Chapter 31
Effects of Motor Imagery on Cognitive Function and Prefrontal Cortex Activity in Normal Adults Evaluated by NIRS

M. Moriya and K. Sakatani

Abstract Recent near-infrared spectroscopy (NIRS) studies demonstrated that physical exercise enhances working memory (WM) performance and prefrontal cortex (PFC) activity during WM tasks in normal adults. Interestingly, the effects of rehabilitation (i.e. physiotherapy) on post-stroke patients could be enhanced by motor imagery (MI), an active process during which the specified action is reproduced within WM without any actual physical movement. However, it is not known whether MI can enhance cognitive function and associated brain activity. To clarify these issues, we evaluated the effect of MI on WM performance and PFC activity during WM tasks in normal adults, employing NIRS. We studied 10 healthy adults. The present study was a crossover comparison test; the MI training and control condition (rest) were applied to the subjects at random. The Time Up and Go method was used for MI training: the subject sat on a chair and conducted MI for 3 min, three times. Neuronal activity (oxyhemoglobin concentration) in the bilateral PFC was measured using 2-CH NIRS during WM tasks. We found that MI improved the behavioral performance of WM compared with the control ($p < 0.01$). NIRS revealed that MI enhanced PFC activity induced by the WM task compared with the control task ($p < 0.01$). These results suggest that MI can improve cognitive function and increase associated PFC activity in normal adults.

Keywords NIRS • Rehabilitation • Working memory • Prefrontal cortex • Motor imagery

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1 Introduction

Motor imagery (MI) involves reproduction of an action within working memory (WM) without any actual physical movement. It has been used in rehabilitation [1], for example to improve recovery of motor function following stroke, and also has a number of exciting potential applications, for example to provide brain-machine interfacing [2]. Reproduction of the motor image by the working memory is associated with activation of the prefrontal cortex (PFC) [3], and PFC activation can be measured by means of near-infrared spectroscopy (NIRS) in terms of oxyhemoglobin concentration changes.

The purpose of this study is to examine the neuro-physiological effects of MI training. Specifically, we used NIRS to examine the effect of MI on PFC activity and we evaluated the influence of MI-induced PFC activity changes on WM task performance in normal adults.

2 Methods

We studied 10 healthy adults (6 males and 4 females, age 25.5 ± 1.2 years). All participants provided written informed consent as required by the Human Subjects Committee of the Nihon University Hospital (Japan).

The subject performed the imagined Time Up and Go for motor imagery (MI) [4] and the control task with the resting condition at random. The motor image task being used in previous studied had Time Up and Go (TUG-i). To recall for 10 min sitting at a chair, Time Up and Go (TUG-real: TUG-r) has conventionally been measured in the same environment in which it has been set. TUG is composed of a plurality of operation of standing, walking, direction-changing and sitting.

The modified Sternberg Test (ST) was used as a working memory (WM) task [5–7]. In ST, subjects were asked to remember one digit and six digits successively. There were eight 1-digit trials and eight 6-digit trials. Each trial began with the presentation of one digit or a set of six digits to be encoded for 1 s on a display. Then a blank display was shown for 2 s, followed by the test digit until a response was obtained within 2 s. Subjects held a small box with two buttons side by side. They were required to press the right button if they thought the test digit was contained within the encoded stimulus and to press the left one if not, as quickly and accurately as possible. Similar tasks have been used in NIRS experiments and demonstrated that they activated the PFC [5–7].

We measured concentration changes of oxyhemoglobin (oxy-Hb), deoxyhemoglobin (deoxy-Hb) and total Hb (t-Hb) in the bilateral PFC during the WM task using a two-channel NIRS (PNIRS-10, Hamamatsu Photonics K.K., Hamamatsu, Japan). The NIRS probes were set symmetrically on the forehead; the positioning is similar to the midpoint between electrode positions Fp1/F3 (left) and Fp2/F4 (right) of the international 10–20 system [8]. The sensor part (weighing approximately

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100 g, which imposes a minimal burden on the subject) communicated with a PC via Bluetooth™ (class 2).

We analyzed the changes in oxy-Hb concentration by subtracting the mean control values from the mean activation values induced by ST. We evaluated behavioral performance (response time and accuracy) of the WM task. The oxy-Hb concentration changes and behavioral performance before and after the exercise were compared using a paired student's t-test.

3 Results

Figure 31.1 shows a typical example of NIRS parameter changes in the PFC during MI and ST. MI increased oxy-Hb and t-Hb associated with a decrease of deoxy-Hb. ST caused similar NIRS parameter changes before and after MI. It should be noted that the ST-induced changes of oxy-Hb after MI were larger than those before MI.

Table 31.1 compares changes of oxy-Hb concentrations induced by ST before and after MI. The mean changes of oxy-Hb concentrations in the PFC induced by ST after MI were significantly higher than those before MI ($p < 0.05$). In contrast, there were no significant effects of the control task on ST-induced oxy-Hb changes.

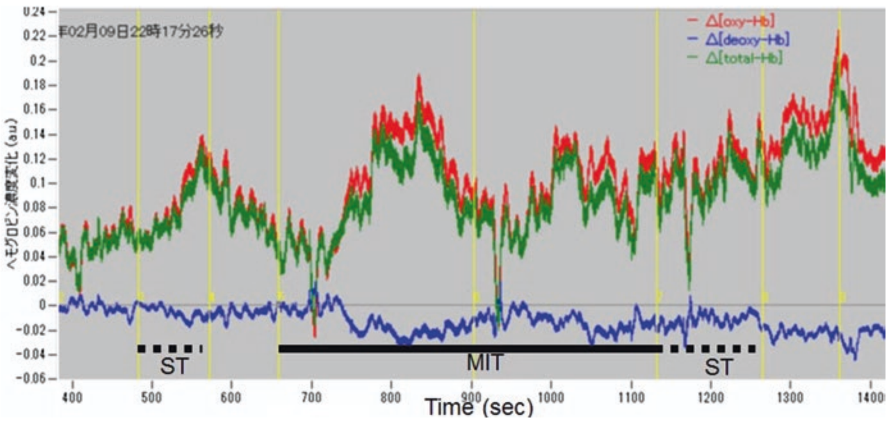

Fig. 31.1 A typical example of NIRS parameter changes during motor imagery (MI) and the Sternberg Test (ST)

Table 31.1 Effects of motor imagery and control task on changes of oxy-Hb induced by the Sternberg Test

	Control		Image	
	Right PFC	Left PFC	Right PFC	Left PFC
Before	0.022 ± 0.02	0.013 ± 0.03	0.007 ± 0.03	0.007 ± 0.04
After	0.019 ± 0.02	0.012 ± 0.03	0.041 ± 0.03*	0.049 ± 0.04*

*$p < 0.05$

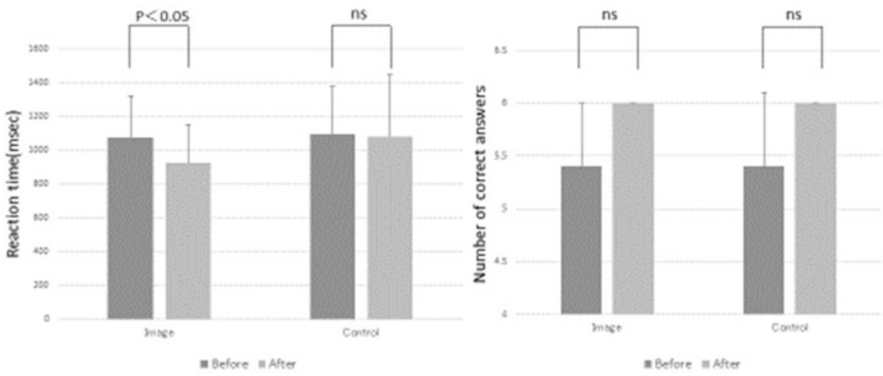

Fig. 31.2 (**a**) Effect of MI on reaction time; and (**b**) Number of correct answers on the Sternberg Test

Figure 31.2 shows the effect of MI on the performance of ST. The response time of ST after MI was significantly shorter than that before MI; there was no effect of the control task on the response time. In contrast, MI had no significant effect on the accuracy of ST (i.e. number of correct answers).

4 Discussion

This is the first study to examine the acute effects of motor imagery on cognitive function in normal adults using NIRS. We measured Δoxy-Hb change at the PFC during the working memory task (i.e. the Sternberg Test) after motor imagery. Behavioral analysis shows that motor imagery improved behavioral performance of the working memory task compared with the control sessions; the subjects responded more quickly after motor imagery. In contrast, there were no significant effects on the PFC activity and behavioral performance after the control sessions. These findings suggest that motor imagery could enhance the PFC activity associated with working memory performance.

Studies have demonstrated that physical exercise enhances cognitive function associated with an increase of brain activity [9, 10]. Employing a similar NIRS and working memory task in the present study, we examined the acute effect of physical exercise (moderate intensity exercise with an ergometer) on PFC activity in older adults using NIRS [5]. We observed that the physical exercise improved the behavioral performance and enhanced the PFC activity, similar to earlier findings.

Some animal studies have proposed physiological mechanisms for the effect of physical exercise on cognitive functions, such as brain-derived neurotrophic factor [11]. However, the physiological mechanism of motor imagery on cognitive function is not yet clear. It is reported that motor imagery activates various cortical areas, including the PFC [3]. Conditioning of the PFC activity induced by motor imagery may enhance PFC activity and the related cognitive function, such as the working memory.

In conclusion, the present study has successfully demonstrated, for the first time, the acute motor imagery effect on cognitive function and PFC activity in normal adults using NIRS.

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References

1. Harris JE, Hebert A (2015) Utilization of motor imagery in upper limb rehabilitation: a systematic scoping review. Clin Rehabil 29:1092–1107
2. Alonso-Valerdi LM, Salido-Ruiz RA, Ramirez-Mendoza RA (2015) Motor imagery based brain-computer interfaces: an emerging technology to rehabilitate motor deficits. Neuropsychologia 79:354–363
3. Hétu S, Grégoire M, Saimpont A et al (2013) The neural network of motor imagery: an ALE meta-analysis. Neurosci Biobehav Rev 37:930–949
4. Beauchet O, Annweiler C, Assal F et al (2010) Imagined Timed Up & Go test: a new tool to assess higher-level gait and balance disorders in older adults? J Neurol Sci 294:102–106
5. Tsujii T, Komatsu K, Sakatani K (2013) Acute effects of physical exercise on prefrontal cortex activity in older adults: a functional near-infrared spectroscopy study. Adv Exp Med Biol 765:293–298
6. Sakatani K, Tanida M, Hirao N et al (2014) Ginko biloba extract improves working memory performance in middle-aged women: role of asymmetry of prefrontal cortex activity during a working memory task. Adv Exp Med Biol 812:295–301
7. Tanida M, Sakatani K, Tsujii T (2012) Relation between working memory performance and evoked cerebral blood oxygenation changes in the prefrontal cortex evaluated by quantitative time-resolved near-infrared spectroscopy. Neurol Res 34:114–119
8. Tanida M, Katsuyama M, Sakatani K (2007) Relation between mental stress-induced prefrontal cortex activity and skin conditions: a near-infrared spectroscopy study. Brain Res 1184:210–216
9. Colcombe S, Kramer AF (2003) Fitness effects on the cognitive function of older adults: a meta-analytic study. Psychol Sci 14:125–130
10. Colcombe SJ, Kramer AF, McAuley E et al (2004) Neurocognitive aging and cardiovascular fitness: recent findings and future directions. J Mol Neurosci 24:9–14
11. Zoladz JA, Pilc A (2010) The effect of physical activity on the brain derived neurotrophic factor: from animal to human studies. J Physiol Pharmacol 61:533–541. Review.