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Reduction in Cortical Activation in the Sensorimotor Cortex during Motor Skill Learning of a Pursuit Rotor Task: A Functional Near-Infrared Spectroscopy Study

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Abstract

To investigate the cerebral mechanisms underlying learning of motor skills, we assessed serial changes of brain activation patterns during a pursuit rotor (PR) task in 12 right-handed healthy subjects using functional near-infrared spectroscopy (fNIRS). The subjects performed the task with their right hand for 15-s, alternated with a 30-s rest period, for 18 repetitions (cycles 1 to 18). Gains in motor skill were evaluated by recording the time for which the stylus remained on the target. Performance improved with repetition of the task. Task-related increases of oxygenated hemoglobin (oxy-Hb) were observed around the predicted location of the sensorimotor cortices on both hemispheres. The increased oxy-Hb levels appeared to reduce with repetition of the task in the channels covering the left sensorimotor area. Furthermore, there was a significant correlation between PR task performance gain and the oxy-Hb signal in the left and right sensorimotor areas. Our results suggest that cortical activation in the sensorimotor cortex reflects changes in a number of factors including sensory feedback processing, correct motor commands, and perceptual or cognitive function during learning of a PR task. Therefore, changes in contralateral sensorimotor cortical activation may serve as a motor sequence learning biomarker for rehabilitation purposes or the prediction of recovery.

Keywords: Motor skill learning; Motor sequence learning; Psuit rotor; Near-infrared spectroscopy; NIRS; Optical topography; Occupational therapy

Introduction

In our daily life, motor skill learning is essential in acquiring or reacquiring motor skills. When we learn or relearn a motor skill, an awkward motion is usually carried out in the early phases of learning, but gradually becomes a smooth and easy motion over time. Motor skill learning can be conceived as the establishment of an internal model that represents the exact matching of perceived sensory and motor information [1]. Motor skill learning comprises motor sequence learning (the incremental acquisition of movements into a well-executed behavior) and motor adaptation (the capacity to compensate for environmental changes) [2]. Motor sequence learning is assessed by the incremental acquisition of movements with repetitions, while motor adaptation refers to the ability to compensate for environmental changes [2].

Behavioral studies have suggested that the brain might update the mechanism for sensorimotor control in every trial when we learn a novel motor task [3,4]. To investigate changes in brain activation associated with practice in a range of motor, visuomotor, perceptual, and cognitive tasks, most studies have used positron emission tomography (PET) or functional magnetic resonance imaging (fMRI) [5-9]. However, when using PET and fMRI, the subjects have to perform the task in a lying position and minimize body motion for image acquisition. Whereas, functional near-infrared spectroscopy (fNIRS) is advantageous in that it 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 [10,11]. There are now a limited number of studies suggesting that changes in cortical response monitored longitudinally by fNIRS evolve as a function of motor skill learning, such as during a pursuit rotor (PR) task [12,13], Kendama task [14], or knot-tying task [15,16]. In these studies, the subjects performed the tasks in a sitting position.

The activities of daily living (ADLs), plays, or works specifically require motor sequence learning [13]; therefore, robust and compact assessment tools for motor sequence learning are highly desirable in the clinical setting for rehabilitation purposes or the prediction of recovery. A PR task is one such tool that can be used to evaluate motor sequence learning by measuring a patient's ability to keep a stylus on a rotating target [13]. In a previous PET study of a PR task performed in a lying position, early phase learning of the PR task using the right upper extremity was related to increased activation in the left supplementary motor cortex or left primary motor cortex [17]. In accordance, an increase of supplementary motor cortex activity, a

decrease of presupplementary motor cortex activation as learning progressed, irrespective of the outcome, and no learning-related sensorimotor cortex activity change were reported for a PR task performed in a sitting posture using fNIRS technique [12,13]. Because the examination periods of these studies were only until motor performance became fixed, changes in brain activity were not recorded after motor performance reached a plateau level.

Consequently, the purpose of the present study was to explore changes in activation around the left and right sensorimotor cortices during motor sequence learning by fNIRS. Therefore, we measured cortical activation during the early phase of PR task learning, including the execution period, and after PR task performance reached a plateau level.

Material and Methods

Subjects

Twelve right-handed, healthy volunteers (9 females; 3 males; average age ± standard deviation = 24.1 ± 5.3 years; range: 19-35 years) participated in the study. Handedness was assessed by means of the Edinburgh Inventory [18]. No subject had previous experience of the PR task. Written informed consent was given by all participants and the study was approved by the institutional ethics committee of the International University of Health and Welfare.

PR task

The subjects were asked to sit in front of the PR instrument (TKK2110; Takei Corporation, Niigata, Japan) (Figure 1) and instructed to keep the tip of a mental stylus upon a round target (11 mm in diameter) within a larger disc (105 mm in radius) rotating counter-clockwise at a constant speed (21 rpm) [12,13]. The distance from the subject's body to the edge of PR instrument was set to approximately 50 cm. The subjects performed the task with their right hand. Japan Neuroscience Society "Non-invasive research on human brain function" Subcommittee has reported that each task session using fNIRS should be limited to 15 minutes or less in Guidelines for ethics-related problems with "non-invasive research on human brain function" [19]. We followed the guidelines and tried to increase the repetition cycles as many as possible. Therefore, we determined that each 15-s task period was alternated with a 30-s rest period for a total of 18 repetitions (cycles 1-18). Furthermore, although the number of repetition cycles was 5 or 8 in the previous studies [12,13,16], statistical analyses could be practiced in their studies. Their capacity for motor skill learning was assessed by the gain in the contact time of the stylus with the target (0-15 s). Because the examination periods of the previous studies [12,13] were only until motor performance became fixed, changes in brain activity were not recorded after motor performance reached a plateau level. We measured cortical activation from starting point of motor sequence learning to acquisition of PR performance, and after PR task performance reached a plateau level.

fNIRS instruments

Data were acquired using a multichannel fNIRS optical topography system ETG-4000 (Hitachi Medical Corporation, Kashiwa, Japan) operating with two wavelengths of near-infrared light (695 and 830 nm). Optical data based on the modified Beer-Lambert Law [20,21] were analyzed as described previously [22]. This method allowed us to calculate signals reflecting concentration changes in oxygenated hemoglobin (oxy-Hb) and deoxygenated hemoglobin (deoxy-Hb) expressed in units of millimolar-millimeter (mMmm) [22]. The sampling rate was set at 10 Hz.

Figure 1: fNIRS measurements. Brain activity was measured while the subjects performed the PR task with their right hand.

fNIRS probe placement

We set the fNIRS probe to cover the sensorimotor cortex by referring to previous studies [23-25]. We used 2 sets of 3 × 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 (CHs) per set. The left probe holder was placed such that CH 11 and CH 34 were placed over the C3 and C4 positions, respectively, in accordance with the international 10-20 system [26] and arranged in a lateral line between the lateral angle of the eye and the external canal (Figure 2a).

Probabilistic registration of fNIRS CHs to MNI space

For spatial profiling of the fNIRS data, we employed a virtual registration technique [27,28] to register the acquired data to Montreal Neurological Institute (MNI) standard brain space [29]. This method allows us to place a virtual probe holder on the scalp by simulating the holder's deformation and by registering probes and CHs onto reference brains in the MNI database [30,31]. Specifically, we measured the positions of CHs and reference points, consisting of the Nz (nasion), Iz (inion), Cz (midline central), and left and right preauricular points, with a 3D-digitizer in real-world space. We affine-transformed the real-world reference points to the corresponding reference points in each entry in reference to the MRI database in MNI space. We were thus able to estimate probabilistically the MNI coordinate values for the fNIRS CHs in our subjects. Spatial variability associated with the estimations due to individual variability in head shape and the replacement of individual MRIs by reference brains were also described previously [32] (Figure 2b). Finally, we anatomically labeled the estimated locations using a macroanatomical brain atlas (LBPA40) [33] and Brodmann's atlas [34].

Analysis of fNIRS data

For each subject, we removed the measurements from CHs showing a low signal-to-noise ratio. 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. Oxy-Hb and deoxy-Hb values were normalized to those during the 30-s rest period prior to the first cycle in order to circumvent the potential influence of differential path-length factors in different regions. The z-score of the oxy-Hb peak during a task block was calculated against the starting point of each cycle in each CH. We focused upon oxy-Hb because of its higher sensitivity to changes in cerebral blood flow than that of deoxy-Hb signals [35,36], its higher signal-to-noise ratio [36], and its higher retest reliability [37]. These analyses were performed using MATLAB 2006a (MathWorks, Natick, MA, USA). We defined a set of 8 CHs on both sides on and around C3 and C4 as a sensorimotor area region of interest (ROI) [23-25]. These regions included the left and right precentral or postcentral gyrus by LBPA40 [33] or Brodmann's areas 4, 3, 2, or 1 by Brodmann's atlas [34] (Figure 2b).

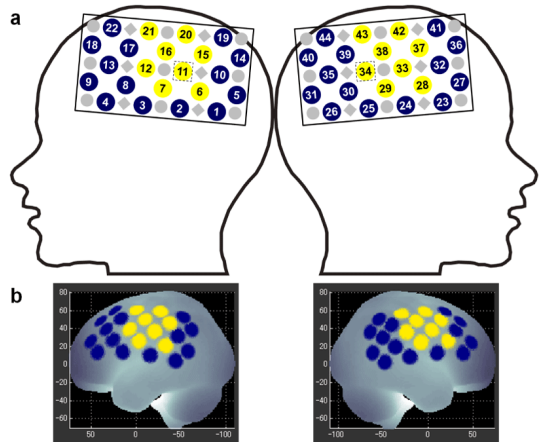

Figure 2: (a) Spatial profiles of fNIRS CHs (left and right side views of the probe arrangements). fNIRS CH orientation is also illustrated. Detectors are shown as gray lozenges, illuminators as gray circles, CHs as black and white numbers (1-44), and ROIs (8 CHs) as yellow circles. CH 11 and CH 34, shown as dotted black squares, were placed over the C3 and C4 positions, respectively, in accordance with the international 10-20 system [26]. (b) CH locations on the brain. Left and right side views are illustrated. Statistically estimated fNIRS CH locations (yellow [ROIs] or blue circles) for all subjects, and their spatial variability associated with the estimation are exhibited in MNI space.

Statistical analyses

Behavioral performance and fNIRS data were non-normally distributed, could not be centralised using common transformations and were therefore analysed using non-parametric tests of significance such as the Friedman test or the and examined the Spearman's rank [16,38]. The Friedman test was used to determine if statistically significant fluctuations had occurred in behavioral performance and sensorimotor hemodynamic data across PR trials. Changes of PR task performance across task cycles were analyzed using the Friedman test with task cycle (1 to 18). Serial changes of the z-score of the oxy-Hb peak with cycle repetition in each region were also evaluated using the Friedman test. To establish a link for the PR performance and brain activation, we sought appropriate methods to compare signals of the performance and fNIRS data and examined the Spearman's rank correlation coefficient between performance gains and changes of oxy-Hb signals in the PR cycles [38]. A value of $p < 0.05$ was assumed to be statistically significant. All statistical analyses were performed with SPSS Statistical Packages version 21 (International Business Machines Corporation, Armonk, NY, USA)

Results

PR performance

In all subjects, PR task performance improved with cycle repetition (mean contact time on the target: 4.4/7.0/7.3/8.5/10.0/10.6/10.7/11.0/10.9/10.5/10.3/10.5/11.2/10.8/11.2/11.6/11.6/10.6s). Friedman's test revealed a significant main effect for task cycle ($T = 85.177$, $p < 0.001$) (Figure 3).

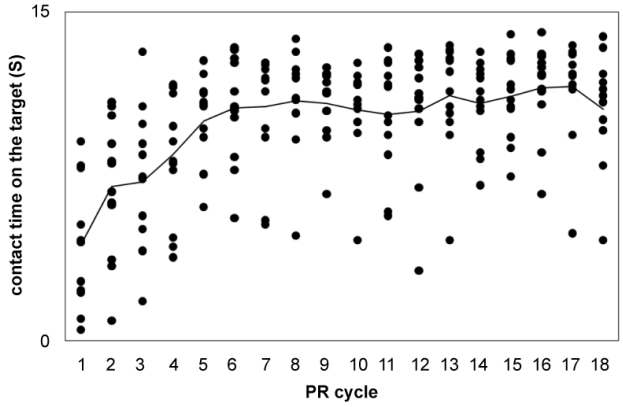

Figure 3: Serial changes of the 12 subjects during PR task performance (black circle: each subject data; black line: mean value of all subjects).

Task-related changes of Hb levels

Task-related increases of oxy-Hb levels were prominent in the ROIs, while there were task-related changes of deoxy-Hb levels that were smaller than those of oxy-Hb (Figure 4). Specifically, the magnitude of oxy-Hb signals was larger in the left sensorimotor area than in the right hemisphere. The increased levels of oxy-Hb appeared to reduce with repetition of the task in the CHs covering the left sensorimotor area. In the left sensorimotor cortex, Friedman's test revealed a significant main effect for task cycle ($T = 27.883$, $p = 0.046$). In the right sensorimotor area, oxy-Hb signals showed a downward tendency ($T = 22.409$, $p = 0.169$).

Association between PR task performance and fNIRS results

We examined the potential correlation between PR task performance and activation of the left and right sensorimotor areas. The correlation coefficients were -0.204 (left, $p = 0.003$, Figure 5) and -0.386 (right, $p < 0.001$), respectively. A better correlation was obtained when data of all the subjects were accumulated and averaged ($r = -0.662$, $p = 0.003$ for left and $r = -0.502$, $p = 0.034$ for right), probably due to between-subjects factors reduction. There was a significant correlation between performance gain and oxy-Hb signals in the left and right sensorimotor areas.

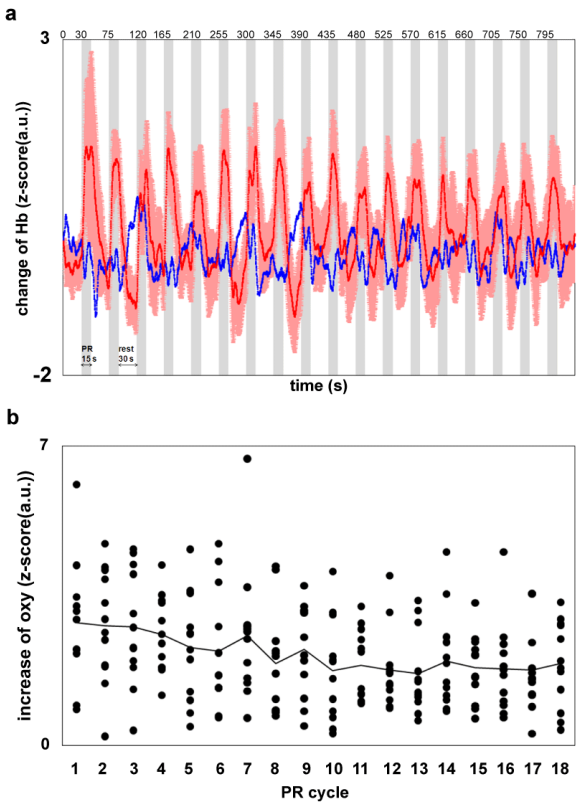

Figure 4: (a) Serial changes of the average waveforms for oxy-Hb (red line) and deoxy-Hb (blue line) for all subjects during the PR task in the left hemisphere ROI. Standard deviations among the 12 subjects are exhibited as pale red areas. (b) Serial changes of left sensorimotor cortex activation (z-score of the oxy-Hb peak of each subject [black circle: each subject data; black line: mean value]).

Discussion

During PR performance, task-related cortical activation was induced principally in both right and left sensorimotor cortices. The magnitude of oxy-Hb signals was larger in the left sensorimotor area than in the right hemisphere. This activation pattern was essentially the same as during right hand movements in healthy subjects in accordance with previous fNIRS studies [22,23,25]. This is consistent with primary motor cortex activity, reflecting the use of the contralateral hand [7]. Therefore, we suggest that the involvement of the primary motor cortex in motor skill learning occurs predominantly at the movement execution level of the contralateral hand.

The magnitude of the oxy-Hb responses was significantly decreased around the left sensorimotor cortex as learning progressed, irrespective of the outcome. This pattern of change was the same as observed in the Kendama task with the right hand in accordance with a previous fNIRS study [14]. This previous study suggested that the reduction in cortical activation of the sensorimotor cortex reflects changes in motor commands for a multi-joint discrete motor task during the course of learning. Likewise, the subjects in the present study used multiple joints on the right side to keep a stylus on a round target.

In this study, the magnitudes of oxy-Hb responses were significantly decreased as learning progressed around the left sensorimotor cortex, irrespective of the outcome of the cycles. In previous studies using PR tasks, activation of the sensorimotor cortex showed no learning-related change during the PR task [12,13]. The difference between our results and the previous studies might be attributable to different subjects age (average age = 24 in this study, 39 [12], and 53 [13]) and different cycle repetitions (number of repetition = 18 in our study, 8 [12], and 8 [13]). We guessed that the reduction in brain activation during motor skill learning in the younger subjects was occurred in early stage compared to the older subjects.

Across such studies, practice may result in an increase or decrease in activation of the brain areas involved in task performance, or it may induce functional reorganization of brain activity, which is a combined pattern of increases and decreases of activation across a number of brain areas [9,39]. For example, learning-related increases of cortical activation during velocity-dependent motor skill learning were shown in the contralateral primary motor area [40,41]. When speed of movement was held constant, cortical activity did not change [42] or show a reduction [43] in the primary motor cortex. Changes in neurological and psychological processes, which involved factors such as variation of the investigated tasks, methodological differences, or motor learning stages, were reflected in practice-related changes of cortical activation [5-9].

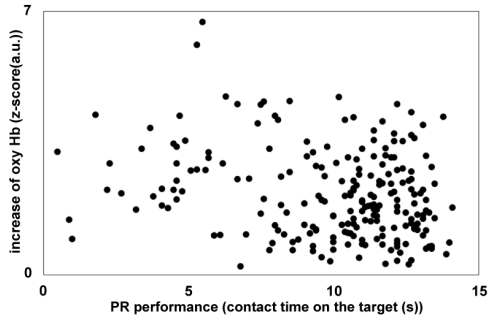

Figure 5: Correlation between PR task performance and oxy-Hb signals (z-score of the oxy-Hb peak among the 12 subjects) in the left sensorimotor area.

When learning a new motor sequence, we must execute the correct order of movements while simultaneously optimizing sensorimotor parameters such as trajectory, timing, velocity, and force [44]. Neuroimaging studies have reported that changes in cortical activation in the sensorimotor cortex are associated with performance changes in relation to the rate of movement [40], force production [45], movement distance [46], motor velocity [47], and integrated muscle torque [14]. The establishment of a novel arbitrary sensorimotor association is closely related to attention, decision and selection of movements, sensory feedback processing, and working memory [6,47]. We suggest that the reduction in cortical activation of the contralateral sensorimotor cortex would be primarily attributed to changes in a number of factors including sensory feedback processing, correct motor commands, and perceptual or cognitive functions, in order to practice the task efficiently.

There is now sufficient evidence to suggest that the changes in cortical response monitored longitudinally by fNIRS evolve as a function of motor skill learning such as during the PR task [12,13], Kendama task [14], and knot-tying task [15,16]. In these studies, the magnitude of the change in cortical oxygenation attenuates in line with behavioral improvements in the task (e.g., time taken, number of movements, trajectory pattern, and muscle kinematics) [39]. Learning-related attenuation of cortical hemodynamic responses have now been observed with fNIRS in the prefrontal cortex [16], presupplementary motor cortex [12,13], and sensorimotor cortex [14]. These fNIRS studies may be considered a result of practice-related "pruning" of functional activation [9], which refers to the pattern of activation change observed when practice is associated with the attainment of automatic or asymptotic performance, and therefore a reduced demand on control or attentional processes and an increased demand upon storage and processing in task-specific areas [9].

Previous studies have proposed that more efficient use of specific neural circuits for an identical task over a number of cycles is accompanied by a reduction in learning-related activation [9]. The efficient use of specific neural circuits has a close relationship with neural models of repetitive suppression [15]. As the present task required the simple repetition of identical shoulder or elbow joint movements, the reduction of activation in the sensorimotor cortex might be partially accounted for by mechanisms related to repetitive suppression [14].

Furthermore, it appeared that both PR task performance and the magnitude of oxy-Hb around the left sensorimotor cortex reached a plateau level during the late cycles. We found significant correlations between PR task performance and the magnitude of oxy-Hb responses in the left and right sensorimotor areas to each cycle. There is evidence to suggest that hemodynamic response can be modulated by the frequency [48], intensity [49], or complexity [50] of a motor task. Stronger sensorimotor activation is reflective of task complexity and does not necessarily depend upon the number of muscles required [51]. Task complexity-related modulation is further indexed by the attenuated sensorimotor cortex response that accompanies motor imagery compared to that accompanying motor execution [52].

There was a reduction in the oxy-Hb signal only in the left sensorimotor area with repetition of the PR task. However, a correlation between performance gain and oxy-Hb signals was found in both hemispheres. During PR task performance, task-related cortical activation was induced principally in both the right and left sensorimotor cortices. Therefore, we hypothesized that PR task performance with the right hand would correlate with sensorimotor cortical activation in both hemispheres. Specially, because primary motor cortex activity reflects the use of the contralateral hand [7,22,23,25], a reduction in the oxy-Hb signal was found only in the left sensorimotor area with repetition of the PR task.

ADLs, plays, or works require motor sequence learning [13], which requires postural control, even during motor performance using the upper extremity. During rehabilitation, patients relearn motor skills for the ADLs, plays, or works by repeating sequential movements. The PR task requires motor control of the proximal parts of the upper extremity including the shoulder and elbow, as well as postural control for sitting or hand-eye coordination [12,13]. Because the PR task is a robust and compact tool with which to evaluate motor skills in a specific patient, medical doctors, occupational therapists, or physical therapists can use the PR task easily in the hospitals or institutions. Assessing the performance in the PR task can be used useful in screening for the levels of disabilities in the ADLs, plays, or works. In our study, each 15-s task period was alternated with a 30-s rest period for a total of 18 repetitions to measure cortical activation during the early phase of PR task learning and after PR task performance reached a plateau level. This protocol enables us to record the behavioral and brain activation changes from starting point of motor sequence learning to acquisition of motor sequence skill. Therefore, changes in sensorimotor activation during a PR task may serve as a motor sequence learning biomarker for the evaluation or development of motor coordination, the judging rehabilitation outcomes, or the prediction of recovery.

In motor sequence learning, the early phase of learning depends on both the cortico-striatal and cortico-cerebellar networks, whereas late motor learning is attributed to the cortico-striatal system [2]. We recorded cortical activation during the early phase of learning; therefore, we needed to examine both the cortico-striatal and cortico-cerebellar networks. By using fNIRS, we could only measure cortical activity in a limited area associated with motor learning. Future neuroimaging studies are required to investigate activation changes over a variety of wider brain regions.

Conclusions

Here, we recorded cortical activation by fNIRS during learning of a PR task. We characterized the learning process as a reduction in cortical activation in the sensorimotor cortex, which was contralateral to the upper extremity used in the task. We also demonstrated a significant correlation between PR task performance and contralateral sensorimotor activation. Our results suggest that the reduction in cortical activation in the sensorimotor cortex reflects changes in a number of factors including sensory feedback processing, correct motor commands, and perceptual or cognitive functions in order for a PR task to be executed efficiently. Therefore, the changes in sensorimotor activation during a PR task may serve as a motor sequence learning biomarker for rehabilitation purposes or the prediction of recovery.

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