Changes in hemoglobin concentration in the lateral occipital regions during shape recognition: a near-infrared spectroscopy study

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Abstract. By using near-infrared spectroscopy (NIRS), we measured the changes in the oxygenated and deoxygenated hemoglobin (oxy-Hb and deoxy-Hb, respectively) concentrations while performing visual tasks. We conducted experiments using two tasks: a shape recognition task and a position recognition task. It was found that the oxy-Hb concentration was substantially higher in the lateral occipital regions during shape recognition than during position recognition. The changes in the oxy-Hb concentration were considered to reflect the activation difference between the two tasks. No difference was observed in the oxy-Hb concentration during the memorization of shape and memorization of position. The deoxy-Hb concentration was different between the two tasks only when different stimuli were used but not when identical stimuli were used. In addition, it was suggested that the deoxy-Hb concentration is more sensitive to activation difference between the hemispheres and the activation at some regions. Measurements of the oxy-Hb and deoxy-Hb concentrations would reflect different aspects of cortical activations. The present results showed that measuring the oxy-Hb and deoxy-Hb concentrations separately can differentiate the activation of the regional cortical functions.
[DOI: 10.1117/1.2815720]

Keywords: near-infrared spectroscopy (NIRS); lateral occipital regions; shape recognition; functional brain imaging.

Paper 06372SSRR received Dec. 20, 2006; revised manuscript received Jun. 14, 2007; accepted for publication Jun. 14, 2007; published online Dec. 11, 2007.

1 Introduction

Near-infrared spectroscopy (NIRS) is a relatively new noninvasive technique used to measure regional brain activity. The general rationale behind NIRS is that the amount of near-infrared light passing through the tissues reflects the hemoglobin concentration depending on the level of brain activity.[1–5] The regional cerebral blood flow (rCBF) increases with the oxygenation demand during neural activation;[6] as a result, in the activated brain regions, the concentration of oxygenated hemoglobin (oxy-Hb) increases, whereas that of deoxygenated hemoglobin (deoxy-Hb) decreases. Therefore, measurement of the oxy-Hb and deoxy-Hb concentrations can be used to infer the activation of the cerebral region.

In comparison to other functional brain imaging techniques, NIRS has disadvantages with regard to its spatial resolution and measurable areas: NIRS can measure only the surface of the cortex (at a depth of 30 mm from the scalp) with a spatial resolution of approximately 30 mm, whereas positron emission tomography (PET) and functional magnetic resonance imaging (fMRI) can measure the entire brain with a spatial resolution of 1 to 10 mm. Nevertheless, the use of NIRS has several advantages over the other brain imaging techniques. First, measurements can be performed in usual settings in which participants are not required to assume the supine position on a scanner table. Second, NIRS has relatively low running cost and is quite easy to handle. Third, NIRS can measure the oxy-Hb and deoxy-Hb concentrations separately based on differences in the optical absorptions of oxy-Hb and deoxy-Hb.

The first objective of the present study was to examine whether NIRS signals are consistent with the findings of PET and/or fMRI studies in order to validate the feasibility of NIRS as an alternative brain imaging technique. It is well known that the lateral occipital regions of the brain are activated during the recognition of complex patterns. By using PET or fMRI, several studies have shown that the lateral bank of the fusiform gyrus extending ventrally and dorsally, which is also known as the lateral occipital complex, is activated when participants recognize complex patterns such as faces and familiar objects.[7–9] Thus, in our study, we tested whether NIRS could measure the brain activity around the lateral occipital regions.

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The second objective was to determine the relationship between the oxy-Hb and deoxy-Hb concentrations. Although researchers have started using NIRS for studying various brain functions pertaining to language recognition,[10] visual perception,[11–13] motor control,[14–16] etc., most of them have studied changes in the concentrations of oxy-Hb and total hemoglobin (the sum of the oxy-Hb and deoxy-Hb concentrations). The study of deoxy-Hb concentration has received considerably less attention, and the nature of deoxy-Hb during neural activation is not thoroughly understood. We want to compare the changes in the oxy-Hb and deoxy-Hb concentrations by using NIRS. We hypothesized that during shape recognition, the oxy-Hb and deoxy-Hb concentrations would increase and decrease, respectively, in the lateral occipital regions.

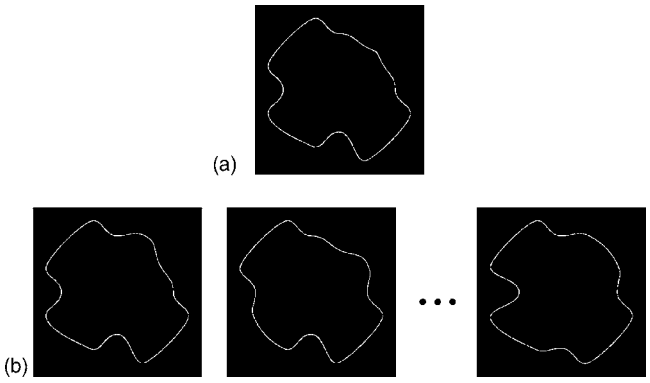

Fig. 1 Examples of stimuli used in the shape recognition task: (a) a target stimulus, (b) distractor stimuli.

2 Experiment 1

We measured the changes in the oxy-Hb and deoxy-Hb concentrations in the lateral occipital regions during shape recognition. Participants performed a shape recognition task and a position recognition task. In the shape recognition task, the participants judged whether successively presented stimuli were identical in shape to the remembered target. In the position recognition task, the participants judged whether successively presented lines were above or below the remembered target line. This task was designed to be compared with the shape recognition task for controlling residual factors such as decision-making, motor control, etc. In the shape recognition task, the participants had to focus more on the shape of the stimuli rather than their position. Therefore, the activation in the lateral occipital regions was expected to be larger in the shape recognition task than in the position recognition task. This would result in higher oxy-Hb concentration and lower deoxy-Hb concentration in the shape recognition task.

2.1 *Participants*

Seventeen volunteers participated in Experiment 1, all of whom were right-handed and had normal or corrected-to-normal visual acuity. Their mean age was 22.2 years (20 to 31 years).

2.2 *Apparatus*

A 22-inch CRT display (Dell P1230) and a personal computer (Apple Power Macintosh G4) were used for presenting stimuli. The display resolution was set at 1024×768 pixels with a refresh rate of 85 Hz. The computer recorded the judgments of the participants. We used a 24-channel NIRS instrument (ETG-4000 Optical Topography System; Hitachi Medical Co.) to measure the relative changes in the oxy-Hb and deoxy-Hb concentrations. This instrument generated near-infrared light at two wavelengths (695 and 830 nm).

2.3 *Stimuli*

Stimuli for the shape recognition task comprised meaningless line drawings that subtended a visual angle of approximately 13 deg $\times$ 13 deg (Fig. 1). The shape of the line drawings was defined by 12 points that were smoothly connected with a Bézier curve. In the position recognition task, the stimuli comprised horizontal lines (visual angle of 2.3 deg $\times$ 0.1 deg). Both stimuli were depicted using white lines on a black background.

2.4 *Procedure*

Each session comprised six experimental blocks. Figure 2 shows the testing protocol for experiments. In each experimental block, participants alternately performed the shape and position recognition tasks with a 60-s resting period between the tasks. During the resting period, a white fixation point was presented at the center of the display, and the participants were asked to keep their eyes on the fixation point.

Each task period for the shape recognition task proceeded in the following sequence. At the beginning of a task period, we presented a red fixation point at the center of the display for 2 s, followed by the memorization phase, during which a target to be memorized was presented for 4 s. Then, after showing a blank screen for 4 s, the recognition phase started. In the recognition phase, 20 test stimuli comprising 4 targets and 16 distractors were successively presented in random order for 2 s each, with 0.5-s intervals. The position of each stimulus was displaced randomly in the horizontal and vertical directions within a range of 1.1 deg of the visual angle. The participants judged whether the presented stimulus was

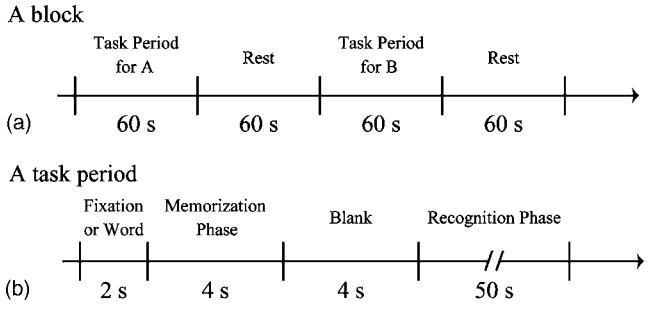

Fig. 2 Testing protocol for Experiments 1 and 2. A block consisted of two task periods and two resting periods. (a) Task periods for the shape and position recognition tasks were alternately performed with a resting period of 60 s. (b) At the beginning of a task period, a red fixation point or a word ("shape" or "position") was presented for 2 s, followed by the memorization phase. After a blank screen for 4 s, the recognition phase started.

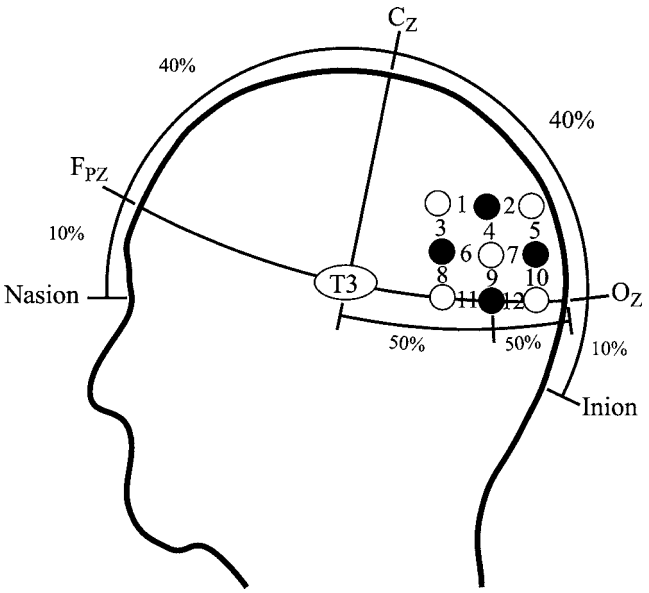

Fig. 3 Position of photodiodes used for NIRS measurements. Two 3 × 3 arrays of photodiodes comprising five light emitters (open circles) and four detectors (solid circles) were placed on the left and right lateral occipital areas of the head. Photodiodes placed on the left side of the head are shown in the figure. The hemoglobin concentration was measured at 24 channels (12 channels for each hemisphere) between the photodiodes. The numbers indicate the measurement areas and the channels.

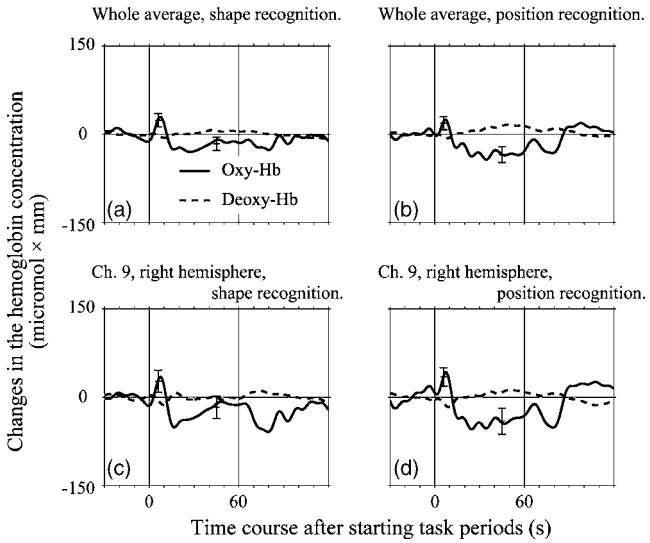

Fig. 4 Time course of changes in the oxy-Hb and deoxy-Hb concentrations in Experiment 1. Error bars show the means during memorization (4 to 10 s) and recognition (30 to 60 s) of stimuli and its standard errors (n=17). (a) Whole average of the changes in the shape recognition task. (b) Whole average of the changes in the position recognition task. (c) The changes at Ch. 9 in the right hemisphere in the shape recognition task. (d) The changes at Ch. 9 in the right hemisphere in the position recognition task.

identical to the remembered target. They responded by pressing two keys with two index fingers or two middle fingers.

The procedure of the position recognition task was similar to that of the shape recognition task. In the position recognition task, the participants memorized the position of a horizontal line instead of the shape of a meaningless line drawing. The target line was presented at 0 deg, 1.5 deg, or 3 deg vertically from the center of the display. In the recognition phase, 20 test lines were successively presented at 1.5 deg, 3 deg, 4.5 deg, or 6 deg above or below the target line presented in the memorization phase. The participants judged whether each test line was above or below the target line.

Before the start of a session, the participants were instructed about the tasks and experimental sequences. However, they were unaware of the purpose of the present study. The participants performed a practice block before beginning the experimental blocks. The practice for the shape recognition task was performed using simple figures (triangle, square, pentagon, hexagon, and circle) instead of meaningless line drawings.

2.5 *NIRS Measurements*

We placed two 3 × 3 arrays of photodiodes comprising five light emitters and four detectors on the left and right lateral occipital areas of the participants' heads (Fig. 3). The distance between the emitters and detectors was 3 cm. The centers of the bottom arrays of the photodiodes were positioned at the midpoints of T3 and O_Z and T4 and O_Z, respectively, according to the International 10–20 System of electrode placement. The bottom array of photodiodes was placed along the line passing through T3, O_Z, and T4. We measured the changes in the oxy-Hb and deoxy-Hb concentrations at 24 channels (hereafter represented as Ch.) corresponding to the 6 × 6 cm areas covered by the emitters and detectors. The sampling rate of each channel was 10 Hz.

2.6 *Data Correction*

Hemoglobin concentration often gradually increases or decreases throughout the experiments. In order to correct such a long-term transition in the hemoglobin concentration, we fitted linear functions to the data for each participant and each channel and subtracted the values of the linear functions from the data. We then applied a temporal low-pass filter with a cutoff frequency of 0.1 Hz to remove noise.

Next, we performed a baseline correction using mean values during the latter half of the resting period as a baseline. Specifically, for each task period, we calculated mean values during the latter half of the resting period that proceeded the task period and subtracted the mean values from the data. The baseline-corrected data were averaged for each task condition. We considered the averaged values as the changes in the hemoglobin concentration in each task.

2.7 *Results and Discussion*

Figure 4 illustrates the time course of changes in the oxy-Hb and deoxy-Hb concentrations. The oxy-Hb concentration abruptly increased soon after the start of the task period and then immediately decreased. This transient increase would reflect activation during the memorization phase. Following the transient increase, the oxy-Hb concentration persistently decreased, and the deoxy-Hb concentration increased. We speculate that this persistent change could be due to head movements such as leaning forward, which decreased the cerebral blood flow in the lateral occipital regions. As expected,

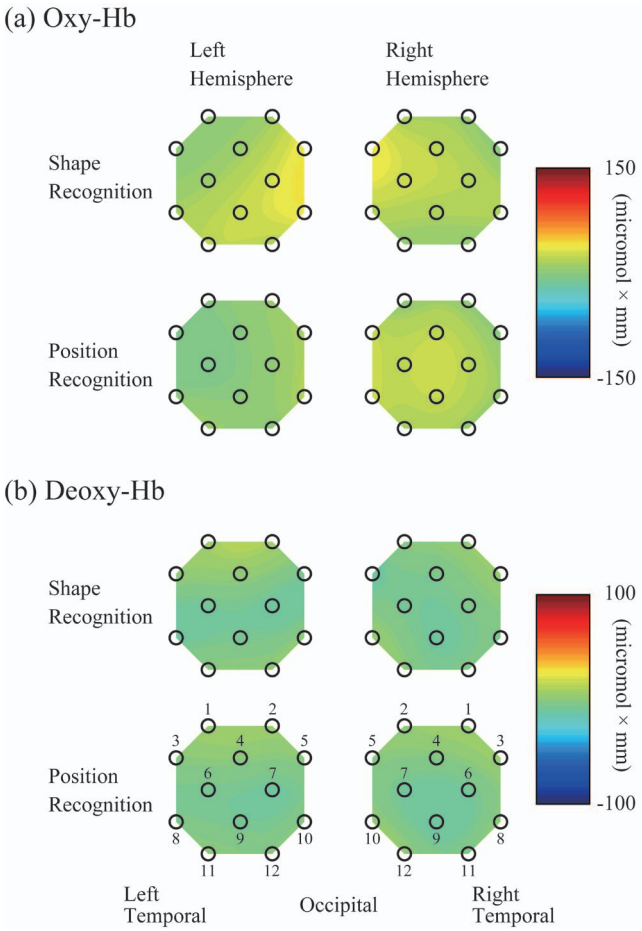

Fig. 5 Activation maps of mean changes in the hemoglobin concentration during 2 to 8 s after the start of the memorization phase in Experiment 1. No significant difference was observed between the tasks. (a) Results of the oxy-Hb concentration. (b) Results of the deoxy-Hb concentration.

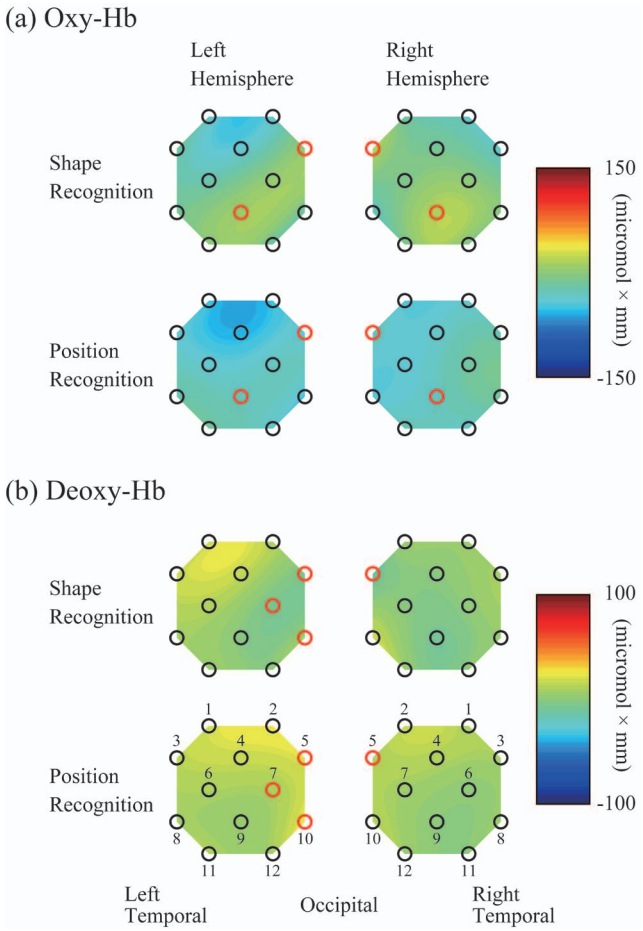

Fig. 6 Activation maps of mean changes in the hemoglobin concentration during the latter half of task periods (20 to 50 s after the start of the recognition phase) in Experiment 1. Circles on the maps illustrate positions of the channels. Red circles indicate the channels where the hemoglobin concentration was significantly different between the tasks. Channel numbers are shown on the bottom maps. (a) Results of the oxy-Hb concentration. (b) Results of the deoxy-Hb concentration.

the results showed higher oxy-Hb concentration in shape recognition than in position recognition during the latter half of the task periods. This trend would reflect activation during the recognition phase.

Figure 5 shows activation maps of mean changes in the oxy-Hb and deoxy-Hb concentrations during 2 to 8 s after the start of the memorization phase. In these maps, we interpolated the data from the mean changes in the hemoglobin concentration at 12 channels by using a spline function. We subjected the means of the oxy-Hb concentration during that time range to a $2\times12\times2$ (task$\times$channel$\times$hemisphere) analysis of variance (ANOVA) with repeated measures. The Huynh-Feldt correction was applied to the degrees of freedom when the data did not meet the sphericity assumption. The main effect of "channel" [$F(5.0,80.4)=3.96$, $p<0.05$] and the task$\times$channel$\times$hemisphere interaction [$F(11.0,175.8)=2.07$, $p<0.05$] were significant. As Fig. 5(a) shows, the activated channels were different between the hemispheres only for position recognition, but not for shape recognition. The three-way interaction reflects this difference. Since we were concerned about the hemodynamic difference between the tasks, we tested the simple interaction between "task" and "channel" and the simple-simple main effects of "task." However, they were not significant. We also applied an ANOVA to the means of the deoxy-Hb concentration in a manner similar to the oxy-Hb concentration. In this case, only the main effect of "channel" was significant [$F(5.6,88.9)=4.68$, $p<0.05$]. The other main effects and all the interactions were not significant. These results suggest that neither oxy-Hb nor deoxy-Hb concentration was different between the tasks during the memorization of stimuli.

Figure 6 shows activation maps of the oxy-Hb and deoxy-Hb concentrations during the latter half of task periods (20 to 50 s after the start of the recognition phase). We applied a $2\times12\times2$ (task$\times$channel$\times$hemisphere) ANOVA with repeated measures to the means of the oxy-Hb concentration. The main effect of "channel" was significant [$F(7.4,118.6)=2.63$, $p<0.05$], indicating that the mean changes in the oxy-Hb concentration were different among the channels. The interaction between "task" and "channel" was significant [$F(5.2,83.6)=2.77$, $p<0.05$]. This interaction implies that the changes in the oxy-Hb concentration

were different between the tasks in some channels. The other main effects and interactions were not significant.

To clarify the task × channel interaction, we tested the simple main effects of "task" for each channel. The simple main effects were significant for Ch. 5 [$F(1,99.6)=5.59$, $p<0.05$] and Ch. 9 [$F(1,99.6)=4.70$, $p<0.05$]; the oxy-Hb concentration at Ch. 5 and Ch. 9 (red open circles) was higher in the shape recognition task than in the position recognition task [Fig. 6(a)]. These results suggest that shape recognition activated regions at and around Ch. 5 and Ch. 9.

We also subjected the means of the deoxy-Hb concentration during the latter half of task periods to a $2\times12\times2$ (task × channel × hemisphere) ANOVA with repeated measures. The main effect of "channel" was significant [$F(7.1,114.3)=3.41$, $p<0.05$], indicating that the deoxy-Hb concentration was different among the channels. The main effect of "hemisphere" was also significant [$F(1,16)=9.39$, $p<0.05$]. This suggests that the deoxy-Hb concentration was lower in the right hemisphere than in the left hemisphere [Fig. 6(b)]. Although the main effect of "task" was not significant, there were significant interactions between "task" and "channel" [$F(7.3,116.1)=3.81$, $p<0.05$] and between "task," "channel," and "hemisphere" [$F(9.2,146.9)=3.35$, $p<0.05$]. These interactions suggest that the mean changes in the deoxy-Hb concentration were different between the tasks at some channels.

To clarify the task × channel × hemisphere interaction, we tested the simple task × channel interactions for each hemisphere. The simple interactions were significant for both the left hemisphere [$F(11,263.0)=3.14$, $p<0.05$] and the right hemisphere [$F(11,263.0)=2.38$, $p<0.05$], indicating that the channels behaved differently across the hemisphere. We then tested the simple-simple main effects of "task" for each hemisphere and each channel. In the left hemisphere, the simple-simple main effects were significant for Ch. 5 [$F(1,295.0)=15.58$, $p<0.05$], Ch. 7 [$F(1,295.0)=6.64$, $p<0.05$], and Ch. 10 [$F(1,295.0)=5.37$, $p<0.05$] [red open circles in Fig. 6(b) left maps]. In the right hemisphere, the simple-simple main effect was significant only for Ch. 5 [$F(1,295.0)=13.99$, $p<0.05$] [red open circles in Fig. 6(b) right maps]. At these channels, the deoxy-Hb concentration was lower in the shape recognition task than in the position recognition task. These results suggest that shape recognition activated regions at and around the channels.

To examine the difficulty of the two tasks, we calculated d' from the correct answer rates (hit and correct rejection rates) for each observer and subjected them to one-factor ANOVA with repeated measures. The values of d' for the shape recognition task (1.89) were lower than those for the position recognition task (2.37) [$F(1,16)=6.89$, $p<0.05$]. In other words, the shape recognition task was more difficult than the position recognition task.

In summary for Experiment 1, during the latter half of the task periods, the oxy-Hb concentration in the shape recognition task was higher than in the position recognition task at Ch. 5 and Ch. 9; on the other hand, the deoxy-Hb concentration was lower in the shape recognition task than in the position recognition task at Ch. 5 in both hemispheres and at Ch. 7 and Ch. 10 in the left hemisphere. These results suggest that the lateral occipital regions were activated when the participants performed the shape recognition task. However, since different types of stimuli were used for the two tasks in this experiment and the difficulty of the tasks differed, it is unclear whether the activation resulted from the properties of the task, stimuli, and/or difficulty. To address these points, we conducted Experiment 2.

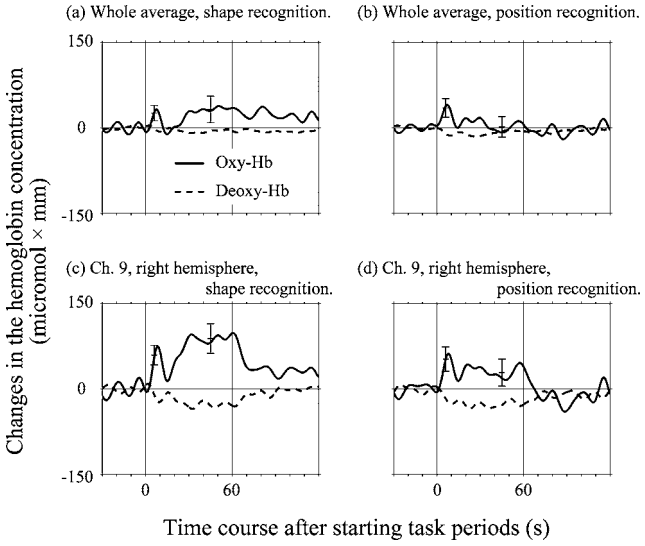

Fig. 7 Time course of changes in the oxy-Hb and deoxy-Hb concentrations in Experiment 2. Error bars show the means during memorization (4 to 10 s) and recognition (30 to 60 s) of stimuli and its standard errors ($n=14$). (a) Whole average of the changes in the shape recognition task. (b) Whole average of the changes in the position recognition task. (c) The changes at Ch. 9 in the right hemisphere in the shape recognition task. (d) The changes at Ch. 9 in the right hemisphere in the position recognition task.

3 Experiment 2

We performed Experiment 2 in a similar manner to Experiment 1, except for the following changes.

3.1 *Changes in Experiment 2*

Each session comprised a practice block and four experimental blocks. We decreased the number of experimental blocks from six to four in order to reduce the fatigue of the participants and to retain their concentration on the experiment.

A chin rest restricted the head movements of the participants during the experiments.

At the beginning of each task period, a word—"shape" or "position"—was placed on the center of the display for 2 s, instead of a red fixation point.

The meaningless line drawings were used as stimuli for both the shape and position recognition tasks (Fig. 1). In the position recognition task, the participants judged whether the position of the meaningless line drawings, instead of horizontal lines, was identical to the position of target presented in the memorization phase. Among the twenty presentations in each recognition phase, the positions of four were identical to that of the target. The shape recognition task was the same as that performed in Experiment 1. The range of random stimulus displacement in each trial was at visual angle of −3 deg, 0 deg, or 3 deg. We increased the range of random stimulus

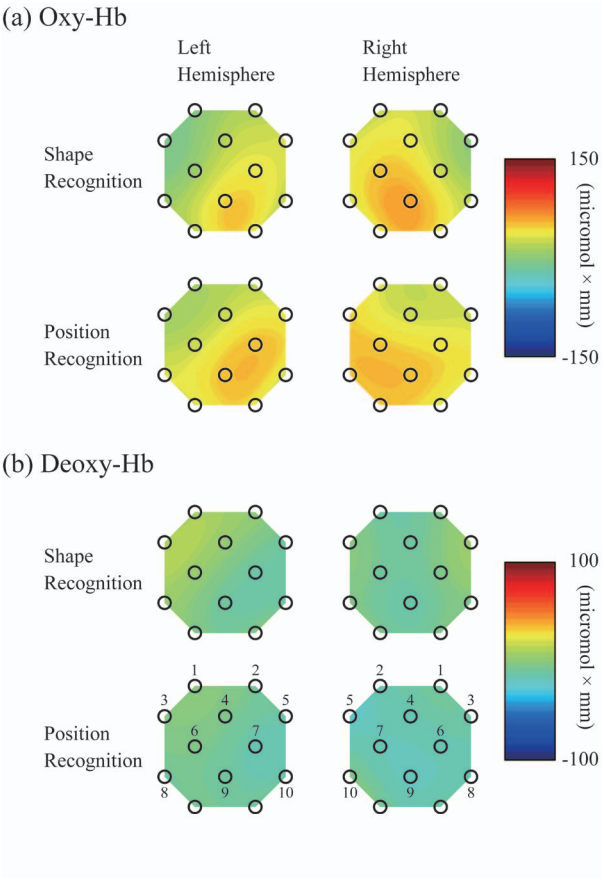

Fig. 8 Activation maps of mean changes in the hemoglobin concentration during 2 to 8 s after the start of the memorization phase in Experiment 2. No significant difference was observed between the tasks. (a) Results of the oxy-Hb concentration. (b) Results of the deoxy-Hb concentration.

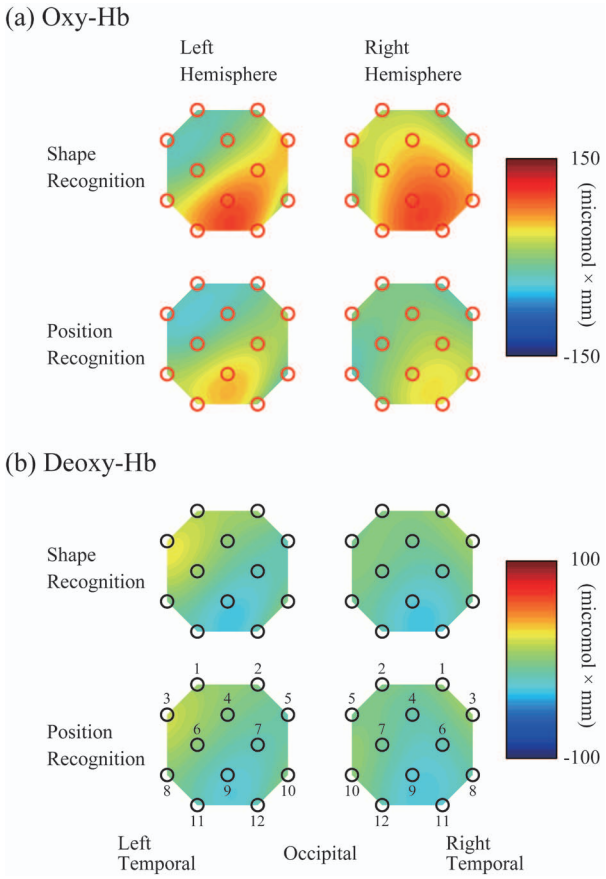

Fig. 9 Activation maps of mean changes in the hemoglobin concentration during the latter half of task periods (20 to 50 s after the start of the recognition phase) in Experiment 2. (a) Results of the oxy-Hb concentration. The oxy-Hb concentration was significantly higher in the shape recognition task than in the position recognition task as a whole. (b) Results of the deoxy-Hb concentration. No significant difference was observed in the deoxy-Hb concentration between the tasks.

displacement so that the difficulty of the task did not extensively differ between the shape and position recognition tasks.

Fourteen volunteers participated in Experiment 2, all of whom were right-handed and had normal or corrected-to-normal visual acuity. Their mean age was 19.9 years (19 to 22 years).

3.2 *Results and Discussion*

Figure 7 illustrates the time course of the changes in the oxy-Hb and deoxy-Hb concentrations. There appears to be at least two components of changes in the oxy-Hb concentration. One component is the transient increase immediately after the start of the task periods. The transient increase would reflect activation during the memorization phase. The other component is the sustained increase during the recognition of the stimulus shape, which appears in the latter half of the task periods. The sustained increase would reflect activation during the recognition phase. The deoxy-Hb concentration decreased immediately after the oxy-Hb concentration started to increase.

Figure 8 shows the activation maps of the oxy-Hb and deoxy-Hb concentrations during 2 to 8 s after the start of the memorization phase. We applied a $2\times12\times2$ (task $\times$channel$\times$hemisphere) ANOVA to the means of the oxy-Hb concentration. Although the main effect of "hemisphere" $[F(1,13)=7.70, p<0.05]$ and the main effect of "channel" $[F(6.76,87.8)=3.70, p<0.05]$ were significant, the main effect of "task" and all the interactions were not significant. We also applied an ANOVA to the means of the deoxy-Hb concentration. Although the main effect of "hemisphere" $[F(1,13)=6.45, p<0.05]$ and the interaction between "channel" and "hemisphere" $[F(7.92,102.9)=2.07, p<0.05]$ were significant, the main effect of "task" and the interaction including "task" were not significant. These results suggest that the oxy-Hb and deoxy-Hb concentrations showed the same activation trend for both tasks during the memorization of stimuli. Further, as observed in Fig. 7, the oxy-Hb concentration increased in both the shape and position recognition tasks.

Figure 9 shows the activation maps for the oxy-Hb and deoxy-Hb concentrations during the latter half of the task periods (20 to 50 s after the start of the recognition phase). The means of the oxy-Hb concentration were subjected to a $2\times12\times2$ (task$\times$channel$\times$hemisphere) ANOVA with repeated measures. The main effect of "task" was significant.

That is, the mean changes in the oxy-Hb concentration were higher in the shape recognition task (32.6 micromol × mm) than in the position recognition task (2.2 micromol × mm) $[F(1,13)=5.21, p<0.05]$. This suggests that the oxy-Hb concentration increased during the shape recognition task. The main effect of "channel" was also significant $[F(5.1,66.1)=7.28, p<0.05]$, indicating that the mean changes in the oxy-Hb concentration were different among the channels. The main effect of "hemisphere" was not significant. The interaction between "channel" and "hemisphere" was significant $[F(6.6,85.8)=2.61, p<0.05]$, indicating that the oxy-Hb concentration was different between the hemispheres at some channels. The other interactions were not significant.

We also subjected the mean changes in the deoxy-Hb concentration during the latter half of the task periods to a $2 \times 12 \times 2$ (task × channel × hemisphere) ANOVA with repeated measures. The main effect of "channel" was significant $[F(3.7,48.5)=6.20, p<0.05]$, indicating that the mean changes in the deoxy-Hb concentration were different among the channels. However, the other main effects and all the interactions were not significant.

We calculated d' as an index of the behavioral performance for each task and subjected them to one-factor ANOVA with repeated measures to determine the differences in the difficulty between the tasks. No significant difference was observed in the values of d' between the shape recognition (2.41) and position recognition (3.07) tasks. This implies that there was no significant difference in difficulty between the tasks in Experiment 2. Therefore, the task difficulty was not the main cause for the higher oxy-Hb concentration during the shape recognition task; rather, the nature of the task was a probable reason for this difference.

4 General Discussion

It was found that the oxy-Hb concentrations during the recognition of stimuli were substantially higher in the shape recognition task than in the position recognition task at Ch. 5 and Ch. 9 in Experiment 1 and as a whole in Experiment 2. These results indicate that the lateral occipital regions were activated when the participants recognized the shapes of stimuli. The oxy-Hb concentration was sensitive to the activations elicited by the shape recognition task in the lateral occipital regions.

The oxy-Hb concentration transiently increased immediately after the start of the task periods in both the shape and the position recognition tasks. Two tentative explanations can be provided for this result. The first explanation is that memorization caused the transient increase. At the beginning of the task periods, the participants had to memorize the shape or position of the stimuli. Such a memorization might have activated the lateral occipital regions, regardless of the stimulus properties that the participants had to remember. The second explanation is that a rise in the alertness level due to a sudden start of the task period caused transient increase in the oxy-Hb concentration. These explanations are admittedly speculative and must be examined in future studies.

The deoxy-Hb concentration was lower in the shape recognition task than in the position recognition task at some channels in Experiment 1. The lower deoxy-Hb concentration is also thought to reflect the substantial activation in these channels during the shape recognition task; this is because the regional cortical activation is typically characterized by a decrease in the deoxy-Hb concentration and an increase in the oxy-Hb concentration. However, in Experiment 2, where the stimuli for the two tasks were identical, no channel showed a significant difference in the deoxy-Hb concentration between the tasks. Therefore, the regional activations during the shape recognition task in Experiment 1 could be attributed to the stimulus difference as well as the task difference.

The oxy-Hb and deoxy-Hb concentrations in Experiment 1 showed different results. The deoxy-Hb concentration was different between the hemispheres during the recognition of stimuli, whereas the oxy-Hb concentration was not. Moreover, the deoxy-Hb concentration showed differences between the tasks at Ch. 7 and Ch. 10, whereas no such differences were observed in the oxy-Hb concentration at these channels. These results suggest that the deoxy-Hb concentrations reflect different types of brain activities that cannot be monitored by the oxy-Hb concentration.

In Experiment 2, the oxy-Hb concentration was significantly different between the 2 tasks, whereas the deoxy-Hb concentration was not. Recently, Suh et al. measured the near-infrared light reflected directly from the human brain and not through the skull and compared the changes in the total and deoxygenated hemoglobin.[17] They found that the decrease in the deoxy-Hb concentration was less localized than the increase in the total hemoglobin. The less-localized changes in the deoxy-Hb concentration lowered the signal-to-noise (S/N) ratio and made it difficult to detect them. The lower S/N ratio in the deoxy-Hb concentration might be responsible for the difference in the oxy-Hb and deoxy-Hb concentrations.

In Experiment 2, the oxy-Hb concentration increased as the deoxy-Hb concentration decreased (Figs. 7–9); this result is consistent with the finding that the rCBF increases according to the oxygenation demand during neural activation.[6] However, the deoxy-Hb concentration changed a little later than the oxy-Hb concentration. This could be attributed to the fact that the first-order response of cells is consumption of glucose and oxygen. In other words, the decrease in the deoxy-Hb concentration was delayed because the deoxy-Hb concentration somewhat increased before the increase in the rCBF.

We found an atypical pattern of hemoglobin changes in Experiment 1. As shown in Fig. 4, the oxy-Hb and deoxy-Hb concentrations decreased and increased, respectively, at many channels during task periods. This trend can be attributed to head movements. When the chin rest restricted the head movements in Experiment 2, the results showed a typical pattern of increase and decrease in the oxy-Hb and deoxy-Hb concentrations, respectively. It has been argued that head movements affect the measurements of NIRS. Perhaps a forward-leaning posture during the task periods in Experiment 1 decreased the cerebral blood flow in the lateral occipital regions.

Activation maps showed the presence of pronounced activities in the cerebral regions corresponding to Ch. 9 during the shape recognition task (Figs. 6 and 9). Although NIRS provides poor anatomical information, we can estimate the cerebral regions where the activated channels were located. As shown in Fig. 3, Ch. 11 on each hemisphere was positioned 1.5 cm anterior to the midpoints of T3 and O_Z (left) or

of T4 and O_Z (right). These positions approximately correspond to T5 or T6. According to Okamoto et al.,[18] T5 and T6 are located on the middle temporal gyrus or the inferior temporal gyrus as well as on the border of the temporal and occipital lobes. Therefore, Ch. 11 can be considered to be located on these areas. Ch. 9 was positioned 1.5 cm posterior and superior to Ch. 11. Thus, Ch. 9 would correspond to the frontal portion of the occipital lobe near the middle temporal gyrus. These areas are included in the lateral occipital complex. The lateral occipital complex contains two spatially segregated subdivisions—a dorsal-caudal subdivision and a ventral-anterior subdivision. The dorsal-caudal subdivision is "situated posterior to MT in the lateral-occipital sulcus and extends into the posterior inferior temporal sulcus."[19] Thus, it is likely that the activated channels were a part of the regions that include the dorsal-caudal subdivision of the lateral occipital complex.

According to the fMRI study conducted by Mendola et al.,[20] the dorsal-caudal subdivision was activated while viewing contours defined by various visual features, i.e., the luminance, illusory, and stereoscopic contours. Based on these observations, the authors argued that this region was responsible for intermediate-level visual processing, i.e., after edge detection but before object recognition, during which the stimulus contours are represented independently from the visual features. The necessity for this kind of intermediate-level processing would be more in the shape recognition task than in the position recognition task and presumably induced the activity at and around Ch. 9.

In summary, the present study showed that by measuring the oxy-Hb concentration, NIRS could differentiate the cortical activations produced by the different tasks in the lateral occipital regions of the human brain. The oxy-Hb concentration in these regions was higher in the shape recognition task than in the position recognition task. The results were consistent with the findings of the fMRI studies,[7–9] suggesting the feasibility of NIRS for monitoring cognitive brain functions. The oxy-Hb concentration was more sensitive to the activation difference between the tasks than the deoxy-Hb concentration. However, the deoxy-Hb concentration could potentially be more sensitive to the activation difference between the hemispheres and the activation at some regions. The measurements of the oxy-Hb and deoxy-Hb concentrations might reflect different aspects of cortical activations. The results of changes in the oxy-Hb and deoxy-Hb concentrations might enable us to obtain more useful information about cortical brain functions and hemodynamic properties.

Acknowledgments

We thank our colleague Mr. A. K. M. Rezaul Karim for helpful comments on this paper and acknowledge support from the COE program of the Japanese Ministry of Education, Culture, Sports, Science, and Technology.

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