

# Individual Differences in Blood Volume and Oxygenation in the Brain during a Cognitive Task based on Time-Resolved Spectroscopic Measurements

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**Abstract** Although a time-resolved near-infrared spectroscopy (TRS) system is difficult to make a measurement into 10 s or less at the moment, the system has a great advantage that it measures absolute values of hemoglobin concentrations. In the present study, using a device equipped with a TRS system, we examined individual differences in changes in cerebral oxygenated, deoxygenated, and total hemoglobin concentrations during two repetitive executions of a cognitive task, and compared these with data from our previous studies performed with a CWS system. As a result, large individual differences were also observed in changes in the cerebral hemoglobin concentrations during a cognitive task in this study using a TRS system. We therefore conclude that large individual differences observed in changes in the cerebral hemoglobin concentrations during a cognitive task in our previous studies using a continuous wave near-infrared spectroscopy (CWS) system would probably be universal, although a CWS system includes the limitation that the absolute value is unable to be measured in the system.

## 1 Introduction

For more than three decades, lots of investigations have been performed on cerebral hemodynamic changes to achieve a better understanding of oxygen transport to the cerebral cortex and to elucidate the prefrontal cortex activation during a mental activity [1–8]. Individual differences, however, in those changes in responses involved in mental activities have been left to be investigated in detail.

We have so far reported changes in cerebral blood volume and oxygenation during a cognitive task by non-invasive measurements using a continuous wave

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near-infrared spectroscopy (CWS) system [9–12]. Although a CWS system made up of relatively simple parts proved useful and is employed for optical topography, a device equipped with the system is unable to measure absolute values, letting us hesitate to make comparisons among experiments and among subjects. On the other hand, a time-resolved near-infrared spectroscopy (TRS) system [13] is difficult to make a measurement into 10 s or less at the moment, because the system requires the integration time of photons, resulting in inadequate detection of a rapid change in hemodynamics. However, the system has a great advantage that it measures absolute values of blood volume and oxygenation. In the present study, using a device equipped with a TRS system, we examined individual differences in changes in the cerebral blood volume and oxygenation during two repetitive executions of a cognitive task, and compared it with our previous studies performed with a CWS system.

## 2 Methods

Eighteen healthy, young, male volunteers with a mean age of 24.5 years participated in this study. All the subjects were right-handed normotensive non-smokers. Informed consent was obtained from all the subjects before participation in the experiment. Subjects were instructed to refrain from taking alcohol and caffeine at the night before the experiment and on the day of the experiment.

Cerebral blood volume and oxygenation were measured using a TRS system. A device [14] equipped with the TRS system consists of a light source of three-wavelength (760, 795, and 830 nm) laser light pulses and a light detector of a photomultiplier tube (TRS-20, Hamamatsu Photonics K. K., Hamamatsu, Japan). The TRS system allows the determination of relative light intensity, mean optical path length, scattering coefficient, and absorption coefficient, enabling measurements of absolute concentrations of oxygenated hemoglobin ([oxy-Hb]), deoxygenated hemoglobin ([deoxy-Hb]), and total hemoglobin ([total-Hb] = [oxy-Hb] + [deoxy-Hb]). TRS-optodes with a source-detector distance of 4 cm were positioned on the left side of the frontal region of a subject's head. Subjects were instructed to sit back in a comfortable chair with a headrest to avoid movements of subjects' heads and measurement cables, which may cause movement artifacts. To eliminate light interference, the measurements were performed in a dark room with an illuminance of about  $8 \text{ lx}$ .

A five-color, computer-controlled version of a modified Stroop color-word task we developed was used as a cognitive task, and was partially described elsewhere [11]. Briefly, a subject is instructed to select one of five colored disks presented simultaneously with one color word on a computer screen, according to the instruction (i.e., "color" or "meaning"). The color of the presented word on the screen is discordant with the meaning of the word. The order of appearance of the instructions and color words is randomized. Subjects must

overcome cognitive interference to respond properly. The original Stroop color-word task [15] has been shown to actually activate the prefrontal cortex in a recent functional magnetic resonance imaging study [16].

Two repetitive task-performing sessions (the first and the second) were administered as an experimental procedure. After a resting period, subjects participated in a 4-min performing session – the first session. After a 15-min break following the first task, subjects participated again in the second performing session – the second session. Each session consisted of the baseline (the last 2-min average of the resting period), the anticipation (2-min average), and the performance (4-min average). Baseline values and changes, namely alteration of the 4-min averaged value during the performing session from the baseline, in each cerebral hemoglobin concentration were analyzed in this study.

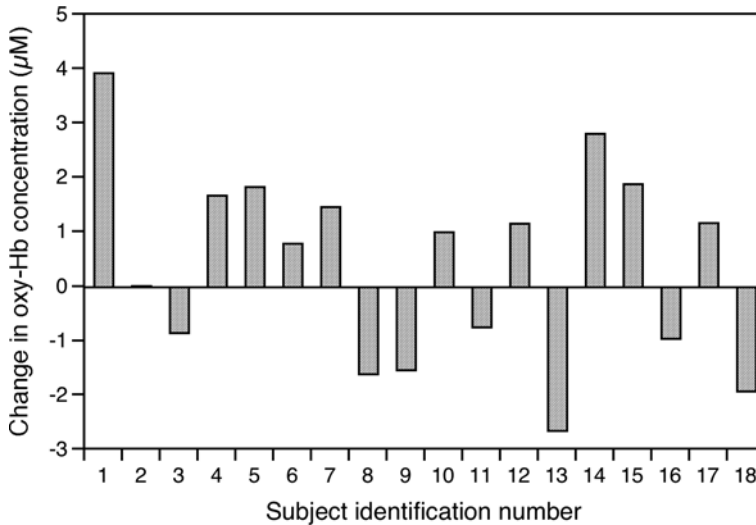
Subjects were encouraged to do their best in the task to earn money prizes awarded to those according to the number of correct answers.

### 3 Results and Discussion

Baseline values of [oxy-Hb], [deoxy-Hb], and [total-Hb] were  $56.4 \pm 6.4 \mu\text{M}$  (mean  $\pm$  SD),  $22.0 \pm 3.3 \mu\text{M}$ , and  $78.4 \pm 8.8 \mu\text{M}$  in the first performing session, respectively; furthermore, they were highly reproducible between the two repetitive performing sessions. These results indicate that the baseline values include relatively small individual differences and are stable.

On the other hand, for the change in hemoglobin concentration from the baseline as a time-averaged value during the performing session, individual differences were large as shown in Fig. 1, and subjects showed on the whole all combinations of an increase and decrease in [oxy-Hb] and [deoxy-Hb], such as, in the first session, a typical change of increase in [oxy-Hb] and decrease in [deoxy-Hb] (in 8 subjects out of 18 ones), an atypical change of decrease in [oxy-Hb] and increase in [deoxy-Hb] (in 3 subjects out of 18 ones), a change of both increases in [oxy-Hb] and [deoxy-Hb] (in 2 subjects out of 18 ones), a change of both decreases in [oxy-Hb] and [deoxy-Hb] (in 4 subjects out of 18 ones), and a very small change or almost constant in [oxy-Hb] and [deoxy-Hb] (in 1 subjects out of 18 ones), proving that cerebral hemodynamic response to the cognitive task includes large individual differences, which was similar to our previous findings observed using a CWS system (Niioka et al., unpublished data).

In addition, the means of changes in hemoglobin concentrations were decreased in terms of the amplitude in the two repetitive performing sessions; from  $0.42 \mu\text{M}$  in the first session to  $0.07 \mu\text{M}$  in the second session in [oxy-Hb] and from  $-0.22 \mu\text{M}$  in the first session to  $-0.20 \mu\text{M}$  in the second session in [deoxy-Hb]. This result was also similar to changes in cerebral hemoglobin concentrations in two repetitive cognitive tasks observed in our previous studies with a CWS system.



**Fig. 1** Individual difference in change in oxy-Hb concentration derived from the left side of the forehead during the first performing session in all the subjects. Subject identification numbers are in order of experiments performed

In conclusion, the results obtained in the present study indicate that individual differences in changes in cerebral hemoglobin concentrations during two repetitive cognitive tasks observed in our previous studies using a CWS system would probably be universal, although a CWS system includes the limitation that the absolute value is unable to be measured in the system.

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