J. Phys. Ther. Sci.
24: 711–713, 2012

Influence of a Plantar Perceptual Learning Task on Brain Activity: a fNIRS Study

Hideki Nakano, RPT, MS[1,2], Kenta Miki, RPT[3], Michihiro Osumi, RPT, MS[1], Kozo Ueta, RPT, MS[1], Seigo Kawami, RPT[3], Shu Morioka, RPT, PhD[1]

[1] *Department of Neurorehabilitation, Graduate School of Health Science, Kio University: 4-2-2 Umami-naka, Koryo-cho, Kitakatsuragi-gun, Nara, 635-0832, Japan. TEL:+81 745-54-1601, Fax:+81 745-54-1600, E-mail: h1081007@kio.ac.jp*
[2] *Research Fellow of the Japan Society for the Promotion of Science*
[3] *Department of Rehabilitation, Higashi Osaka Yamaji Hospital*

Abstract. [Purpose] The present study investigated the influence of a plantar perceptual learning task on brain activity using functional near-infrared spectroscopy. [Subjects] Ten healthy volunteers participated in this study. [Methods] Seated subjects performed a hardness discrimination task using the soles of their feet to discriminate between sponges with 5 different levels of hardness over a period of 10 days. Brain activity was measured using fNIRS during the discrimination task on the first and final days. A cap with optical fibers covered to cover the frontal and parietal lobes, as well as the temporal and occipital lobes. [Results] On Day 1 of the task, oxyhemoglobin (oxyHb) increased significantly in the prefrontal and premotor areas, and the parietal association and motor-speech areas. On Day 10 of the task, oxyHb levels increased significantly in the supplemental motor area, and the parietal association and motor-speech areas. [Conclusion] Activation of the brain was noted in the prefrontal, premotor, and supplemental motor areas as well as the parietal association and motor-speech areas during the plantar perceptual learning task.

Key words: Perceptual learning, Error learning, fNIRS

(This article was submitted Feb. 15, 2012, and was accepted Mar. 13, 2012)

INTRODUCTION

In recent years, perceptual learning tasks with discrimination have been utilized in rehabilitation. Morioka et al. reported that the center-of-gravity sway and functional reach test (FRT) of healthy adults improved significantly after a plantar perceptual learning task with discrimination[1]. In addition, Morioka et al. reported that the center-of-gravity sway and FRT of hemiplegic stroke patients, as well as elderly and very old individuals, were improved significantly by the task[2–4]. Moreover, we reported that the center-of-gravity sway of healthy adults, while standing on one leg, was improved significantly by the task[5]. These reports demonstrate that postural control improves through plantar perceptual learning. However the neuroscientific basis of this phenomenon is unclear. Clarification of the neuroscientific basis of the plantar perceptual learning task, and the difficulty, term, and frequency of training in relation to subjects' abilities, is required for clinical rehabilitation.

Motor learning occurs through the activation of areas such as the dorsal prefrontal cortex, premotor cortex, supplementary motor cortex, parietal association cortex, and cerebellum, and these regions are involved in the cognitive control of movement and the construction of neural networks[6]. It was reported that blood flow in the dorsolateral prefrontal cortex and the premotor area increased significantly during a shape discrimination task with shoulder joint movement and finger movement[7, 8]. Thus a plantar perceptual learning task would be expected to increase blood flow in those regions.

This study investigated the influence of a plantar perceptual learning task on brain activity using functional near-infrared spectroscopy (fNIRS).

SUBJECTS AND METHODS

Ten healthy adult volunteers participated in this study (5 men and 5 women; mean age, 25.4 ± 2.7 years). Subjects were excluded if they had a chronic (orthopedic, neurological, or psychiatric) disease that might have influenced the results. The study protocol was explained to each subject and they subsequently provided their informed consent. The research ethics committee of Kio University approved this study.

The subjects performed a plantar perceptual learning task with sponges of different hardness that were arranged on the floor[1–5]. We used squares of sponge mat with the five different levels of hardness (INOAC Co., Aichi, Japan). The hardness levels of these sponge mat squares were 58.8, 78.5, 107.9, 200, 308 N, respectively, as measured by Asker JA type JIS K6400. All were made of the same material and were of the same size (30-cm length, 30-cm width, 40-mm

Table 1. Changes in the number of correct answers given in the plantar perceptual learning task over 10 days

	Day									
	1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th
Mean	5.20	5.30	5.80	6.30	6.80	7.20	7.70	8.10	8.40	8.60**
SD	1.48	1.34	1.23	1.16	1.14	1.03	1.06	0.99	0.97	0.84

Max: 10, Min: 0, **: $p<0.01$

thickness) and shape. During the perceptual learning task, subjects were seated with their eyes closed. The task was performed in pairs comprising an assistant and a subject. The assistant set the sponge on the floor, and the subject's foot was placed on it. The subject then moved their ankle joint in plantarflexion and dorsiflexion, with the plantar surface remaining on the sponge, and was attempted to discriminate the sponge's hardness. Initially, the subjects were asked to memorize hardness in sets of 5 by discriminating the hardness in ascending (from sponge 1 to 5) and descending (from sponge 5 to 1) orders. Verbal feedback was provided by the assistant to enable memorization of sponge hardness. After memorization, the subject performed 10 repetitions of hardness discrimination based on a table created by a random number generation program (RAND function; Microsoft Excel 2007), and was thereafter instructed to determine the levels of hardness (without verbal feedback). The number of correct answers in the random table was used as the assessment of perceptual ability. The table was formulated such that each of the 5 hardness-graded sponges was included twice in the 10 repetitions that comprised the perceptual learning task. This task was performed on 10 days over a 2-week period. The control condition was the moment at which the subject's foot was placed on the sponge.

Brain activity was measured on the first and tenth days of the task, during the 10 repetitions of hardness discrimination based on the random table. Two fNIRS apparatuses (FOIRE-3000; Shimadzu Co. Ltd., Tokyo, Japan) were used to measure brain activity. A cap with optical fibers was positioned over the frontal, parietal, temporal and occipital lobes. Changes in blood flow were measured through a total of 100 channels. To keep light traveling along the fibers, room lighting was adjusted to minimize the level of external light interference. Prior to the start of measurement, the subject was in a seated position and resting. Measurement began when blood flow at all of the channels had stabilized. The timing protocol for the measurement was (5.0, 10.0, 5.0 s [rest, task, rest]), which was repeated in each of the 10 trials. Signal averaging of the 10 trials was performed. During rest times, the subject sat in the starting position, and at the start of each task, the subjects moved their right ankles.

For data analysis, the blood flow at the start of the measurement was set to 0 by a custom correction, and the relative change in blood flow (mM/mm) was subsequently determined. Mean relative change in blood flow during each task was determined in Channel 1 (ch-1) through ch-100. The first and tenth repetition of the task were compared in each channel. Oxyhemoglobin (oxyHb) served as the parameter. To test the number of correct answers, the one-way repeated measure ANOVA (Sheffe post hoc test) was used for statistical analysis. To evaluate the oxyHb, the Wilcoxon test was used for statistical analysis with a 5% significance level. Following measurement, brain mapping was performed, and the result was superimposed on standard MRI images of the brain. Fusion Imaging (Shimadzu Co. Ltd.) was used for this superimposition.

RESULTS

Table 1 shows the changes in the number of correct answers for the plantar perceptual learning task over the 10-day period. The number of correct answers increased significantly with the number of days ($F = 12.3$, $p < 0.01$). Sheffe post hoc comparisons revealed a statistically significant difference between Day 1 and Days 7–10 ($p < 0.01$), Day 2 and Days 7–10 ($p < 0.01$, $p < 0.05$), Day 3 and Days 8–10 ($p < 0.01$, $p < 0.05$), and Day 4 and Day 10 ($p < 0.05$).

Tables 2 and 3 display the OxyHb values of each channel on Day 1 and Day 10 of the plantar perceptual learning task. On Day 1 of the task, the OxyHb levels in ch-1, ch-3, ch-7, ch-11, ch-15, ch-18, ch-27, ch-32, ch-42, and ch-47 increased significantly. On Day 10 of the task, the OxyHb levels of ch-7, ch-18, ch-43, and ch-45 increased significantly. As a result of superimposing this data on MRI images, ch-27 and ch-32 were mapped to the left dorsolateral prefrontal cortex; ch-1, ch-42, and ch-47 to the left premotor cortex; ch-43 and ch-45 to the supplementary motor cortex; ch-11, ch-15, and ch-18 to the left motor-speech area; and ch-3 and ch-7 to the left parietal association cortex.

DISCUSSION

The number of correct answers in the plantar perceptual learning task increased significantly with the number of days. This result shows that plantar perceptual ability improved through repetition of the perceptual learning task.

The oxyHb levels of the regions in the left dorsolateral prefrontal cortex, the left premotor cortex, the left parietal association cortex, and the left motor-speech area increased significantly only on Day 1 of the task. The left dorsolateral prefrontal cortex functions in working memory. Working memory retains meaningful information by situation and leads to answers (the decision and the action)[9]. It is reported that the dorsolateral prefrontal cortex functions in the early learning process[10]. The premotor cortex receives sensory information from somatesthesia and vision, and plays a central role in motor learning based on sensory information. It is reported that the premotor cortex also functions in

Table 2. OxyHb values of each channel in day 1

	Control	Task	
ch-1	0.0008 ± 0.0082	0.0140 ± 0.0103	*
ch-3	−0.0004 ± 0.0034	0.0103 ± 0.0074	*
ch-7	−0.0025 ± 0.0054	0.0107 ± 0.0084	*
ch-11	−0.0011 ± 0.0047	0.0135 ± 0.0103	*
ch-15	0.0004 ± 0.0050	0.0197 ± 0.0112	*
ch-18	0.0012 ± 0.0031	0.0186 ± 0.0111	*
ch-27	−0.0010 ± 0.0059	0.0212 ± 0.0110	*
ch-32	0.0015 ± 0.0061	0.0197 ± 0.0133	*
ch-47	0.0012 ± 0.0054	0.0178 ± 0.0154	*

(Unit; mM/mm) Mean ± SD, *: $p<0.05$

Table 3. OxyHb values of each channel in day 10

	Control	Task	
ch-7	−0.0025 ± 0.0054	0.0170 ± 0.0096	*
ch-18	0.0012 ± 0.0031	0.0124 ± 0.0234	*
ch-43	0.0099 ± 0.0358	0.0126 ± 0.0374	*
ch-45	0.0124 ± 0.0161	0.0164 ± 0.0215	*

(Unit; mM/mm) Mean ± SD, *: $p<0.05$

the early learning process[11]. In the early phase of the plantar perceptual learning task, the subjects were asked to memorize somatosensory information. This may explain the significant increase in the oxyHb levels in the regions of the left dorsolateral prefrontal cortex and the left premotor cortex on Day 1 of the task.

The oxyHb levels in the supplementary motor cortex increased significantly only on Day 10 of the task. The supplementary motor cortex functions in action execution based on memory information, and operates in the late stages of the learning process[12]. The number of correct answers in the plantar perceptual learning task increased significantly on Day 10 of the task, which may have not only required sensory information but also information from memory. This may explain the significant increase in the oxyHb levels in the supplementary motor cortex region on Day 10 of the task.

The oxyHb levels of the left parietal association cortex and the left motor-speech area increased significantly on both Days 1 and 10 of the task. The parietal association cortex is tightly connected to the prefrontal cortex, which functions in the early stages of the learning process[13]. The parietal association cortex is involved in memory and the recollection of acquired skills and is used in the late stages of the learning process[14]. The motor-speech region works to verbalize internally[15]. The subjects were asked to verbalize internally what they had memorized and had discriminated as sponge hardness in the plantar perceptual learning task. This would explain the oxyHb increase in the left parietal association cortex and the significant increases in the left motor-speech area on both Day 1 and Day 10 of the task.

The results of this study indicate that the brain areas activated during the plantar perceptual learning task are similar to the areas that are activated during motor learning[6]. This study clarified the neuroscientific basis of the plantar perceptual learning task with discrimination.

A limitation of the present study was that we were unable to examine whether the brain activity reflected the correct or incorrect answers given by the subjects. In addition, we could not examine the brain activity changes relative to the subjects' changes in ability. In the future, we would like to demonstrate these aspects and develop an understanding of the perceptual learning task in relation to subjects' abilities.

REFERENCES

1) Morioka S, Yagi F: Influence of perceptual learning on standing posture balance: repeated training for hardness discrimination of foot sole. Gait Posture, 2004, 20: 36–40. [Medline] [CrossRef]
2) Morioka S, Yagi F: Effects of perceptual learning exercises on standing balance using a hardness discrimination task in hemiplegic patients following stroke: a randomized controlled pilot trial. Clin Rehabil, 2003, 17: 600–607. [Medline] [CrossRef]
3) Morioka S, Hiyamizu M, Fukumoto T, et al.: Effects of plantar hardness discrimination training on standing postural balance in the elderly: a randomized controlled trial. Clin Rehabil, 2009, 23: 483–491. [Medline] [CrossRef]
4) Morioka S, Fujita H, Hiyamizu M, et al.: Effects of plantar perception training on standing posture balance in the old old and the very old living in nursing facilities: a randomized controlled trial. Clin Rehabil, 2011, 25: 1011–1020. [Medline] [CrossRef]
5) Nakano H, Miki K, Fujita H, et al.: Influence of plantar hardness discrimination training on center-of-gravity sway while standing on one leg: a randomized controlled trial. J Phys Ther Sci, 2011, 23: 741–744. [CrossRef]
6) Jenkins IH, Brooks DJ, Nixon PD, et al.: Motor sequence learning: a study with positron emission tomography. J Neurosci, 1994, 14: 3775–3790. [Medline]
7) Morioka S, Yamada M, Komori T: Frontal lobe activity during the performance of spatial tasks: fNIRS study. J Phys Ther Sci, 2008, 20: 135–139. [CrossRef]
8) Yamada M, Morioka S, Sugimura S: Influence of a discrimination task during movement on cerebral blood flow measured by fNIRS. Rigakuryoho Kagaku, 2008, 23: 261–265. [CrossRef]
9) Baddeley A: Working memory. Science, 1992, 255: 556–559. [Medline] [CrossRef]
10) Sakai K, Hikosaka O, Miyauchi S, et al.: Transition of brain activation from frontal to parietal areas in visuomotor sequence learning. J Neurosci, 1998, 18: 1827–1840. [Medline]
11) Hikosaka O, Miyashita K, Miyachi S, et al.: Differential roles of the frontal cortex, basal ganglia, and cerebellum in visuomotor sequence learning. Neurobiol Learn Mem, 1998, 70: 137–149. [Medline] [CrossRef]
12) Hikosaka O, Sakai K, Miyauchi S, et al.: Activation of human presupplementary motor area in learning of sequential procedures: a functional MRI study. J Neurophysiol, 1996, 76: 617–621. [Medline]
13) Deiber MP, Wise SP, Honda M, et al.: Frontal and parietal networks for conditional motor learning: a positron emission tomography study. J Neurophysiol, 1997, 78: 977–991. [Medline]
14) Shadmehr R, Holcomb HH: Neural correlates of motor memory consolidation. Science, 1997, 277: 821–825. [Medline] [CrossRef]
15) Binkofski F, Buccino G, Posse S, et al.: A fronto-parietal circuit for object manipulation in man: evidence from an fMRI-study. Eur J Neurosci, 1999, 11: 3276–3286. [Medline] [CrossRef]