Prefrontal Cortex Activation during Writing and Hand-Shape Changing Dual-Task Performance: A Near-Infrared Spectroscopy Study

Noriko Yamaguchi¹, Sayaka Okahashi², Priscila Yukari Sewo Sampaio³, Toshiko Futaki²

¹ Division of Occupational Therapy, Department of Rehabilitation Medicine, Kobe Rehabilitation Hospital, Kobe, Japan
² Division of Occupational Therapy, Department of Human Health Sciences, Graduate School of Medicine, Kyoto University, Kyoto, Japan
³ School of Physical Education, University of Campinas, Campinas, Brazil

Abstract: Aim: To clarify the characteristics of desktop dual tasks that cause dorsolateral prefrontal cortex (DLPFC) activation. Methods: Subjects (29 young adults and 22 middle-aged adults) performed three different combinations of dual tasks composed of a pencil and paper task (copying numbers or calculation) and a hand-shape changing task (in response to visual hints or self judgment). We measured brain activation using near-infrared spectroscopy. Results: Right DLPFC activation was significantly higher for the simplest dual task than the complex dual task with the younger group, whereas there was no significant difference between tasks with the middle-aged group. Task performance was higher in the younger group than the middle-aged group, whereas there was no difference in brain activation between the two age groups. Conclusion: A dual task including two of each task performed automatically could be used for training frontal lobe functions, and the difficulty level should be adjusted depending on age.

Keywords: dual task, near-infrared spectroscopy, prefrontal cortex

Introduction

In Japan, which is becoming a super-aged society, care for patients with dementia is one of the main issues for mental health and rehabilitation services. A significant symptom of dementia, the behavioral and psychological symptoms associated with dementia (BPSD), prevents patients from doing many activities of daily living (ADL) by themselves in their home and community life. Therefore, it is important not only to inhibit the disease progression but also to prevent and care for BPSD. One of the countermeasures for these illnesses is cognitive rehabilitation, which is a non-pharmacotherapy approach and is well-recognized to prevent or delay dementia.

So far, several studies have reported the effectiveness of cognitive training in improving patients’ quality of life [1–5]. Cognitive rehabilitation programs for activating the prefrontal cortex (PFC) help to prevent dementia and mild cognitive impairment (MCI) [3]. However, there is not enough evidence for clinical applications.

Nowadays, there are various functional neuroimaging methods to measure human brain activation, for example magnetic resonance imaging, single photon emission computed tomography, positron emission tomography, and so on. Near-infrared spectroscopy (NIRS) has benefits for subjects because it is not invasive or restrictive of body movement, so that the flexibility of the method is high [6], and we have used this technique to investigate the difference on task performance, brain activation and subjective assessment in relation to the difficulty levels of a virtual shopping test [7]. In the present study, we tried to clarify what kind of task activates the PFC highly by comparing hemodynamic data during different types of dual-task performance using NIRS.
It was reported that elderly people maintain the ability to perform ADLs such as eating and getting dressed for a long time by increasing their neural network, regardless of neurodegeneration caused by aging or disease [8]. There are many possibilities that cognitive training using a dual task that needs working memory and alternating attention in relation to PFC activation could lead to an increase in neural networks and help to maintain independent personal/social life. Working memory plays an important part in the functioning of alternating attention [9]. A neuropsychological model of attention: the supervisory attention system (SAS) was proposed as a central executive of working memory in PFC [10, 11]. The dorsolateral prefrontal cortex (DLPFC) plays a major role in modulating working memory [12].

Additionally, it was reported that dual-task performance required working memory in relation to the DLPFC, in particular, the left DLPFC was activated during mental calculation performance [13]. It has also been reported that performing a dual task (e.g. doing arithmetic and a physical activity task at the same time) was effective for maintaining cognitive functions in elderly people [14]. Therefore, we adopted a type of asthmatic task as part of our dual tasks to investigate DLPFC activation.

We designed dual tasks that could be used conveniently at home or in occupational therapy sessions in various facilities. We combined two simple and familiar desktop tasks together as a dual task: a writing task based on the hundred square calculation task, and a hand-shape changing task based on the “rock-paper-scissors” game [15]. The hundred square calculation involves simple addition, and is widely used with elementary school students to improve their basic learning skills including attention and memory. “Rock-paper-scissors” is a popular children’s game using the hand in Japan. We considered that Japanese people could perform the hand gestures in this game automatically regardless of their age, using both procedural memory and declarative memory.

This study aimed to clarify the characteristics of the desktop dual task in relation to working memory and alternating attention, which causes DLPFC activation, and to verify the difference between healthy younger adult subjects and middle-aged adult subjects in dual-task performance and DLPFC activation.

Methods  
1. Subjects

Subjects’ characteristics are described in Table 1. A total of 51 subjects participated in this study. They were divided into two groups: a younger adult group (n = 29, age range: 20–35) and a middle-aged adult group (n = 22, age range: 48–60). Frontal assessment battery (FAB) and trail making test (TMT) were conducted as neuropsychological assessments. There were significant differences in age, years of education, MMSE, FAB, and TMT between the two groups.

The selection criteria were persons who lived independently in the community without mental and/or neuropsychological diseases such as cerebrovascular disease; and those who were right hand dominant as evaluated using the Edinburgh inventory (laterality quotient > 0) [16]. The exclusion criteria were 1) individuals who had visual impairment; 2) individuals with motor deficits that affected dual-task performance; 3) Mini-Mental State Examination (MMSE) score of ≤ 26 points.

All cognitive functions decrease consistently with aging. In particular, processing speed starts decreasing rapidly around the age of 50 years [17]. For this reason, we set subjects in the middle-aged group as people aged over 45 years old. The study protocol was approved by the Kyoto University Graduate School of Medicine Ethics Committee (E-1114, 2011).

2. Three dual tasks using both hands

We utilized three original dual tasks (e.g. Tasks A, B, and C) consisting of a “hundred square calculation task” performed with the right hand and a “hand-shape changing task” with the left hand placed on a table.

Fig. 1 shows the task sheets used in Tasks A, B, and C (in Fig. 1a, 1b, and 1c, respectively). Subjects were asked to fill in the blank squares with numbers by referring to the top and left edges of the table while using their right hand. They completed each row of the table...
starting from left to right and then working from top to bottom. Subjects were asked to add the two numbers shown at the top and the left side of the table, then write the answer in the intersection square between them.

In addition, subjects were also asked to switch the shape of their left hand whenever they filled in a square with a thick border in Tasks A and B. Conversely, in Task C they were asked to switch the shape of their hand whenever they wrote an odd number after writing an even number (or an even number after writing an odd number) in the previous square. Subjects started with a “rock” pattern, in which the fist was clenched, then change to the “scissors” shape by extending only two fingers (index and middle fingers like scissor blades) and finally “paper” by extending all five fingers out flat.

Subjects were instructed to perform the dual tasks as accurately and quickly as possible. The evaluation items were the number of answers written in 60 seconds, and the number of completed switches of the left hand shape.

3. Procedure
The experimental protocol is shown in Fig. 2. In advance, we provided the instructions and a small practice task for subjects to understand how to execute the dual tasks, then NIRS data during the tasks were measured for a total of six 60-second sessions (3 tasks × 2 trials) continuously. We set a rest period between sessions to allow brain activation level to subside after the previous task. Subjects were instructed to sit in a comfortable and relaxed position, placing both hands on the armrests for the rest periods while looking at the white paper in front of them.

4. NIRS data collection
As shown in Fig. 3, subjects sat in a chair with their feet on the ground during task performance, and they were asked not to talk or move their body or head except for the hand movements required in task execution. Subjects filled in a sheet for the hundred square calculation on a document stand by using their right hand, and they kept their left hand placed on the left side of the document stand on the desk.

We used a multichannel NIRS instrument, FOIRE-3000 (SHIMADZU Co. LTD, Kyoto, Japan) to measure brain activation status from the point of view of hemodynamic changes during dual-task performance. As shown in Fig. 4, we set 27-channel NIRS probes on
Prefrontal Cortex Activation during Dual-Task Performance

The forehead of the subject corresponding to the international 10–20 system, and the lowest probes were placed along Fp1-Fp2. We set a total of 18 probes including emitters and detectors, in which the distance between each probe was 3 cm.

The NIRS system calculated relative changes in the concentrations of oxygenated hemoglobin ([OxyHb]), deoxygenated hemoglobin ([DeoxyHb]), and total hemoglobin. We used the changes in [OxyHb] values to investigate changes in regional cerebral blood volume in this study, based on the report that [OxyHb] is more sensitive than [DeoxyHb] as a parameter to measure blood flow changes associated with brain activation [18]. We reset hemodynamic data at the start of each task and recorded the change in [OxyHb] for 60 seconds during the performance of each task.

The system used a sampling time of 260 milliseconds. The intensity of the light detected at three wavelengths (780, 805, and 830 nm) was measured, and changes in the optical density were calculated.

5. Data analysis

We selected one of five specified channels in each DLPFC area (e.g. channels 6/12/17/18/23 for right DLPFC, channels 11/16/21/22/27 for left DLPFC) on the basis of the waveforms. We determined these channels as the DLPFC region, which was nearly the same as the Brodmann area 46 involving executive functions, by referring to a previous study [19]. The positions of two channels adopted were symmetrical and fixed on all tasks individually. A dual-task type (Task A, B, or C) × Group (younger, middle aged) analysis of variance (ANOVA) was conducted to evaluate behavioral data and changes in [OxyHb] in DLPFC using SPSS Version 19. Differences were reported as significant when p < 0.05.

Results

1. Comparison of task performance between younger and middle-aged adult groups

Regarding the hundred square calculation task, the mean (SD) accuracy scores were 100% (0) in Task A, 99.02% (1.31) in Task B, and 99.41% (0.93) in Task C in the younger group, while they were 99.97% (0.12) in Task A, 97.25% (3.54) in Task B, and 99.00% (1.57) in Task C in the middle-aged group.

Fig. 5a shows the comparison of writing task performance between the two age groups. The task performance score indicated the total number of written answers, including correct and incorrect ones. The result of ANOVA (3 tasks × 2 age groups) showed a significant main effect of the task (p < 0.0001) with no interaction. There was also a significant main effect of age group (p < 0.0001). The scores were higher in Task A than in Tasks B and C (p < 0.001); scores were also higher in
Task B than in Task C \((p < 0.001)\) in both groups.

Fig. 5b shows a comparison of hand-shape changing performance between the two age groups. The task performance score indicated the total number of left hand movements including correct and incorrect ones. The result of ANOVA \((3 \text{ tasks} \times 2 \text{ age groups})\) showed a significant main effect of the task \((p = 0.005)\) with no interaction.

There was also a significant main effect of the age group \((p < 0.0001)\). The score was higher in Task B than in Task A \((p = 0.007)\) and Task C \((p < 0.001)\) in the younger adult group, whereas it was higher in Task B than in Task C \((p = 0.016)\) in the middle-aged adult group.

2. Comparison of DLPFC activation between younger and middle-aged adult subjects

Fig. 6 shows sample NIRS data on changes in [OxyHb] during Task A. Right DLPFC (e.g. channel 17) and left DLPFC (e.g. channel 22) activation was observed during task performance.

Fig. 7 shows a comparison of DLPFC activation between tasks in the two age groups. Fig. 7a shows the right DLPFC, and Fig. 7b shows the left DLPFC. The result of ANOVA \((3 \text{ tasks} \times 2 \text{ age groups})\) on [OxyHb] change showed a significant main effect of the task in the right and left DLPFC \((p = 0.003 \text{ and } p = 0.019, \text{ respectively})\) with no interaction. There was no significant main effect of age group in any area of DLPFC. The right and left DLPFC were activated more highly during the performance of Task A than during Task C \((p = 0.002 \text{ and } p = 0.007, \text{ respectively, after Bonferroni correction})\).

Analysis using the Holm method showed the following. The right DLPFC was activated more highly during the performance of Task A than during Task C \((p = 0.007)\). There was no significant difference between Task A and Task C in the middle-aged adult group \((p = 0.030)\) in the right DLPFC. On the other hand, there were no significant differences...
Prefrontal Cortex Activation during dual-task Performance

Differences between Task A and Task C in either group \( (p = 0.037 \text{ and } p = 0.034, \text{ respectively}) \) in the left DLPFC.

Discussion

This study aimed to clarify the characteristics of a desktop dual task to determine which caused DLPFC activation more easily, and to verify the difference between younger and middle-aged adults during dual-task performance and with regard to DLPFC activation. Participants performed three dual tasks composed of a pencil and paper task using their right hand (copying numbers in Task A; calculation in Tasks B and C) and a hand-shape changing task using their left hand (on cue from visual hints in Tasks A and B, and by self-judgment in Task C).

Regarding the characteristics of DLPFC activation, it found that the right DLPFC activation was significantly higher with the simplest task (Task A) compared with the complex task (Task C) in the younger adult group, whereas there was no significant difference between tasks in middle-aged adult group. We considered that Task A was a dual task composed of the easiest tasks of the three, which should not interfere with each other directly, and it was possible for the subjects to perform this task without much difficulty. On the other hand, Task C was a dual task combined of two tasks requiring both calculation and self-judgment, which could interfere with each other. On the basis of data from younger subjects, it was suggested that the simple dual task composed tasks performed using both hands automatically had a tendency to activate the DLPFC highly.

As a reason for the fact that there was no significant difference in DLPFC activation between tasks for the middle-aged group, we considered that all dual tasks used in this study, even Task A, imposed too high a load for middle-aged subjects to activate their brain. So far, it has been reported that the compensation-related utilization of neural circuits hypothesis (CRUNCH) has a relationship with age-related brain activation [20]. According to this hypothesis, more neural resources are engaged by older brains to accomplish computational goals completed with fewer resources by younger brains. Therefore, older adults were more likely than younger adults to show over-activation at low load, and under-activation at high load.

The task performance results varied depending on age: younger adult subjects performed better on each dual task than the middle-aged subjects. In contrast, there was no significant difference in brain activation during each task execution, although the activation patterns in [OxyHb] change were similar between the groups. As shown in Table 1, there were differences in cognitive test scores (e.g. TMT representing attention and FAB representing frontal lobe function) between the two age groups. There is a possibility that the differences in basic cognitive functions were related to the difference in the tendency on task performance between the two groups.

In addition, the characteristics of attention required in the execution of a specific task influenced the task difficulty [21]. We considered that all of the three dual tasks would need attention capacity but have their own characteristics. With respect to the hand-shape changing task performance, subjects could execute the motion switching itself automatically in all dual tasks. However, Tasks A and B required the processing of visual information as a trigger for the hand-shape change by using divided attention and procedural memory mainly. Task C required higher functioning such as SAS [10, 11] involved in working memory, as described in Introduction section, by judging the number in each answer in comparison with the previous one. We considered that these various aspects of cognitive functions required in each dual task could influence task performance and brain activation.

A previous study reported that young and old participants showed significantly greater PFC activation during dual-task performance than single-task performance by using stepping and mental arithmetic called “serial 7”, which are simple tasks using automatic
processing [22]. Although the type of dual task used here was different from the previous study, we found that the dual task using both hands but composed of two tasks that subjects performed automatically activated the DLPFC similarly.

Our study had some limitations. The brain activation data varied even in a single age group owing to individual differences. We plan to collect a larger data set to resolve the relationship between task performance and brain activation as a subsequent study. After revisions to make our dual tasks easier, a further study investigating brain functions according to task characteristics is needed to improve cognitive rehabilitation for elderly people and patients with dementia or MCI.

**Conclusion**

This study examined the impact of the characteristics of dual tasks on prefrontal lobe activation in younger and middle-aged adult subjects. As a result, a simple dual task composed of two tasks each performed automatically caused higher DLPFC activation than a more complex dual task requiring judgment in younger subjects. The task performance was higher in the younger adult group than in the middle-aged adult group. It was suggested that a desktop dual task including the performance of two easy tasks using both hands simultaneously could provide a cognitive training task to promote DLPFC activation, and the task level should be adjusted for each person’s ability considering age.

**Acknowledgments:** We thank the subjects who participated in this experiment. We are grateful to Professor Motomi Toichi of the Graduate School of Medicine, Kyoto University, Associate Professor Hiroshi Sakai of the Graduate School of Medicine, Nagoya University, and Associate Professor Katsumi Inoue of the Graduate School of Medicine, Kanazawa University. This research was supported by KAKENHI; a Grant-in-Aid for Scientific Research (C) (24500643).

**References**


