skill between sessions (last epoch of Session 1 versus the first epoch of Session 2). ANOVA revealed significant off-line motor skill improvement (indicated by the main effect of session: $F (1, 57) = 171.46$, $p <.00001$) participants responding faster at the beginning of Session 2 than at the end of Session 1. The elapsed time between the two sessions influenced the improvement of motor skill improvements as well (indicated by the Session × Delay interaction: $F (2, 57) = 13.23$, $p = .001$). Thus, participants' response speed improved more after the 24-, 72hr than after the 6-hr (least significant difference post hoc test: $p = .004$), whereas there was no difference between the 24-hr and 72-hr delay conditions ($p = .59$). The subsequent paired-samples t-tests conducted separately for all delay groups revealed that the off-line improvement of motor skill was significant in all groups ($p < .05$), and in all groups the 6, 24, 72-hr delay led to off-line enhancement ($p< .05$) (see figure 3).

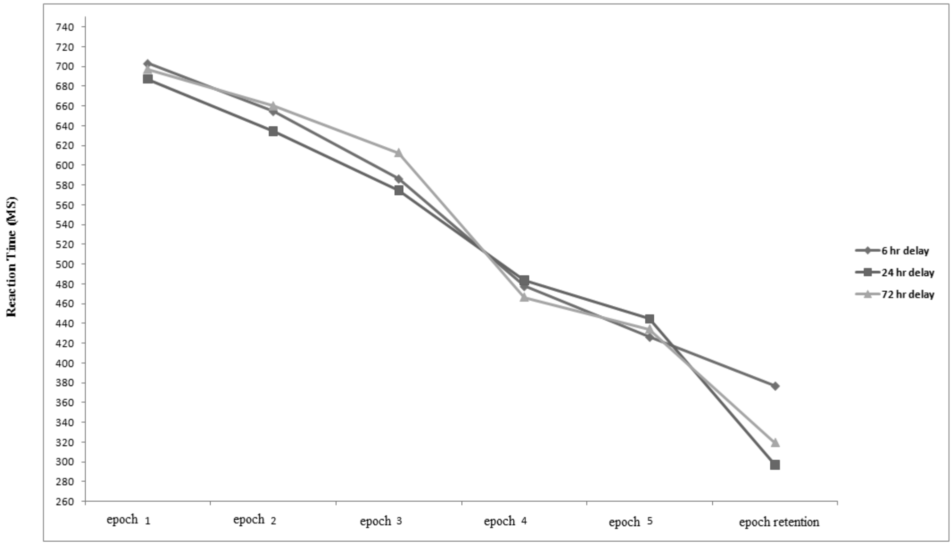

Figure 3. RTs for correct responses as a function of epochs in 3 experimental groups for the Alternating Serial Reaction Time Task, Each epoch consists of five blocks of 80 learning trials.

Discussion

We studied the time course of implicit skill consolidation in young adults. The present findings demonstrate that sequence motor skills acquired in the Alternating Serial Reaction Time Task can be retained after 6-, 24-, 72hr. In this study, overall RT was faster at the beginning of Session 2 than at the end of Session 1 (epoch 5), consistent with the conclusion that at least some retention of sequence motor skill occurred.

We suggest that passage of time is essential for a maximum benefit of practice to be gained, as the time delay may allow for consolidation of learning, possibly reflecting plastic changes in motor cortical representations of the skill (33). It is also possible that the improvement in overall RTs after the delay period reflects a release from fatigue rather than consolidation per se. However, studies that have included that a fatigue control group makes this interpretation unlikely (1, 32).

These results are congruent with recent theories of motor skill consolidation (11, 20, 28, 29) that claim that memory stabilization occurs during the first 5–6 hr after learning. The observed strong off-line improvement after 6 hr may reflect this first stabilization process of memory traces, including the previously mentioned critical time period (1). The results demonstrate that the development of skill can continue over an interval in the absence of continued practice and that the process occurs over hours (29). The nature of the paradigm used helps to eliminate a number of potential confounding factors: (1) fatigue; (2) motor imagery; (3) diurnal factors; (4) varying levels of awareness of the task. The findings suggest that the improvement in performance between sessions is related to an active off-line mechanism rather than resolution of fatigue. Fatigue could build up with exposure to a task and then dissipate over a delay, thereby improving performance without any actual improvement in skill (30). These results argue strongly against fatigue as a basis for off-line learning on the ASRTT. The task compares sequential trials to random trials immediately following and fatigue would be expected to affect both trial types equally. Further, fatigue should be fully dissipated after an hour and we saw the majority of the skill improvement after 1 h. Another potential confounding mechanism is motor imagery. When subjects mentally rehearse a task, they activate similar networks as compared to actually performing the task and their performance is enhanced (29, 34). In the current paradigm, participants could not spend the interval between testing and re-testing either using motor imagination or physical practice to improve their skill, because participants were not even aware that they had acquired a novel skill. Diurnal factors are also unlikely to affect the expression of skill. The measure of skill in this sequence-learning task, the difference between the random and sequential response times, lessens any diurnal effect upon skill. Individuals generally develop the same amount of skill on this task regardless of the time of day they perform it ((8, 29) but see also (35)). Finally, different levels of awareness in the groups could confound the results. Those tested at longer intervals may have acquired more explicit knowledge of the sequence, allowing them to demonstrate increased skill at session 2. But participants showed not levels of awareness in a free recall test (29). These findings are consistent with the ‘‘procedural reinstatement theory’’ that posits that skills are well retained to the extent that the perceptual, motor and cognitive procedures underlying their learning are reinstated at test (4, 36).

Other studies (37) conclude that implicit sequence learning is retained after 1 or 2 weeks, Willingham and Dumas (1997) conclude that it is not retained over a longer 1-year interval, even when the original procedures were reinstated at retest (38). However, the present results indicate that implicit sequence learning is retained for 72hr. Willingham and Dumas (1997) outline several possible reasons why retention of sequence knowledge was not revealed in their study, two of which are considered here. First, since a number of participants showed evidence of declarative knowledge, it is possible that learning the simple repeating pattern tapped into the declarative system which, although developing more quickly, lasts for a shorter time than procedural memory does (29, 38). Thus declarative learning of the simple repeating pattern may have interfered with procedural learning. However, since Willingham and Dumas (1997) found no sequence retention, even when the individuals with declarative knowledge were removed, this cannot fully account for their null findings (29, 38).

Second, a more likely explanation for the lack of retention that Willingham and Dumas (1997) consider is that their participants may not have had enough training for long-term retention to occur. In their experiment individuals received only 40 repetitions of the pattern in the initial session. They point out that this is much less practice than had been used where long-term retention of implicit skill is observed, and it may not be sufficient for retention of sequence knowledge after 1 year. In order to test this hypothesis, participants could receive more training. However, in the simple repeating SRTT, with extended practice, individuals become increasingly aware of the regularity and the explicit declarative system plays a larger role in learning. Even with only 40 pattern repetitions (480 trials), Willingham and Dumas (1997) reported that over half of the participants had some level of declarative knowledge, as assessed by post-learning free recall and sequence-recognition tests. Therefore simply extending practice does not allow unbiased evaluation of the long-term effect of practice in the SRTT context (4).

In the present study, using the ASRTT paradigm, participants responded to a subtle pattern that repeated 2000 trials during session 1. Our findings are consistent with their conjecture that long-term retention of implicit sequence skill in the SRTT requires extensive practice prior to the retention interval. This possibility is consistent with evidence from other well-remembered procedural tasks that often require extensive practice to learn and remember (14, 28, 32) as well as with the procedural skills we learn in everyday life, such as riding a bike or learning natural language grammar (4).

In conclusion, we have shown 6-, 24-, 72 hr retention of sequence procedural skills in the ASRTT for younger people. This finding is consistent with theoretical accounts of the procedural memory system and the procedural reinstatement theory as well as with previous demonstrations of long-term motor skill retention using other tasks (4).

Based on these results, therapists, coaches and educators can design more effective educational, training, and rehabilitation programs for disorders and learners. But Critical questions remain: does consolidation occur with other implicit motor tasks and what are the factors and neural mechanisms that contribute to such long-term retention of the tasks.

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