Chapter 60
NIRS-Based Neurofeedback Learning Systems for Controlling Activity of the Prefrontal Cortex

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Abstract The aim of this study was to develop a NIRS-based neurofeedback system to modulate activity in the prefrontal cortex (PFC). We evaluated the effectiveness of the system in terms of separability of changes in oxy-Hb and its derivative. Training with neurofeedback resulted in higher separability than training without neurofeedback or no training, suggesting that the neurofeedback system could enhance self-control of PFC activity. Interestingly, the dorsolateral PFC exhibited enhanced activity and high separability after neurofeedback training. These observations suggest that the neurofeedback system might be useful for training subjects to regulate emotions by self-control of dorsolateral PFC activity.

60.1 Introduction

Neurofeedback is a specific form of biofeedback, which feeds back information about brain activity to allow for training of subjects to achieve voluntary regulation of brain activity. Data for neurofeedback has been obtained by using electroencephalography [1], magnetoencephalography [2], real-time fMRI [3, 4], and NIRS [5]. The EEG feedback system has been successfully used clinically, for example, in epilepsy or as a brain-computer interface (BCI); however, EEG provides only unreliable localization of active brain areas. MEG and real-time fMRI have high spatial resolution, but the systems are bulky and expensive. In contrast, NIRS is

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compact and less expensive than MEG or fMRI and should be more suitable for practical use.

In the present study, we developed a NIRS-based neurofeedback system to modulate activity in the prefrontal cortex (PFC). We evaluated the effect of the neurofeedback system in terms of separability of changes in oxy-Hb and its derivative. Separability is an index that shows how easily groups can be distinguished [6, 7]. It can be calculated from the variance of each class (in this study, activation or deactivation trajectory of oxy-Hb and its derivative) and the distance between the classes as described in Sect. 2.2.

60.2 Materials and Methods

60.2.1 Experimental Settings

We monitored concentration changes of oxyhemoglobin (oxy-Hb) in the bilateral PFC employing a multichannel NIRS (OMM 3000, Shimadzu, Japan) connected to a computer. This system consists of 16 light-source fibers and 16 detectors resulting in 48 source-detector pairs; each light source has three laser diodes with wavelengths of 780, 805, and 830 nm. The optodes for the NIRS were placed on the skull to cover the bilateral frontal lobes, including the dorsolateral PFC, employing a holder cap to avoid motion-related artifacts; the source-detector distance was 30 mm.

The subjects were instructed to concentrate on the display so as to make the color on the screen become red. The display showed a red color when oxy-Hb increased above the baseline, whereas a blue color was displayed when oxy-Hb decreased below the baseline.

We studied 26 young adult subjects, who were classified into groups A, B, and C.

In group A ($n=14$), subjects were trained to change the color on the display to red for 7 days using the neurofeedback system. In group B ($n=5$), subjects were trained to do so for 7 days without the system. In group C ($n=7$), subjects did not receive training. The subjects were trained for about 1 h a day for 1 week.

60.2.2 Data Analysis

NIRS signals are relative values; thus, it is difficult to compare changes of NIRS signals among subjects. We therefore calculated the Z-score of the NIRS signals and averaged the Z-scores (Fig. 60.1a):

$$Z = \frac{X - \mu}{\sigma} \tag{60.1}$$

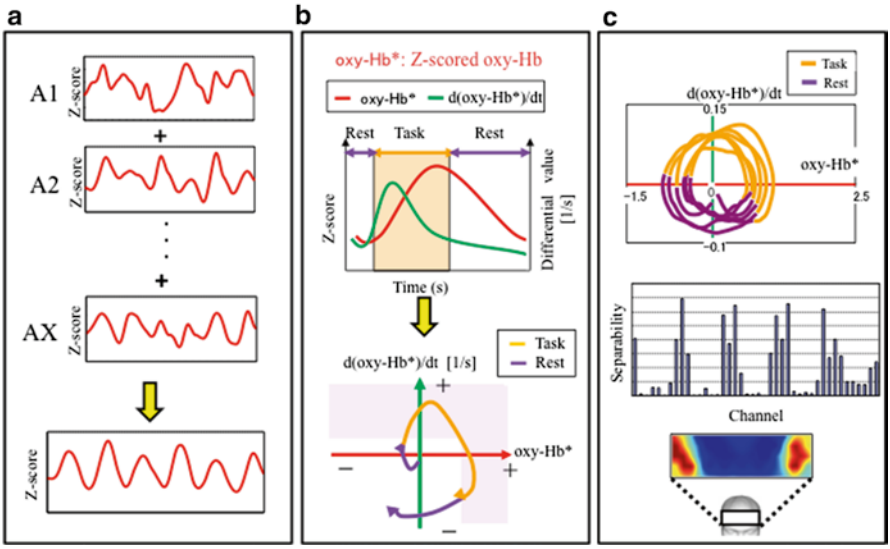

Fig. 60.1 Analysis of NIRS signals. Averaging using Z-score (**a**). Trajectory of Z-scored oxy-Hb and differential value (**b**). Evaluation of separability (**c**)

where X, μ, σ denote measurement value, mean value, and standard deviation of the NIRS signals, respectively.

In order to define the activated cortical area, we calculate differential values of oxy-Hb (i.e., d(oxy-Hb)/dt) during rest and during the task. The differential value was computed by finite difference with a sampling time 0.205 s. Then, we plotted a phase plane of oxy-Hb and its derivative (Fig. 60.1b). We defined the activated cortical area as the area where both oxy-Hb concentration and differential value increased.

The feature quantity is identified using a vector of oxy-Hb (p_{oxy}) and its derivative ($\dot{p}_{oxy}$) as $\mathbf{p} = (p_{oxy}, \dot{p}_{oxy})$. Within-class variance, σ_W^2, and between-class variance, σ_B^2, are calculated by

$$\sigma_W^2 = \left(\sum_{\mathbf{p} \in X_{task}} (\mathbf{p} - \mathbf{m}_{task})^T (\mathbf{p} - \mathbf{m}_{task}) + \sum_{\mathbf{p} \in X_{rest}} (\mathbf{p} - \mathbf{m}_{rest})^T (\mathbf{p} - \mathbf{m}_{rest}) \right) / n, \quad (60.2)$$

$$\sigma_B^2 = \left(n_{task} (\mathbf{m}_{task} - \mathbf{m})^T (\mathbf{m}_{task} - \mathbf{m}) + n_{rest} (\mathbf{m}_{rest} - \mathbf{m})^T (\mathbf{m}_{rest} - \mathbf{m}) \right) / n \quad (60.3)$$

where n, n_{task}, n_{rest} are a total number of signals of all, the task, and the rest, respectively. m, m_{task}, m_{rest} are an averaged vector of all signals, the task signal, and the rest signal, respectively.

The separability can be defined as

$$J_\sigma = \frac{\sigma_B^2}{\sigma_W^2} \tag{60.4}$$

Within-class variance represents an average spread in the class, and between-class variance represents a spread between classes [6, 7]. When the value of J_σ is large, groups can be easily distinguished.

In order to assess the reproducibility of PFC activation, we evaluated the separability of NIRS signals during the task and rest periods (Fig. 60.1c).

60.3 Results

Figure 60.2 shows pseudo-color 2D images of the averaged Z-score of oxy-Hb in groups A, B, and C. In group A, the bilateral lateral PFC exhibited higher activation than other PFC regions after neurofeedback training. In group B, the training without neurofeedback increased activity only in the left lateral PFC. No effect on PFC activity was observed in group C.

Figure 60.3a shows pseudo-color 2D images of separability of oxy-Hb changes in group A. Separability increased from 1.037 to 3.449, indicating that the subjects were well able to control PFC activity after training. The training effect was observed mainly in the lateral PFC. Figure 60.3b shows the results in group B. Separability increased from 0.729 to 2.080. Thus, training without neurofeedback was less effective than training with neurofeedback. In addition, the training effect was observed only in the left lateral PFC. In group C, no change was observed (Fig. 60.3c).

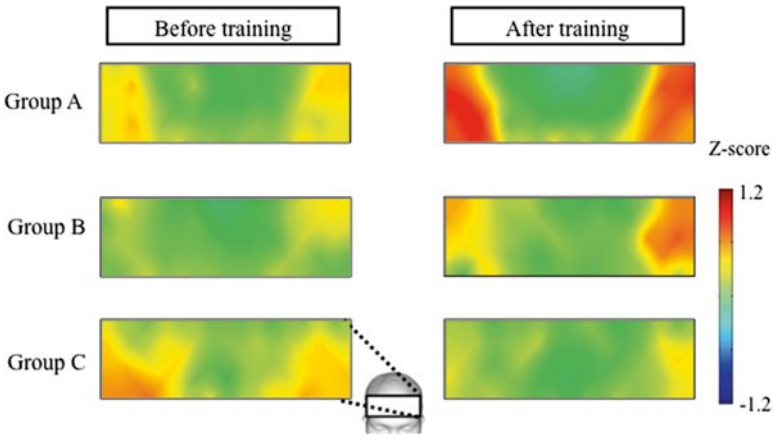

Fig. 60.2 Pseudo-color 2D images of Z-score for averaged oxy-Hb changes in groups A, B, C before and after training; *red color* indicates higher values of Z-score, while *blue color* indicates lower values of Z-score

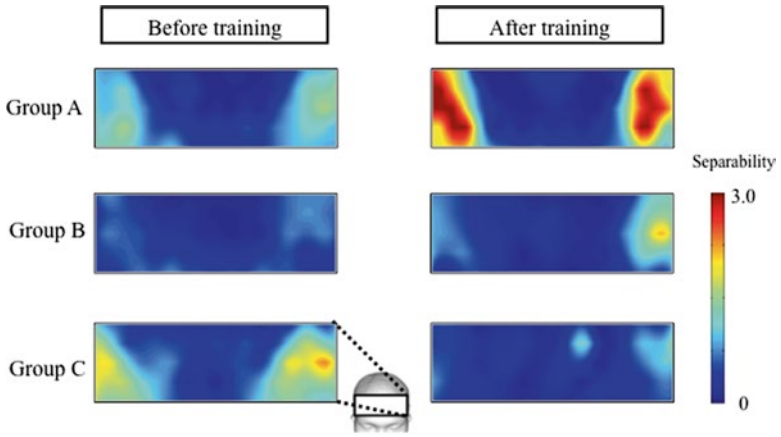

Fig. 60.3 Pseudo-color 2D images of separability of oxy-Hb changes in groups A, B, C before and after training; *red color* indicates higher values of separability, while *blue color* indicates lower values of separability

60.4 Discussion

We evaluated the effect of neurofeedback training on self-control of PFC activation by examining the separability of NIRS signals, which allows assessment of the reproducibility of PFC activation. We found that subjects trained with neurofeedback exhibited higher separability than those trained without neurofeedback or those who received no training. These results suggest that our neurofeedback system could enhance self-control of PFC activity compared with training without neurofeedback and no training. Interestingly, the lateral PFC exhibited enhanced activity and high separability after neurofeedback training.

The PFC plays a key role in both negative and positive emotional regulation via connections with subcortical nuclei, including the amygdala [8–10]. Specifically, the dorsolateral PFC is one of the brain regions implicated in emotional processing, particularly during downregulation of negative emotional conditions [11]. It has been reported that increased activity in the dorsolateral PFC was associated with suppression of fearful stimuli [12] and processing of positive emotional stimuli [13]. In addition, increased activity in the dorsolateral PFC was observed during modification of the intensity of emotional stimuli using cognitive strategies [14, 15]. These observations suggest that neurofeedback training using the present system might be useful for regulatory control of impulses and emotions by self-control of dorsolateral PFC activity.

Finally, it should be emphasized that the present neurofeedback system with NIRS is compact and practical for use in both normal subjects and patients with mental disorders. However, further studies are necessary to evaluate the psychological effects of the system and to establish its usefulness in self-control of emotions.

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