Brain and Cognition 69 (2009) 398–405

Contents lists available at ScienceDirect

Brain and Cognition

journal homepage: www.elsevier.com/locate/b&c

Sleep-related improvements in motor learning following mental practice

Ursula Debarnot [a], Thomas Creveaux [a], Christian Collet [a], Angelo Gemignani [b], Raphael Massarelli [a], Julien Doyon [c], Aymeric Guillot [a,*]

[a] CRIS, Performance Motrice, Mentale et du Matériel, (P3M) Université Claude Bernard Lyon I, Université de Lyon, 27-29 Boulevard du 11 Novembre 1918, 69622 Villeurbanne cedex, France

[b] Università degli Studi di Pisa, Dipartimento di Fisiologia "G. Moruzzi", Facoltà di Medicina, Via San ZENO, Pisa, Italy

[c] Functional Neuroimaging Unit, University of Montreal Geriatric Institute, University of Montreal, Canada

ARTICLE INFO

Article history:
Accepted 26 August 2008
Available online 5 October 2008

Keywords:
Motor imagery
Sleep
Goal-based strategy
Movement-based strategy
Motor consolidation
Mental chronometry
Motor performance

ABSTRACT

A wide range of experimental studies have provided evidence that a night of sleep may enhance motor performance following physical practice (PP), but little is known, however, about its effect after motor imagery (MI). Using an explicitly learned pointing task paradigm, thirty participants were assigned to one of three groups that differed in the training method (PP, MI, and control groups). The physical performance was measured before training (pre-test), as well as before (post-test 1) and after a night of sleep (post-test 2). The time taken to complete the pointing tasks, the number of errors and the kinematic trajectories were the dependent variables. As expected, both the PP and the MI groups improved their performance during the post-test 1. The MI group was further found to enhance motor performance after sleep, hence suggesting that sleep-related effects are effective following mental practice. Such findings highlight the reliability of MI in learning process, which is thought consolidated when associated with sleep.

1. Introduction

There is now ample evidence that sleep plays a crucial role in motor skill consolidation and memory retention (Brashers-Krug, Shadmehr, & Bizzi, 1996; Smith, 1995; Stickgold, Hobson, Fosse, & Fosse, 2001). Specifically, sleep has been implicated in the consolidation process, which is the conversion of an unstable memory trace into a stable form that becomes increasingly resistant to interferences resulting from competing or disrupting factors, hence highlighting the performance gains in the absence of further practice (McGaugh, 2000). Despite such evidence, there is still no consensus regarding the sleep stages that are preferentially involved in the memory phase (see Rauchs, Desgranges, Foret, & Eustache, 2005). Yet, the importance of the alternate periods of Non-Rapid Eyes Movements (NREM) and Rapid Eyes Movements (REM) is still controversial. Recent data have reported that sleep spindles may be involved in the off-line consolidation of a new sequence of finger movements known to be sleep-dependent, hence suggesting changes in NREM sleep following motor learning for consolidation (Morin, Doyon, Dostie, Barakat, Tahar, & Korman, et al., 2008). Furthermore, other findings have shown that beside the memory stabilization that occurs during wake cycles (Muellbacher et al., 2002; Walker, Brakefield, Hobson, & Stickgold, 2003), the enhancement phase arises primarily during sleep, either by promoting memory formation (Gais, Plihal, Wagner, & Born, 2000), restoring previously lost memories (Fenn, Nusbaum, & Margoliash, 2003) or consolidating and optimizing motor skills (Fischer, Hallschmid, Elsner, & Born, 2002). Accordingly, many authors have shown that subjects were more accurate and performed finger-tapping sequences faster after sleep, while equivalent time during wake did not provide significant changes (Fischer et al., 2002; Karni, Tanne, Rubenstein, Askenasy, & Sagi, 1994; Kuriyama, Matthew, & Walker, 2007). Delayed gains on a sequential finger-tapping task would thus trigger only after a night of sleep, whereas a comparable interval without sleep may not provide additional benefit. In addition, Huber, Ghilardi, Massimini, and Tononi (2004) used a kinematic and dynamic controlled pointing motor task to investigate the sleep-related effects on performance. In their experiment, the participants were requested to perform out-and-back movements from a central starting point to one of eight peripheral location targets. The authors reported a significant motor skill performance enhancement after sleep. Such effect may be elicited by slow potential oscillations of neurons membrane (<1 Hz), which predominantly arise from the prefrontal cortex and then propagate in anteroposterior direction (Massimini, Huber, Ferrarelli, Hill, & Tononi, 2004; Sejnowski & Destexhe, 2000; Steriade & Timofeev, 2003). These oscillations were also hypothesized to be primarily

* Corresponding author. Fax: +33 4 72 43 28 46.
E-mail address: aymeric.guillot@univ-lyon1.fr (A. Guillot).

0278-2626/$ - see front matter © 2008 Elsevier Inc. All rights reserved.
doi:10.1016/j.bandc.2008.08.029

related to local homeostasis changes which have a causal role in the sleep-associated consolidation of memory (Huber et al., 2004; Marshall, Helgadóttir, Mölle, & Born, 2006). These latter results, as those mentioned previously, support the hypothesis stating that physical practice (PP) of sequential and pointing motor tasks before sleep may enhance performance through the declarative and procedural memory consolidation processes (Fischer et al., 2002).

In the wealth of the motor learning literature, mental practice, and most especially motor imagery (MI), is considered a reliable complement to PP in enhancing cognitive and motor performance. Accordingly, the effects of MI on the improvement of motor skill learning are now well-established (for reviews, see Feltz & Landers, 1983; Guillot & Collet, 2008), including pointing and graphic tasks (Gentili, Papaxanthis, & Pozzo, 2006; Yagüez et al., 1998). MI is a dynamic state during which an individual simulates the performance of a specific motor task mentally, without any movement (Decety, 1996; Jeannerod, 1994). Visual imagery (self-visualisation of the movement) and kinesthetic imagery (the ability to perceive the somatic feedbacks that the actual movement should elicit) are the most common MI modalities. To date, a large body of research has shown that the execution of a movement and MI showed several parallel characteristics. First, MI duration has been found to be highly correlated with the time taken to perform the same movement (e.g. Decety, Jeannerod, & Prablanc, 1989; Guillot & Collet, 2005a). Imagined actions have also been found to obey to similar motor rules and biomechanical constraints than PP (Johnson, 2000; Maruff, Wilson, Trebiolcock, & Currie, 1999). Second, MI and motor performance have been shown to elicit similar peripheral activity of the autonomic nervous system (Decety, Jeannerod, Germain, & Pastene, 1991; Guillot & Collet, 2005b). Finally, an important number of neuroimaging studies have provided evidence that the neural networks mediating MI and motor performance are quite similar, albeit not identical (e.g. Decety et al., 1994; Gerardin et al., 2000; Guillot et al., 2008a; Lotze & Halsband, 2006), hence supporting the functional equivalence principle (Holmes & Collins, 2001). Especially, both MI and motor performance have been shown to activate the ventral premotor cortex, which corresponds to the human analog of the so-called mirror neuron system (for review, see Buccino, Solodkin, & Small, 2006). Thus, MI shares some common mental processes with the observation of movement.

Despite accumulated evidence that MI and motor performance share common neural substrates, little is known about the possible effect of sleep on the consolidation of memory processes following mental practice. The functional and structural equivalences between MI and motor performance suggest that off-line performance gains following MI may occur during sleep, just as it has been well-established for PP. Hence, in the present experiment, we investigated, for the first time, whether the enhancement of the memory representation following MI learning after a night of sleep resulted in improved physical performance the next day. A quite similar experimental design to that proposed by Huber et al. (2004) was used to investigate the consolidation effect of both procedural (trajectories movement) and declarative (working memory) learning following MI, PP or control (i.e. no-practice, but neutral activity) training conditions. Motor performance was evaluated before training, as well as just before and after a night of sleep. Both MI and PP groups were expected to significantly improve performance, as compared to the control group. Furthermore, they were also expected to increase their level of performance after sleep, hence supporting the hypothesis of sleep consolidation process. These results finally aimed at highlighting the efficacy of MI-based mental practice techniques in learning processes and the impact of the sleep consolidation process.

2. Method

2.1. Participants

Thirty healthy participants (12 males and 18 females) aged between 20 and 35 years (mean age 25.7 years ± 2.1) gave their informed consent to take part in this experiment, which was approved by the local Research Ethics Committee. All were right-handed, as measured by the Edinburgh Handedness Inventory (Oldfield, 1971). They were enrolled at the university, in the close environment of the laboratory, and were thus not paid to take part in the study. The procedure of the experiment and the tasks were explained, while no information was provided about the objectives of the study or about the variables to be assessed.

2.2. Design and apparatus

All participants were tested on a pointing task similar to that used by Huber et al. (2004), requiring to move a cursor with the computer mouse from a central white target toward peripheral black targets. Two distinct sequences with different orders in the templates to be completed were used (Fig. 1), in order to maximize probability to observe changes in behavioral performance with practice, and to prevent the participants to rapidly reach a floor effect.

Each pointing task was composed of six hand movements. One hand movement was defined as the subjects' hand motion from the white central target to reach the pre-determined black peripheral target, and then back to the white target. The black targets (width 15 mm) were located 45° apart and 35 mm away from the central one. Kinematics data were acquired at 500 Hz frequency. The directional errors were recorded as the angle between the line from the initial position of the central target (solid line) and the line of the hand position at the peak outward velocity (dotted line). The optimal point performance was defined as the shortest point to be reached by the participant from the central target. Thus, the absolute error (AE) was defined as the distance between the optimal point movements to the reversal point (Fig. 1). The movement time was also recorded for each hand movement. Finally, each incorrect pointing movement was taken into consideration (target missed, wrong target or more than three seconds to reach one of the peripheral black target).

2.3. Baseline measures

All the participants were first asked to fill out the Pittsburg Sleep Quality Index (PSQI, Buysse, Reynolds, Monk, & Timothy, 1989) to assess sleep quality and quantity. This test was administered to check the lack of obvious disturbances during sleep/wakefulness cycles and to ascertain the participants' predisposition to benefit from the natural effects of sleep. The Corsi Block Test (Milner, 1971) was also administered to estimate the individual visuospatial working memory capacity. Sequences that had to be memorized and recalled were composed of two to eight successive blocks. After each presentation of the sequence on the computer screen, the participants were required to point out the blocks in the same order they appeared on the screen. The individual's performance was then determined by the longest sequence of blocks recalled in the correct order before two successive errors. The participants finally filled out the revised version of the Movement Imagery Questionnaire (MIQ-R, Hall & Martin, 1997). The MIQ-R measures the ability to form kinesthetic and visual mental images. It is an 8-item self-report questionnaire, in which subjects have to rate the vividness of their mental representation using two 7-point scales. The first series of items measures the individual ability to form visual images (1 = very hard to see and 7 = very easy to imag-