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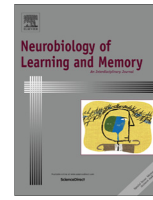

Variable motor imagery training induces sleep memory consolidation and transfer improvements

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A B S T R A C T

Motor-skill practice in repetitive or variable orders leads to better within-day acquisition and facilitates retention and transfer, respectively. This practice pattern effect has been robustly found for physical practice, but little is known about its effect after motor imagery (MI) practice. In the present study, we investigated the effect of constant or variable MI practice, and the consolidation following a day-time or a sleep interval. The physical performance was assessed before (pre-test) and after MI training (post-test), as well as after a night or day-time consolidation (retention test). Finally, a transfer test on an unpracticed task was further performed. Results revealed that in all participants, performance increased significantly in the post-test when compared with the pre-test, while only subjects in the variable MI training showed further gains in performance in the retention test following a night of sleep, and exhibited the best transfer of performance to a novel visuomotor sequence. In contrast, subjects in the constant MI training did not show any delayed performance gain following both day and sleep-consolidation. Overall, and for the first time, these findings partially support the practice pattern effect of motor learning with MI, and further highlight a new difference between mental and physical practice, especially on consolidation. To conclude, variable MI practice, rather than constant, seems to be the valuable condition that should be considered in the practical implications of mental training in motor learning and rehabilitation.

1. Introduction

A wide range of experimental studies have provided strong evidence that training conditions that make the performance harder during practice improve long-term retention (Schmidt & Bjork, 1992). Especially, previous works have shown that when only one motor skill is learned in a single session, its acquisition is facilitated compared to when multiple skills are learned, while such latter condition of practice leads to a better retention and transfer. This acquisition–retention 'paradox' is termed the contextual interference effect (CI, Battig & Shea, 1980) and is well-documented in the motor learning literature (Brady, 2008 for review).

Classically, motor training structure can be positioned on a continuum between a simple structure such as constant practice, and more complex structures, such as variable practice. A constant practice structure consists in performing the same task in a row, whereas variable practice structure consists in the execution of a motor task randomly interleaved with trials of different motor tasks. Interestingly, it has been demonstrated that variable practice, rather than constant, results in a stronger and more flexible representation of the movement (Albaret & Thon, 1998). Two theoretical positions have emerged to explain the CI effect. On the one hand, some authors suggest that when practice is undertaken in a variable order, the learning benefit occurs by the introduction of two or more similar tasks into working memory (Shea & Morgan, 1979). The interference created in working memory during practice results in an enhanced elaborative and distinctive processing that ultimately facilitates retention. On the other hand, interference might lead to forget action plans in working memory, thus necessitating the reconstruction of plans on each new trial under variable conditions (Lee & Magill, 1983). Such reconstruction process is suggested to facilitate the retention of the practiced skill

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and the ability to generalize the existing knowledge from the practiced skill to a new situation, or in other terms the transfer of performance. Recently, Kantak, Sullivan, Fisher, Knowlton, and Winstein (2010) hypothesized that differences in the practice structure may drive subsequent offline activity in distinct neural structures that are critical to motor-memory consolidation. Using repetitive transcranial magnetic stimulation (rTMS), they demonstrated that transient inhibition of the dorsolateral-prefrontal cortex (DLPFC), but not of the primary motor cortex (M1), 24 h after variable practice, attenuated motor-skill retention, whereas the reverse effect was reported after constant practice. Therefore, motor memory consolidation engages distinct neural substrates that depend on the practice structure. In a subsequent study, the same authors extended the dissociation between the DLPFC and M1 processing with respect to variable and constant practice to the transfer of the learned skill (Kantak, Sullivan, Fisher, Knowlton, & Winstein, 2011). Taken together, these findings suggest that M1 contributes to motor memory consolidation and transfer following constant practice, while processing within the DLPFC is necessary when variable practice is at stake. It is likely that the benefits of variable practice to transfer to unpracticed movements, compared to constant practice, might be due to the development of a generalized 'schema' that is inferred or adapted from experience of different practice conditions (Shea & Kohl, 1990). Taking advantage of variable practice in motor skill consolidation and transfer, paradigms investigating schema notions to facilitate motor adaptation should be expanded.

In the wealth of the mental practice literature, motor imagery (MI) is a reliable complement to physical practice in enhancing cognitive and motor performance (Guillot & Collet, 2008), hence promoting the consolidation process toward the long term memory system (Jackson, Lafleur, Malouin, Richards, & Doyon, 2001). MI is the mental simulation of an overt action without any corresponding motor output, and substantially contributes in improving motor learning and performance (for reviews, see Driskell, Copper, & Moran, 1994; Feltz & Landers, 1983; Guillot & Collet, 2008). It is now well-established to what extent goal-directed actions, whether executed or imagined, share common neuro-cognitive processes. For instance, several experiments have provided evidence that there is a correlation between the duration of a mentally simulated action and that of the overt execution of the same movement (functional equivalence, Holmes & Collins, 2001). Moreover, executing or imagining an action recruits similar (albeit not identical) neural substrates (Decety, 1996; Lotze & Halsband, 2006). Up to now, only one study investigated the effect of practice structure using either physical or MI practice on motor skill learning, but only the acquisition phase was tested (Coelho, Nusbaum, Rosenbaum, & Fenn, 2012). Results showed that both physical and MI practice elicited significant improvement of performance in a post-training test, while variable practice was better than constant only when practiced physically. These data somewhat challenge the classical higher benefit in performance of constant compared to variable practice during physical acquisition. Additionally, the authors discussed the claim that motor representations for both overt and imagined movements are qualitatively equivalent. However, the effects of practice structure with MI during the retention and the transfer processes of motor learning have not been directly assessed thus far. Regarding the consolidation process, Debarnot et al. (Debarnot, Castellani, & Guillot, 2012; Debarnot, Castellani, Valenza, Sebastiani, & Guillot, 2011; Debarnot, Creveaux, Collet, Doyon, & Guillot, 2009; Debarnot et al., 2009) demonstrated sleep-related gains of performance on an explicit sequence of finger movements with MI, while using an observation learning of a sequential arm movement Trempe, Sabourin, Rohbanfard, and Proteau (2011) found a stabilization of the motor skill and its long-term retention. These contrasting insights in the consolidation process between MI and observation learning may relate to the difference in the nature of the motor task, but there is still a substantial lack of knowledge on this issue.

The present study thus aimed to investigate in which extent constant and variable structures of motor practice with MI might impact the performance in the acquisition, the consolidation and the transfer processes. First, we tested the effect of constant and variable MI training on a visuomotor sequential task during the acquisition session. Then, we explored whether the different structures of MI training (i.e., constant vs. variable) elicited different effects in performance following 10 h of consolidation (with or without intervening sleep) as well as on a transfer task. To address these issues, participants were randomly assigned to five different groups subjected either to constant or variable MI training, with half of them re-tested after a night of sleep and the other half after the same interval without sleep; a group that did not received any training was tested as a control group: MIC Night group, MIV Night group, MIC Day group, MIV Day group and no-training group. Motor performance was evaluated before the MI training, as well as just before and after a night- or day-time consolidation. Based on the CI effect as well as the functional equivalence between MI and physical practice, we predicted that compared to the no-training group, MI groups would demonstrate an improvement in performance following the training session, whereas the MIC group would show better performance than the MIV group after the acquisition session (i.e., post-training). By contrast, we hypothesized that greater offline delayed gains and better transfer of performance would be observed in the MIV group especially following a night of sleep, whereas those in the MIV day, MIC and no-training groups would not.

2. Method

2.1. Participants

A total of 71 healthy volunteers aged 18–40 years (mean age: 25.1 ± 6 years; 42 women) took part in this study. They were right handed, as assessed by the Edinburgh Handedness Inventory (Oldfield, 1971). None had any prior history of drug or alcohol abuse or neurologic, psychiatric, or sleep disorders, and they were instructed to be drug and alcohol free for 24 h prior to and during the experiment. Additionally, they reported sleeping regularly between 7 and 9 h per night, and extreme evening- and morning-type individuals, as well as regular nappers, were excluded based on subjective reports. This study was approved by the Ethics Committee of the University Paris Descartes, and all participants signed an informed consent.

2.2. Design and apparatus

Participants were tested in a quiet room, without any distracting stimuli, in order to help them focusing on the motor task. They seated on a chair at a distance of 35 cm from a keyboard and 45 cm in front of a 17-in. computer screen. A computer mouse was disposed 30 cm forward the keyboard (Fig. 1A). Such standardized distances between the subject and the experimental material (screen, keyboard and mouse) were suitable for a large range of individual. All participants were tested on a sequential finger task, consisting in moving the index finger of the left hand (nondominant) from the left button of the computer mouse toward 4 colored targets on the keyboard. The four keys A, F, I, M (AZERTY keyboard) were respectively colored in blue, red, green and yellow. All other keys were black but still functional; hence the sequential finger movements required precision to be correct. On each trial, four colored circles (3 cm in diameter), corresponding to the four key on