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Neuromuscular Adaptation Induced by Motor Imagery Training in the Serial Reaction Time Task

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Abstract. [Purpose] This study examined whether motor imagery leads to a decrease in the temporal process in terms of the onset of muscle activation and reaction time according to acquisition of motor skills in a serial reaction time (SRT) task. [Subjects] Forty one healthy, right-handed subjects with no history of neurological, orthopedic, or psychiatric disorders were enrolled in this study. The subjects were assigned randomly to the motor training group (n=13), motor imagery group (n=14), and control group (n=11). [Methods] After six visual stimuli, the subjects were instructed to move or press a moveable arm/button according to the corresponding stimuli. However, the motor imagery group performed the task without actual movement in the same task paradigm. The kinetic parameters (i.e. muscle activation and movement initiation) were analyzed before and after the training/controlled session over three consecutive days with two repetitions per day for each group. [Results] After motor skill acquisition, the motor training group and motor imagery group showed a significant decrease in processing times between the visual stimuli and two predetermined onsets, which consisted of the onset of muscular activation and reaction time. However, there were no significant changes in the control group. [Conclusion] The decrease in processing time through motor imagery can be attributed to the rapid onset of muscle activation and movement initiation, which might be induced by neuromuscular adaptation in the motor performance phase. Furthermore, we assumed that imagining the performance of a motor task could contributes to improving the motor performance in motor sequential learning.
Key words: Motor Imagery, Neuromuscular adaptation, Motor sequential learning

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INTRODUCTION

Motor learning is defined as a set which result in acquisition of skilled movements through practice and experience. While acquiring motor skill, the motor program for the performance of movements is modified and intergrated[1]. To promote the extent of motor learning, a variety of training methods have been used to improve motor learning, such as crossed education, mental practice with motor imagery, complex practice conditions, motor training with biofeedback, etc[2–6]. It is well known that such learning paradigms are of benefit for reducing of movement times and errors in the motor performance[7,8]. Of these methods, several studies have revealed that mental practice with motor imagery is useful for improving motor learnings[9,10].

Motor imagery (MI) is defined as the ability to imagine performing a movement without any corresponding motor output. It is a representation of a specific action that is internally reproduced within the working memory (i.e., cognitive rehearsal of a task in the absence of any real movement)[11]. Hence, mental practice (MP) is the repeated imagination of movements using MI. Motor imagery-based mental practice is commonly used in many fields of neuroscience, such as physical therapy, rehabilitation medicine, sports science, etc[12–14]. Many studies have reported that the imagination of performing a motor task improves the ability of the performance and is accompanied by effective processing in the motor learning system[13,15,16].

A variety of motor tasks have been used to demonstrate the efficacy of motor learning with motor imagery training, including the target acquisition task, tracking task, and serial reaction time (SRT) task. In particular, SRT is commonly used as an experimental tool in many motor learning studies[3,17,18]. In our prior study[18], we showed that the successful performance of a SRT task consists of two main temporal points in the movement system, such as the onset of muscle activation and the reaction time. Until now, Numerous reports that elucidating the effect of MI have been published[15,16,19]. MI has been demonstrated to modify the real velocity of movement[20,21]. In addition, with regard to the movement rate, a combination of MI with actual motor training was demonstrated to be sufficient to produce a performance similar to physical training alone[5]. However, although the neurophysiological mechanism of actual motor training has been well established, there are no reports on how the onset time of muscle activation and muscle reaction time are modified as a result of motor imagery in a motor learning task.

Therefore, in this study, we tried to demonstrate whether motor imagery leads to a decrease in temporal processing in terms of the onsets of muscle activation and reaction time, through skill acquisition of a repeated SRT task or not.

SUBJECTS AND METHODS

Forty one healthy subjects were enrolled in this study after providing their informed consent in accordance with the ethical standards of the Declaration of Helsinki. All subjects were right-handed, as verified by a handedness questionnaire using the modified Edinburgh Handedness Inventory[22]. The inclusion criteria were (1) no previous history of neurological or psychiatric disorders, (2) no pathology of musculoskeletal function in the upper limb, (3) no previous exposure to other sequence-learning studies or externally-stimulated experiments of the cerebral cortex, such as transcranial magnetic stimulation or transcranial direct current stimulation, and (4) no color blindness. All Subjects were assigned randomly to the motor training group (8 men; mean age: 22.56 ± 1.93), motor imagery group (12 men; mean age: 23.59 ± 2.06), or control group (10 men; mean age: 25.33 ± 1.75). Three subjects who did not attend all the training session were excluded from the final data analysis.

The equipment used consisted of the two personal computers interconnected with digital interface hardware (a digital I/O PCI card with 37 pin DSUB connector, Cedrus, San Pedro, CA), which had a built-in stimulus presentation system, and an EMG acquisition system. The SRT task was presented on the first computer using stimulus presentation software (SuperLab Pro ver 4.0, San Pedro, CA, USA) and a custom-made response pad consisting of a movable arm with a button on its top and a stationary arm fixed on a table. The moveable arm was allowed to move up 60° from a central position to the stop switches toward each of two directions on the horizontal plane. The three sensors built into the custom-made response pad consisted of two stop switches and a button on the top of the bar. The digital signals related to the presented visual stimulus and the reaction times were recorded on the second computer together with the EMG (MP150, Biopac system, USA) and accelerometer (BSL-SS27L, Biopac, USA) signals. The EMG activity from the wrist extensor muscles was recorded using a pair of surface electrodes while performing the SRT task. The amplified EMG and accelerometer signals were filtered (band-pass, 5

Hz to 1 kHz) and sampled at 200 Hz. All digital signals were acquired and analyzed using Acknowledge software (version 4.0, Biopac system, USA) installed on the second computer. The signals included the point of the visual stimulus, the onset of muscle activation and the reaction time.

The subjects were seated in front of a table with their right elbow flexed at approximately 90°. They grasped the bar with their thumb resting on the button, which was on the bar on the custom-made response pad. After receiving a visual stimulus displayed on the computer monitor set at the front, the subjects were instructed to move or press the moveable arm/the button, and then return it toward the central position as quickly as possible according to the corresponding stimulus.

All subjects performed a pre-and post-test through the SRT task, which consisted of Six colored-arrows (yellow, green, red, blue, white, black) were presented randomly on the center of the computer monitor. In the SRT task, a total of 10 stimuli per session were delivered and each session was repeated 10 times. The SRT task was to respond to each stimulus with a predetermined set of three motions: the yellow or green arrow meant that the subject had to perform wrist flexion; the red or blue arrow indicated wrist extension; and the white or black arrow meant that the subject had to press the button. However, the direction of the arrows pointed in the direction opposite to the predetermined three motions according to the color of the arrows in order to increase the task difficulty. In each condition, the yellow and green arrows were presented 30 times, the red and blue arrows were presented 20 times, and white and black arrows were presented 50 times. The presented stimuli lasted for 2,500 ms, and the inter-stimuli interval was provided for 2,000 ms in order to allow for a return to the starting position. The actual experiment was performed in the pre- and post-test after one demonstration and practice trial.

The motor imagery group performed the same task paradigm as the motor training group but with no actual movement over three consecutive days with two repetitions per day. The presented stimuli lasted for 800 ms and the inter-stimuli interval was 20 ms for 10 minutes. During each motor imagery session, the subjects were positioned similar to that used in the test session. The subjects were required to imagine the same sequence of movements after presentation of the visual stimuli on the same computer monitor and to perform the motor imagery task. The task protocol was to imagine the execution of a motor sequence with the right hand as quickly as possible, according to the six colored-arrows shown randomly. In the visual imagery task, they were instructed to refrain from verbalizing or verbally imagining any movement and asked to feel themselves performing the task. In addition, it was emphasized that they should perform the imagined movement with high frequency and engage in the performance intensively by emphasis. Five minutes rest intervals were provided between each session. The subjects were expected to engage actively in unrelated thinking during the rest intervals. They were instructed to imagine performing the task during the entire imagination period and, if a movement finished early, to start over with the same movement until the imagination period had finished. The motor training group was instructed to actually perform the same task paradigm and the training duration was the same as the motor imagery training. The control group carried out the pre- and post-test over three consecutive days without a training session. They were not instructed in any type of motor training or motor imagery throughout the test period.

All the data and two dependent variables, such as the onset of muscular activation and reaction time, were analyzed only when the movement responses (the wrist extension) to the blue and green arrows occurred correctly. Analysis of the onset of muscle activation was carried out using Di Fabio's method[23], which was defined as the using of the time when the rectified EMG activity had reached the specific threshold: mean value of baseline plus three times the standard deviation during the rest period (over 25 ms) in the targeted muscle. The reaction time between the presentation of the visual stimulus and the final movement was determined.

Demographic data such as gender, age, height, and weight were analyzed by one way ANOVA. The effect of motor imagery was determined using two-way ANOVA (groups: motor training, motor imagery, control x test session: pre-test, post-test) with repeated measures of the two dependent variables; the onset of muscle activation and the reaction time. Post hoc analyses by using the Tukey test were performede for the between-groups comparison. All statistical analyses were performed using SPSS, version 15.0. A p value <0.05 was considered significant.

Table 1. General characteristic of each subject

	Training group	Imagery group	Control group
Gender (M/F)	13 (8/5)	14 (10/4)	11 (6/5)
Age (years)	22.92 ± 1.97	23.57 ± 2.24	24.63 ± 1.50
Height (cm)	169.84 ± 7.19	171.64 ± 4.19	169.45 ± 7.59
Weight (kg)	64.46 ± 10.65	66.14 ± 7.59	61.27 ± 14.04

Mean ± S.D.

Table 2. The comparison of the temporal processing time from the presentation of the visual stimulus to onset of muscle activation and reaction time at the pre and the post test in the each group

	Training group		Imagery group		Control group		Time	Group	Interaction
	pre	post	pre	post	pre	post			(Time × Group)
Onset of MA	817.73 ± 151.89	598.45 ± 96.94	808.95 ± 130.44	564.67 ± 73.72	812.09 ± 108.04	772.54 ± 118.01	.000	0.042	.000
RT	1095.20 ± 184.85	825.39 ± 121.33	1042.55 ± 133.50	762.44 ± 84.82	1050.48 ± 130.66	1008.36 ± 137.80	.000	0.037	.000

MA; muscle activation, RT; reaction time.

RESULTS

Among the three groups, there was no significant difference in terms of gender ($p=0.678$), age ($p=0.116$), height ($p=0.651$) or weight ($p=0.536$), which are known to affect the performance of the SRT task (Table 1). Table 2 lists the pre-test and post-test scores for each group. The processing time from the presentation of the visual stimulus to each division using the onset of muscular activation and the reaction time was determined. In both variables (onset of muscle activation, reaction time), univariate analysis revealed a large main effect of the group ($p<0.05$), time ($p<0.001$) and group-by-time interaction ($p<0.001$). Regarding the processing times, there was a significant decrease in the training group whereas the control group did not show a significant change in the processing times.

DISCUSSION

In the current study, we found that both the motor training group and motor imagery group showed a significant decrease in the processing times between the presentation of the visual stimulus and each of two predetermined onsets, which consisted of the onset of muscular activation and the reaction time. However, there were no significant changes in the control group. This suggests that the motor imagery training for three consecutive days resulted in a decrease in the internal processing times needed for a rapid response to visual stimulus (i.e. onset of muscular activation and the reaction time). In addition, there were few differences between the reduction in times achieved by the motor imagery and motor training. Therefore, the effect of motor imagery on enhancing the learning of a motor task might be similar to that of the actual motor training. Accordingly, we consider that the decrease in the total process time to the final motor response might be due to the rapid onset of muscle activation, because motor skill learning is acquired through actual motor training or motor imagery training.

These behavioral changes are in line with previous motor imagery experiments with a SRT task, exhibiting a gradually decrease in reaction time[5,21,24]. Yaguez L et al.[6] reported that motor imagery could improve the acquisition of the spatio-temporal patterns in grapho-motor trajectorial learning tasks, and that different processes were involved in visual and motor imagery. Avanzino L et al.[20] reported that additional motor imagery training with actual practice could affect the performance of repetitive finger opposition movements according to an increase in the velocity of movement and modification in the motor strategy. Other studies also report that motor imagery leads to an increase in the motor function of the affected limb in patients with damage to the central nervous system[25–27].

Recently, many neuroimaging studies that investigating the changes in brain activity and their relationships with behavioral changes have been attempted. According to previous neuroimaging studies, neural areas concerned with the actual motor function, such as the supplementary motor area, premotor areas, basal ganglia, and cerebellum, are activated during motor imagery[15,28]. A PET study by Lafleur et al.[29]'s reported that brain activation during motor imagery was equivalent to the actual execution of foot movement. In an fMRI experiment by Lacourse et al.[30], it was suggested that motor imagery would be effective both for rehearsing a skilled movement and for learning a novel movement, and that almost all features of brain activation involve greater commonality between execution and motor imagery in the skilled learning phase compared to the novel learning phase. Therefore, it is believed that a decrease in the total processing time is probably the result of efficient neural and neuromuscular processing.

Possible explanations for these findings are that the physiological mechanism of motor imagery is similar to the actual physical movement. Many studies have reported that motor imagery without a corresponding motor output exhibiting mechanisms similar to movement preparation and the processing required during actual motor execution[31,32]. In addition, the motor imagery effects on motor learning may be due to rehearsing the cognitive components of the actual task[1,6,32]. The cognitive elements of the motor task predict that motor imagery will have greater effects on the motor tasks with relatively more cognitive components than other tasks. Heuer[33], reported that imagining of performance a motor task actually has an inherent physical component, in which a firm link between the imagination of a movement and its achieved performance exists inside. This link is referred to as the ideomotor principle. According to previous experiments examining the ideomotor principle, there were some evidences of EMG activity and autonomic reactions had been measured during the imagination of movements[34,35]. Guillot et al.[36] reported that a corresponding muscle activation pattern was detected in EMG when subjects imagined a range of different types of muscle contractions. Slade et al.[37] observed EMG activity in the targeted muscle groups after motor imagery. Accordingly, it is believed that the change of processing time in motor imagery may result from psychophysiological constituents, such as the cognitive element, neuromuscular adaptation, and neurophysiological plasticity in the preparation phase of motor performance in motor learning, which may lead to a decrease in processing time and have similar positive effects on actual execution.

These findings showed that motor imagery for motor skill acquisition could provide a highly effective, and improve motor training in healthy volunteers. Furthermore, combining motor imagery with actual training may be a valuable rehabilitation practice for therapeutic intervention. We acknowledge that this study has some limitations. For example, the task complexity was not considered in this study. In addition, factors, such as a person's ability to imagine performing a task and attention span, are crucial components that can not quantified. Therefore, further studies will be needed to determine the detailed efficacy and mechanisms of motor imagery in a complex movement task by taking these additional factors into consideration.

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