



Original Article

The effects of tool holding on body schema during motor imagery: a near-infrared spectroscopy study

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Abstract. [Purpose] The purpose of this study is to assess the influence of tool holding on brain activities during motor imagery in two tasks: imagining the movement of writing the alphabet while holding a pen and without holding the pen. [Subjects and Methods] Eleven healthy right-handed adults performed two tasks, holding a pen and not holding the pen during imagining the movement of writing the alphabet using a pen. Regions of targets were Brodmann areas 6 which were a motor-related region, 44/45 and 39/40 which taken on the role of forming the body schema. Change of the oxygenation state of hemoglobin associated with brain activity were acquired using a near-infrared spectroscopy. [Results] When using their dominant right hands, task-related increases in oxy-Hb were prominent in Brodmann areas 44/45 and 39/40 when imagining writing while actually holding the pen than when not. When using the non-dominant left hands, there were no significant differences between the two conditions in the same areas. [Conclusion] These results suggest that the tool held can be incorporated into the body schema in the motor imagery of an automated tool use task. Therefore, tool holding during motor imagery might be more effectively influence during rehabilitation.

Key words: Motor imagery, Body schema, NIRS

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INTRODUCTION

Motor imagery is the process of simulating movement mentally without physical execution of the movement¹⁾. This mental practice of motor imagery is being considered as a technique for improving performance during rehabilitation for motor recovery²⁾.

It is difficult for us to objectively evaluate motor imagery because it is only a mental representation of the movement. On the other hand, it is possible to visualize brain activity during motor imagery using human brain mapping, and a common neural network was found in both motor imagery and real movement in studies using positron emission tomography (PET) and functional magnetic resonance imaging (fMRI)³⁻⁶⁾.

As during movement execution, same brain regions are active during motor imagery, including the premotor area, pre-supplementary and supplementary motor areas, primary motor area, primary somesthetic area, and the superior and inferior parietal lobules⁷⁾. In particular, the inferior parietal lobule takes on the role of forming the “body schema”. The body schema is defined as a posture model that is constantly modified by changes in posture⁸⁻¹⁰⁾. The body schema is generated by interactions of the body with the environment, which play an important role in incorporating the use of tools in the body schema¹¹⁾. This interaction with the environment, including tool use, is also very important for clear motor imagery. Motor imagery may become clearer by performing the act of holding a tool, as seen in the case of exercise when using a tool.

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Near-infrared spectroscopy (NIRS) represents a safer method that does not require strict motion restriction, and as a result, can be used with subjects in a sitting posture in natural environments^{12, 13}. During rehabilitation, which is widely practiced in a great variety of environments, the findings obtained by NIRS have been utilized to evaluate and examine intervention plans and means and to judge intervention outcomes, and have been of significant benefit.

Murata et al. investigated that brain activation adapting the strength of the body schema modification by using NIRS¹⁴. However, few studies have focused on the use of NIRS to assess the differences in cerebral activation during motor imagery in the presence or absence of tool holding. Consequently, the purpose of the present study was to assess change of the oxygenation state of hemoglobin in two tasks: imagining the movement of writing the alphabet while holding a pen and without holding the pen.

SUBJECTS AND METHODS

Eleven healthy right-handed volunteers (5 females; 6 males; average age \pm standard deviation=22.8 \pm 2.7 years) participated in the study. The handedness was evaluated by Edinburgh Inventory¹⁵, and all subjects were right-handed. Informed written consent was given by all participants, and the study was approved by the institutional ethics committee of the International University of Health and Welfare (13-10-198).

With closed eyes, the subjects imagined the movement of using a pen to write the alphabet from A to J, either while actually holding a pen (with tool condition; WT condition) or while not holding the pen (without tool condition; NT condition). In the WT condition, they held the pen in the same way as during real writing. In the NT condition, they held their fingers in a position as close as possible to that during real writing. In both conditions, subjects were instructed not to contract muscles as if writing, but to only allow the pen to rest in their fingers as it would during writing and to imagine kinesthetically performing the writing movement. They performed the tasks sitting in front of a table with their heads fixed to a chin support to prevent artifactual movements. Each 20-s task period was alternated with a 30-s rest period for a total of 3 repetitions with the dominant (right) and non-dominant (left) hands. The order of with tool condition and no tool condition was random. Subjects performed the tasks with their right hands at first and then performed with their left hands. After imagining the writing movements, the subjects used a seven-point Likert scale used in MIQ-RS to rate the ease or difficulty of feeling the movements¹⁶. A score of 1 represents “very hard to feel,” and a score of 7 represents “very easy to feel”.

Data were acquired using a multichannel NIRS optical topography system (ETG-4000 Hitachi Medical Corporation, Kashiwa, Japan). This method allowed us to calculate signals reflecting concentration changes in oxygenated hemoglobin (oxy-Hb) and deoxygenated hemoglobin (deoxy-Hb) expressed in arbitrary units of millimolar-millimeter (mMmm)¹⁷. The sampling rate was set at 10 Hz.

We set the NIRS probe to cover the sensorimotor cortex by referring to previous studies¹⁸⁻²⁰. We used 2 sets of 3 \times 5 multichannel probe holders, consisting of 8 illuminating and 7 detecting probes arranged alternately at an inter-probe distance of 3 cm, resulting in 22 channels per set. The left and right probe holder was placed such that its center was placed over the C3 and C4 position in accordance with the international 10–20 system²¹.

For spatial profiling of the NIRS data, we employed a virtual registration technique^{22, 23} to register the acquired data to the Montreal Neurological Institute (MNI) standard brain space²⁴. This method allowed us to place a virtual probe holder on the scalp by simulating the holder’s deformation and by registering probes and channels onto reference brains in the MNI database²⁵⁻²⁷. We anatomically labeled the estimated locations using a macroanatomical brain atlas (LBPA40)²⁸ and Brodmann’s atlas²⁹. Statistically estimated NIRS channel locations and their spatial variability associated with the estimation were exhibited in MNI space (left hemisphere: premotor area [Brodmann area 6] [Ch 3, 12, and 21], inferior frontal gyrus [Brodmann area 44/45] [Ch 4, 8, 9, and 13] and inferior parietal lobule [Brodmann area 39/40] [Ch 10, 14, 15, and 19]; right hemisphere: premotor area [Brodmann area 6] [Ch 33 and 42], inferior frontal gyrus [Brodmann area 44/45] [Ch 23, 27, 28, and 32] and inferior parietal lobule [Brodmann area 39/40] [Ch 35, 39, 40, and 44]).

For each subject, we omitted the measurements from channels showing low signal-to-noise ratios. Linear trends of continuous oxy-Hb and deoxy-Hb fluctuations were also removed. Changes in oxy-Hb and deoxy-Hb levels were smoothed with a 5-s moving average and were averaged synchronously to the tasks. Oxy-Hb and deoxy-Hb values were normalized to those during the 10-s rest period prior to the task. The average of z-scores for 1 s before and after the oxy-Hb peak during a task block was calculated in each channel. We focused on oxy-Hb because of its higher sensitivity to changes in cerebral blood flow^{30, 31} and its higher signal-to-noise ratio³¹ than those of deoxy-Hb signals. These analyses were performed using MATLAB 2006a (MathWorks, Natick, MA, USA).

To compare changes in brain activities in each region during the NT and WT conditions of the imagery task, we calculated oxy-Hb data from each subject, and used the Wilcoxon signed-rank test. All statistical analyses were performed using the JSTAT software for Windows (Nankodo Corporation, Bunkyo, Japan).

RESULTS

The tendency that was easy to image movement in WT was found in right and left hands. Task-related increases in oxy-Hb were prominent in Brodmann areas 6, 44/45 and 39/40. Specifically, the magnitudes of oxy-Hb signals during the WT

Table 1. Brain activities during writing imagery task under NT and WT conditions (right hand)

Hemisphere	Brodmann area	NT condition	WT condition
Left	6	4.06 (2.07–5.51)	3.67 (2.09–8.91)
	44/45	3.19 (0.75–3.69)	6.32 (3.38–8.33) *
	39/40	2.27 (1.57–2.86)	3.41 (2.73–4.56) *
Right	6	2.63 (1.34–4.26)	4.40 (2.78–6.02)
	44/45	2.60 (0.57–3.87)	5.44 (3.33–8.99) *
	39/40	1.94 (0.44–2.50)	3.97 (3.64–6.82) **

Values are the median (IQR) of z-scores for 1.0 s before and after the oxy-Hb peak during task per block in all subjects in the indicated brain areas. NT: without holding the tool; WT: holding the tool. * $p < 0.05$, ** $p < 0.01$, NT condition vs. WT condition. Brodmann area 6: premotor area, 44/45: inferior frontal gyrus, 39/40: inferior parietal lobule

Table 2. Brain activities during writing imagery task under NT and WT conditions (left hand)

Hemisphere	Brodmann area	NT condition	WT condition
Left	6	2.57 (1.31–3.59)	2.66 (1.62–4.32)
	44/45	2.48 (1.40–3.93)	1.62 (1.12–7.70)
	39/40	1.80 (1.59–3.55)	2.15 (0.81–3.99)
Right	6	3.58 (1.49–5.36)	2.56 (1.20–5.66)
	44/45	3.59 (0.58–4.67)	1.97 (1.23–3.62)
	39/40	2.28 (0.71–3.84)	2.31 (0.59–3.89)

Values are the median (IQR) of z-scores for 1.0 s before and after the oxy-Hb peak during task per block in all subjects in the indicated brain areas. NT: without holding the tool; WT: holding the tool. * $p < 0.05$, ** $p < 0.01$, NT condition vs. WT condition. Brodmann area 6: premotor area, 44/45: inferior frontal gyrus, 39/40: inferior parietal lobule

condition were larger than those during the NT condition using the right hand, while oxy-Hb and deoxy-Hb changes were few in these areas when the left hand was used. When the right hand was used, significant activation was found in WT and NT conditions in area 6 on the left hemisphere. Moreover, when the right hand was used, brain activities in the bilateral Brodmann areas 44/45 and 39/40 were significantly larger during the WT condition than during the NT condition (Table 1, left 44/45 and 39/40, right 44/45 $p < 0.05$, right 39/40 $p < 0.01$). When the left hand was used, there were no significant differences between the WT and NT conditions in these areas (Table 2).

DISCUSSION

This is one of the first studies to assess differences in brain activities during motor imagery related to tool holding using NIRS. In this study, significant activation occurred in left 6 field which were a motor-related region in the motor imagery task of both NT and WT conditions of the right hand. These results showed that the brain region same as movement execution activated even motor imagery and supported preliminary research^{3–7}.

Interestingly, that holding a pen during a writing imagery task resulted in significant brain activation in the bilateral Brodmann areas 44/45 and 39/40 boundary region compared with not holding the pen indicates that the cerebral activation area during motor imagery. The inferior parietal lobule has the role of unifying information from a variety of sensory modalities, such as visual and somesthesia. The inferior parietal lobule of the left hemisphere has a strong association with routine tool use³², and it is said that ideomotor apraxia, ideational apraxia, and constructional apraxia can occur when this region is damaged. The inferior parietal lobule of the right hemisphere has a strong association with self-somatognosia, and it is said that left unilateral spatial neglect, anosognosia, can occur when this region is damaged³³. Whereas the inferior frontal gyrus corresponds to the Broca's field and is known as motor speech center. Particularly, it is found that the left inferior frontal gyrus carries the important role in the tool use as well as motor speech center³⁴. Naito et al. reported that a frontal-parietal network that connects body schema and external objects is found in the left hemisphere⁹, and a frontal-parietal network associated with updating the body schema and physical self-consciousness is found in the right hemisphere¹⁰. A recent study showed that there is a tertiary branch of the superior longitudinal fasciculus that acts as an intracerebral nerve fiber connecting Brodmann area 39/40, equivalent to inferior parietal lobule, with Brodmann area 44/45, equivalent to inferior frontal gyrus, in both hemispheres³⁵. We suggest that neuronal activation in the inferior parietal lobule and the inferior frontal gyrus are related to uptake of the pen as a tool into the body schema in the left hemisphere, and update of the body schema in real

time in the right hemisphere.

There were no significant differences in brain activities while performing the imagery task under the NT and WT conditions when the left hand was used. Thus, it appears that the level of proficiency of the movement influenced our results. Fourkas et al. reported that in a motor imagery task of tennis, excitatory augmentation of the corticospinal tract occurred with experienced tennis players but not with beginning players³⁶. They also reported that the experienced tennis player did not experience corticospinal tract reinforcement for other movements that they were not proficient in³⁶.

This study results suggest that the tool held can be incorporated into the body schema in the motor imagery of an automated tool use task. Our another studies indicate that holding a tool can effectively conjure an image of a movement that was mastered using this tool³⁷. Therefore, tool holding during motor imagery might be more effectively influence during rehabilitation. However, the influence of holding the tool has little impact in motor imagery when not proficient in the movement³⁷. Thus, motor imagery tasks chosen to augment rehabilitation and recovery from motor deficits must be of movements that were already automated and proficient on the side of the injury.

The NIRS technique that we used to measure cerebral function is inferior to other cerebral function imaging methodologies in terms of spatial resolution and in that it cannot measure activities in the cerebellum or basal ganglia. However, it has the clear advantage of being a very safe method that does not require strict motion restriction, can be used with subjects in a sitting posture during rehabilitation that is widely practiced in a great variety of environments. Future neuroimaging studies are required to investigate activation changes over a wider variety of brain regions. Further examination is also warranted to evaluate the effects of this result on people with disabilities or the elderly.

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