Chapter 27
PFC Blood Oxygenation Changes in Four Different Cognitive Tasks

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Abstract Aging often results in a decline in cognitive function, related to alterations in the prefrontal cortex (PFC) activation. Maintenance of this function in an aging society is an important issue. Some practices/drills, moderate exercise, mastication, and a cognitive task itself could enhance cognitive function. In this validation study, before evaluating the effects of some drills on the elderly, we examined the neural substrate of blood oxygenation changes by the use of four cognitive tasks and fNIRS. Seven healthy volunteers (mean age 25.3 years) participated in this study. Each task session was designed in a block manner; 4 periods of rests (30 s) and 3 blocks of four tasks (30 s). The tasks used were: a computerized Stroop test, a Wisconsin Card Sorting Test, a Sternberg working memory paradigm, and a semantic verbal fluency task. The findings of the study are that all four tasks activated PFC to some extent, without laterality except for the verbal fluency task. The results confirm that NIRS is suitable for measurement of blood oxygenation changes in frontal brain areas that are associated with all four cognitive tasks.

Keywords Cognitive function • NIRS • PFC • Stroop test • Wisconsin Card Sorting Test

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1 Introduction

Japan is rapidly becoming a super-aging society. As indicated in previous re-search, aging is associated with a decline in cognitive function, related to alterations in prefrontal cortex (PFC) activation [1, 2]. Maintenance of this function in an aging society is an important issue. Many cognitive tasks, such as the Stroop task (ST) [3, 4], the Wisconsin Card Sorting Test (WCST) [5, 6], the Sternberg working memory paradigm (SWMP) [7], and the verbal fluency task (VFT) [8–10], are widely used for evaluating and improving cognitive function using near-infrared spectroscopy (NIRS) [3, 5, 8, 9] or functional MRI [4, 6, 7, 10]. Unique studies concerning the cognitive function and gum chewing have been conducted and suggested the relation in it [11, 12]. Some practices/drills, moderate exercise, mastication, and cognitive tasks themselves could enhance cognitive function in older adults.

PFC plays an important role in the process of the cognitive function. Many functional neuroimaging techniques, including positron emission tomography, functional MRI, magnetoencephalography, and NIRS are thought to objectively evaluate human cranial nerve activity. NIRS measures the concentration changes of oxygenated hemoglobin (oxy-Hb), deoxygenated hemoglobin (deoxy-Hb), and total hemoglobin (total hemoglobin = oxy-Hb + deoxy-Hb) [13, 14]. Signal changes represent changes in local cerebral blood flow and oxygen expenditure, and the oxy-Hb concentration changes represents brain activity [15]. Functional NIRS is a powerful, non-invasive imaging technique that offers many advantages, including compact size, no need for specially equipped facilities, and the potential for real-time measurement [16, 17]. Thus, fNIRS could evaluate the effects of the practices/drills on cognitive tasks [3, 5, 8, 9].

In this validation study, before evaluating the effects of the drills, we examined the neural substrate of blood oxygenation changes due to the cognitive tasks. The study design was approved by the Ethics Committee of Tokyo Dental College, Japan (No.436).

2 Methods

Seven healthy volunteers (mean age 25.3 years) participated in this study after written informed consent was obtained. Participants had no personal or family history of neuropsychiatric illness, were free of medication, and all were right-handed. Activity in the PFC was measured by a multi-channel NIRS (OEG-16, Spectratech, Japan). The set of measurement probes (inter-optode distance 30 mm) were affixed to the participant's forehead. The recording channels resided in the brain between the nearest pairs of emitter and detection probes. A 2 × 6 probe configuration, involving 6 light emitters (wavelength 840 and 770 nm) and 6 detector probes, was used, which resulted in a total of 16 channels. The array of the light emitter and detector probes covered an area of the forehead, with the most inferior channel located at Fp1 and Fp2 according to the International 10–20 system of electrode placement [18]. Each task session was designed in a block manner, i.e. 4 periods of rest (30 s) and 3 blocks of four tasks (30 s). The tasks used were: a computerized ST [3, 4] (including both congruent and incongruent Stroop tasks), the WCST [5, 6], the SWMP [7], and a semantic VFT [8–10].

To obtain the hemodynamic response, concentration changes in oxy-Hb, deoxy-Hb and total hemoglobin (tHb = [oxy-Hb] + [deoxy-Hb]) were calculated. BRain Suite (BRSystems, Japan) software was used for analysis. A bandpass filter (0.02–0.5 Hz) and a moving average (7 samples) with a 1.53 Hz sampling frequency were used. A linear fitting function for baseline correction was employed. The pre-task baseline was determined as the mean across 7 s just before the active task period; the post-task baseline was determined as the mean across the last 8 s of the resting period; then, linear fitting was performed on the task data between these two baselines. Following this correction, the four tasks were performed; data were averaged in each channel for each subject. For subsequent analyses, only oxy-Hb concentration changes registered during each task were considered; this is because this NIRS parameter usually shows the clearest pattern of activation and is proposed to be the most sensitive indicator of changes in regional cerebral blood flow [15]. Since the neural activity did not increase immediately after beginning the tasks, the oxy-Hb values between 10 and 30 s in each task were used for analysis. To investigate the involvement of a laterality of the PFC in each task, we divided the measured points into seven right and seven left channels (two central channels were not involved in laterality comparison). Also, to examine the influence of the task difference on total PFC activity, averaged oxy-Hb concentration changes in each channel were totaled in each task and compared. Statistical evaluations of the laterality in each task were performed using a one-sided paired Student's t-test, and one-way analyses of variance for repeated measurements were calculated for total PFC activity in each task using Excel Statistics (Microsoft Japan). A p-value of <0.05 was considered significant.

3 Results

Figure 27.1 shows a representative subject's curves during the WCST. Figure 27.2 shows the average curves of the changes in oxy-Hb concentration over time in the four tasks. Laterality and total comparison results for each task are summarized with statistical results in Table 27.1.

The findings of the study are that all four tasks activated bilateral PFC to some extent, with no significant differences in task comparison and in laterality except for the verbal fluency task.

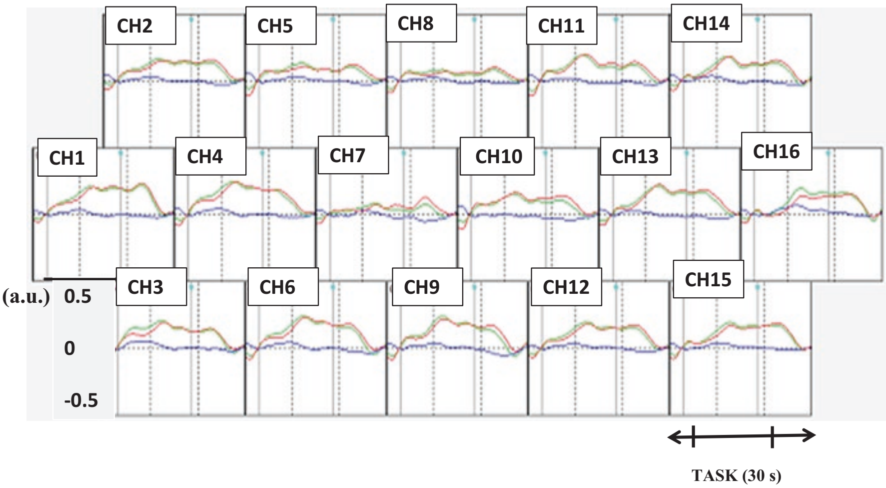

Fig. 27.1 Representative NIRS waves in the WCST

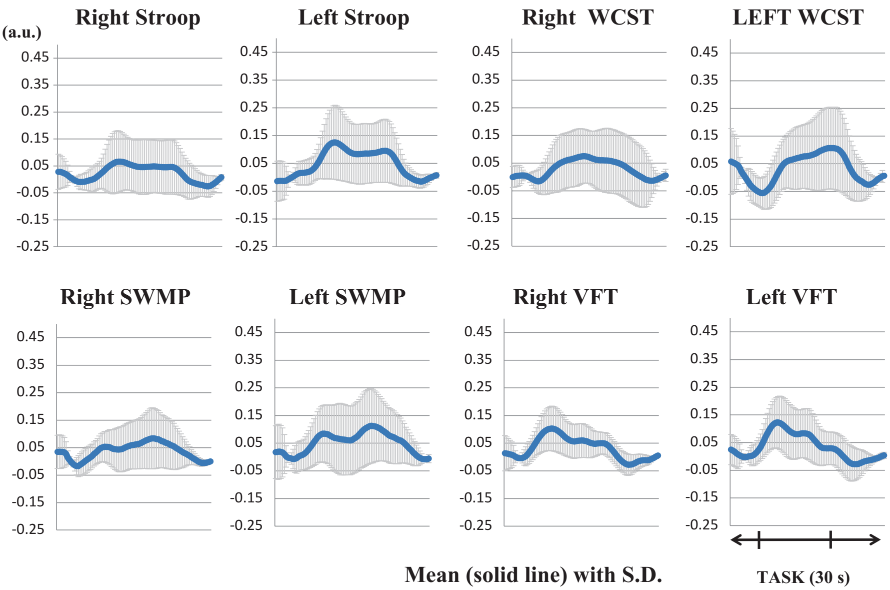

Fig. 27.2 Average curves of changes in oxy-Hb concentration over time

4 Discussion

The findings in this study are in line with previous studies. Activation for the ST was found in the bilateral prefrontal area [4]. A bilateral increase in oxygenated hemoglobin (oxy-Hb) was observed in the PFC in the majority of subjects during the

Table 27.1 Data on the comparison of laterality and the total results for each of the four tasks

	Left (M ± S.D.)	Statistics	Right (M ± S.D.)	Total (M ± S.D.)	ANOVA: P-Value
ST	0.083 ± 0.026	n.s.	0.079 ± 0.030	0.082 ± 0.026	0.41
WCST	0.079 ± 0.026	n.s.	0.098 ± 0.038	0.085 ± 0.033	
SWMP	0.078 ± 0.005	n.s.	0.079 ± 0.060	0.076 ± 0.039	
VFT	0.080 ± 0.016	[a]	0.060 ± 0.023	0.069 ± 0.024	

Unit: (a.u.) *M* mean, *S.D.* standard deviation
[a]$p < 0.05$ *n.s* non-significant

WCST [5, 6]. In an fMRI study, SWMP involved the anterior portions of the lateral PFC, bilaterally [7]. Some studies have mentioned laterality of the left hemisphere is thought to be dominant in VFT [9, 10]. However, a study has mentioned laterality in the ST [3] and a significant increase of oxy-Hb in both hemispheres during a VFT [8]. We plan to examine these issues in future studies on the elderly.

The NIRS method has some shortcomings, e.g. NIRS mainly detect in surface areas of the cerebral cortex; NIRS measurement is associated with possible confounders such as skin blood flow [19], respiration and blood pressure; and NIRS has a relatively low spatial resolution. Despite these shortcomings, NIRS is becoming increasingly useful in neuroscience.

In summary, within the limitations of this study, the findings are that all four tasks activated PFC to some extent, without laterality except for the verbal fluency task. The results confirm that NIRS is suitable for the measurement of blood oxygenation changes in frontal brain areas that are associated with all four cognitive tasks.

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References

1. Jimura K, Braver TS (2010) Age-related shifts in brain activity dynamics during task switching. Cereb Cortex 20:1420–1431
2. Paxton JL, Barch DM, Racine CA et al (2008) Cognitive control, goal maintenance, and prefrontal function in healthy aging. Cereb Cortex 18:1010–1028
3. Ehlis AC, Herrmann MJ, Wagener A et al (2005) Multi-channel near-infrared spectroscopy detects specific inferior-frontal activation during incongruent Stroop trials. Biol Psychol 69:315–331
4. Langenecker SA, Nielson KA, Rao SM (2004) fMRI of healthy older adults during Stroop interference. NeuroImage 21:192–200
5. Sumitani S, Tanaka T, Tayoshi S et al (2006) Activation of the prefrontal cortex during the Wisconsin card sorting test as measured by multichannel near-infrared spectroscopy. Neuropsychobiology 53:70–76

6. Nyhus E, Barcelo F (2009) The Wisconsin card sorting test and the cognitive assessment of prefrontal executive functions: a critical update. Brain Cogn 71:437–451
7. Heinzel S, Lorenz RC, Pelz P et al (2016) Neural correlates of training and transfer effects in working memory in older adults. NeuroImage 134:236–249
8. Herrmann MJ, Ehlis AC, Fallgatter AJ (2003) Frontal activation during a verbal-fluency task as measured by near-infrared spectroscopy. Brain Res Bull 61:51–56
9. Yeung MK, Sze SL, Woo J et al (2016) Altered frontal lateralization underlies the category fluency deficits in older adults with mild cognitive impairment: a near-infrared spectroscopy study. Front Aging Neurosci 8:59
10. Schlosser R, Hutchinson M, Joseffer S et al (1998) Functional magnetic resonance imaging of human brain activity in a verbal fluency task. J Neurol Neurosurg Psychiatry 64:492–498
11. Tucha L, Simpson W (2011) The role of time on task performance in modifying the effects of gum chewing on attention. Appetite 56:299–301
12. Hirano Y, Obata T, Takahashi H et al (2013) Effects of chewing on cognitive processing speed. Brain Cogn 81:376–381
13. Hoshi Y (2003) Functional near-infrared optical imaging: utility and limitations in human brain mapping. Psychophysiology 40:511–520
14. Jobsis FF (1977) Noninvasive, infrared monitoring of cerebral and myocardial oxygen sufficiency and circulatory parameters. Science 198:1264–1267
15. Hoshi Y, Kobayashi N, Tamura M (2001) Interpretation of near-infrared spectroscopy signals: a study with a newly developed perfused rat brain model. J Appl Physiol 90:1657–1662
16. Shibusawa M, Takeda T, Nakajima K et al (2009) Functional near-infrared spectroscopy study on primary motor and sensory cortex response to clenching. Neurosci Lett 449:98–102
17. Tanida M, Sakatani K, Takano R et al (2004) Relation between asymmetry of prefrontal cortex activities and the autonomic nervous system during a mental arithmetic task: near infrared spectroscopy study. Neurosci Lett 369:69–74
18. Konno M, Takeda T, Kawakami Y et al (2016) Relationships between gum-chewing and stress. Adv Exp Med Biol 876:343–349
19. Tachtsidis I, Scholkmann F (2016) Erratum: Publisher's note: false positives and false negatives in functional near-infrared spectroscopy: issues, challenges, and the way forward. Neurophotonics 3:039801