**ORIGINAL**

# Bilateral Prefrontal Cortex Blood Flow Dynamics during Silent and Oral Reading Using Near-Infrared Spectroscopy

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**Abstract : This study aimed to investigate blood flow dynamics in the bilateral prefrontal cortex during silent and oral reading using near-infrared spectroscopy (NIRS). The subjects were 40 right-handed university students (20.5 ± 1.8 years old, 20 men and 20 women). After completing the NIRS measurements, the subjects were asked to rate their level of proficiency in silent and oral reading, using a 5-point Likert scale. During oral reading, the left lateral prefrontal cortex (Broca's area) was significantly more active than the right side. During silent reading, prefrontal cortex activity was lower than that during oral reading, and there was no significant difference between both sides of the brain. A significant negative correlation was found between the change in oxy-hemoglobin (oxy-Hb) concentration in the left and right lateral prefrontal cortex during silent reading and silent reading speed. In addition, students with lower self-reported reading proficiency had significantly greater changes in oxy-Hb concentrations in the left and right lateral prefrontal cortex during silent/oral reading than did students with higher self-reported reading proficiency. Reading task assessment using NIRS may be useful for identifying language lateralization and Broca's area. The results demonstrate that NIRS is useful for assessing effortful reading and may be used to diagnose developmental dyslexia in children. J. Med. Invest. 71 : 92-101, February, 2024**

***Keywords*** **:** *near-infrared spectroscopy (NIRS), frontal lobe, oral and silent reading, developmental dyslexia*

## INTRODUCTION

Developmental dyslexia is classified as a "reading impairment" under the category of "Specific Learning Disorders" in the American Psychiatric Association's Diagnostic and Statistical Manual of Mental Disorders, Fifth Edition (1). Despite the absence of intellectual delay, a patient with developmental dyslexia has significant difficulty in reading letters, which interferes with learning. The basic pathophysiology of this disorder is that the correspondence between letters and their readings does not become automatic because the phonological processing of heard word sounds is impaired (2-4). It is a decoding disorder that requires effort and time to recall the sounds that correspond to letters. In addition, it is very difficult for these individuals to group words and phrases to result in sequential reading, due to a deficit in the ability to establish the correspondence between graphemes (letters) and phonemes (sounds) (2).

Patients with developmental dyslexia have greater difficulty in reading silently than in reading aloud. The dyslexic reader subvocalizes and reads silently. In other words, it has been theorized that they are recognizing the "sound structure of a word" by using Broca's area, which controls pronunciation. These articulatory strategies (sub-vocalization) that are used during reading allow them to read all be it at a slow reading speed (2). Functional magnetic resonance imaging (fMRI) studies conducted by Shaywitz (2) have shown that brain activity during silent/oral reading in such patients differs from that of typically developing children.

Broca's area is a region in the frontal lobe of the dominant, usually the left, hemisphere of the brain with functions related to language production. Because of its location on the lateral cortex of the cerebral hemisphere, Broca's area receives blood supply from the superior division of the middle cerebral artery. Most people are left hemisphere dominant, which means that the left middle cerebral artery most often supplies Broca's area (12).

Near-infrared spectroscopy (NIRS) is a method of measuring cerebral blood flow using near-infrared light, taking advantage of the difference in light absorption between oxy- and deoxy-hemoglobin (Hb) concentrations (5). During brain activity, regional blood flow increases, and fresh arterial blood flows in, resulting in a significant increase in oxy-Hb concentration and a decrease in deoxy-Hb. Conversely, when brain activity decreases, the oxy-Hb concentration in the region likewise decreases. NIRS is minimally invasive and is widely used to study brain function from neonates to adults (6-11).

Few reports have been published dealing with brain responses during reading activities in children with developmental dyslexia using NIRS, even overseas (13-15), and none have been reported in Japan. As a preliminary study to elucidate the pathophysiology of developmental dyslexia, this study aimed to investigate blood flow dynamics in the bilateral prefrontal cortex during silent and oral reading using NIRS in university students.

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## METHODS

### *Subjects*

The subjects were 40 Japanese university students (20.5 ± 1.8 years old, 20 men and 20 women) who were native speakers of Japanese at National University A. All subjects were right-handed.

### *NIRS Data Collection Period*

Data were collected between July 2021 and March 2023.

### *NIRS Data Collection Methods*

Shimadzu NIRStation, OMM-3000-12, which is near-infrared optical brain function imaging with 25-channel probes, was placed on the frontal area to measure bilateral prefrontal cortex activity. The position of the probes was set in a grid pattern with light-emitting probes (red circles) and light-receiving probes (blue circles) 3 cm apart on either side of the frontopolar midline or Fpz electrode position, which is based on the international 10-20 electrode nomenclature system for electroencephalography (EEG). The space between the light-emitting and light-receiving probes is called the channel (ch) (Fig. 1).

When the probes were placed as shown in the figure, the left ch16 or right ch10 were considered to correspond to Broca's area, which is the motor center for language (16, 17).

For the silent reading and oral reading tasks, a mixed Kanji/Hiragana text of one of Grimm's fairy tales (with total Kanji ruby) was used as the character text. For the silent reading task, participants were asked to read silently for 60 seconds while the text was presented to them. This task was performed twice with a 60-second rest task in between that involved reading the hiragana characters "aiueo" repeatedly and silently.

The two times were added and averaged to obtain an additive mean waveform, and the amount of change in oxy-Hb concentration in each channel during the task was calculated. The same method was then used for the oral reading task.

The number of letters read during the silent and oral reading tasks was calculated as the silent and oral reading speed (number of letters/minute).

Participants were individually interviewed about their reading habits (frequency of reading, how many books/month they read, etc.) and whether they liked or disliked reading. After completing the NIRS measurements, participants were asked to rate their ability to read silently and orally on a 5-point Likert scale (1 = very poor, 2 = poor, 3 = fair, 4 = good, and 5 = very good).

### *Data Analysis*

For the paired samples, the Wilcoxon signed-rank test was used to compare the width of cerebral blood flow during silent and oral reading and the width of left and right cerebral blood flow during silent and oral reading. Spearman correlation coefficient was used to determine the correlation between (1) oxy-Hb changes and silent/oral reading speed, and (2) silent/oral reading speed and self-reported reading ability. The Kruskal-Wallis test with Dwass-Steel-Critchlow-Fligner pairwise comparisons was used to explore the relationship between a continuous dependent variable, and a categorical explanatory variable. Data were analyzed using Jamovi (version 2.3.21) (The Jamovi project, Sidney, Australia) and IBM SPSS Statistics for Windows (version 21.0 ; Armonk, NY, IBM Corp). The level of significance was set at $p < 0.05$.

### *Ethical Considerations*

This study was approved by the Tokushima University Hospital Ethics Board (No. 1671). Subjects were assured that their personal information would be protected and that the results of the study would only be reported as aggregate data and solely be used for research purposes. The purpose and procedure of this study were explained to all subjects, and informed consent was obtained.

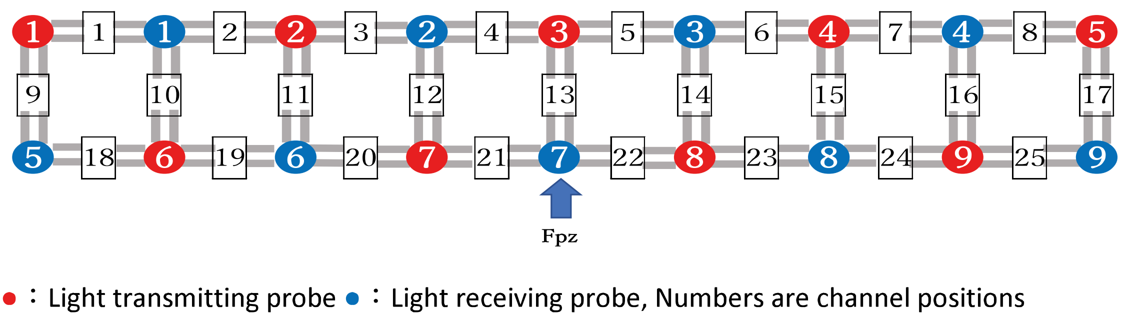
## RESULTS

The amount of change in oxy-Hb concentration in the left lateral prefrontal cortex (ch16) and right lateral prefrontal cortex (ch10) during silent and oral reading is shown in Table 1. Left-right differences in oxy-Hb concentration changes during silent and oral reading were examined. No left-right difference was observed during silent reading (Z = -0.316, p = 0.752). However, during oral reading, oxy-Hb concentration changes were significantly greater on the left side (Z = -3.322, p<.001).

Silent-oral reading differences in oxy-Hb concentration changes were also examined (Table 2). During oral reading, oxy-Hb concentration changes were significantly greater than those during silent reading in the left lateral prefrontal cortex (ch16) (Z = -3.589, p<.001). However, no silent-oral reading difference was observed in the right lateral prefrontal cortex (ch10) (Z = -1.479, p = 0.139).

The following are representative examples.

Figure 2 shows a trend graph of a person with difficulty in silent reading (Likert scale rating 1, very poor), showing an




*Left ch16 or right ch10 correspond to Broca's area, which is the motor center for speech.*

Fig 1. Arrangement of the light transmitting probes and light receiving probes

Table 1. Left-right Differences in Oxy-Hb Concentration Changes during Silent and Oral Reading (N = 40)

| | Mean (mMcm · sec) | Median (mMcm · sec) | SD | Z | p |
|---|---|---|---|---|---|
| Ch16 Left (Silent reading) | 0.98 | 0.69 | 1.15 | -0.316 | 0.752 |
| Ch10 Right (Silent reading) | 0.96 | 0.70 | 1.17 | | |
| Ch16 Left (Oral reading) | 1.76 | 1.19 | 1.67 | -3.322 | < .001 |
| Ch10 Right (Oral reading) | 1.30 | 1.08 | 1.35 | | |

Wilcoxon signed-rank sum test. SD = Standard Deviation.

Table 2. Differences in Left and Right Oxy-Hb Concentration Changes during Silent and Oral Reading (N = 40)

| | Mean (mMcm · sec) | Median (mMcm · sec) | SD | Z | p |
|---|---|---|---|---|---|
| Ch16 Left (Silent reading) | 0.98 | 0.69 | 1.15 | -3.589 | < .001 |
| Ch16 Left (Oral reading) | 1.76 | 1.19 | 1.67 | | |
| Ch10 Right (Silent reading) | 0.96 | 0.70 | 1.17 | -1.479 | 0.139 |
| Ch10 Right (Oral reading) | 1.30 | 1.08 | 1.35 | | |

Wilcoxon signed-rank sum test. SD = Standard Deviation.

increase in oxy-Hb concentration in the left and right lateral prefrontal cortex, centered on ch16 and ch10. The increase was slightly greater on the left side.

Figure 3 shows the trend graph of the person who demonstrated the most ease in silent reading (Likert scale rating 5, very good). No significant increase in oxy-Hb concentration was observed in the bilateral prefrontal cortex.

Figure 4 shows the trend graph of a person with difficulty in oral reading (Likert scale rating 1, very poor), in which the oxy-Hb concentration increased in the left and right lateral prefrontal cortex, mainly in ch16 and ch10. The increase was slightly greater on the left side.

Figure 5 shows the trend graph of a person who was very good (Likert scale rating 5, very good) at oral reading, in which no significant increase in oxy-Hb concentration was observed in the bilateral prefrontal cortex.

The relationship between the change in oxy-Hb concentration and silent reading speed in the left and right prefrontal lateral areas (ch16 and ch10) was examined (Fig.6). The changes in oxy-Hb concentration were significantly negatively correlated with silent reading speed in right channel 10 ($\rho$ = -0.77, $p < 0.001$) and left channel 16 ($\rho$ = -0.82, $p < 0.001$). However, no significant correlation was found with changes in oxy-Hb concentration and oral reading speed in right channel 10 ($\rho$ = -0.15, p = 0.37) and left channel 16 ($\rho$ = 0.05, p = 0.78) (Fig.7).

The relationship between reading speed during silent and oral reading and students' self-assessments of their silent and oral reading skills is shown in Figure 8. A significant correlation was found between reading speed and self-reported reading proficiency in silent reading ($\rho$ = 0.942, $p < 0.001$), whereas no significant correlation was found between reading speed and self-reported reading ability in oral reading ($\rho$ = 0.085, p = 0.06).

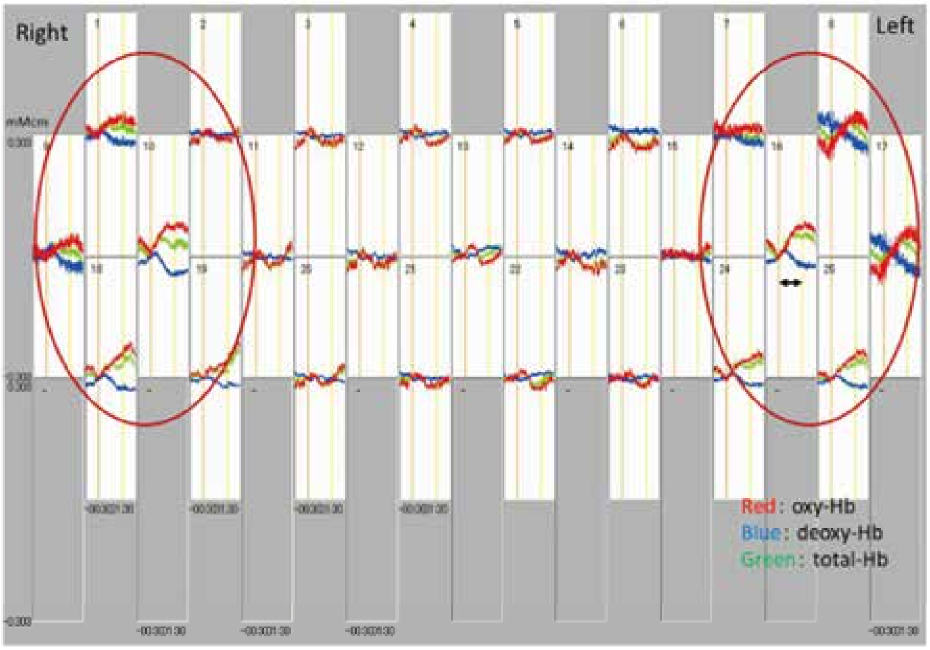
In self-reported reading ability, the values of oxy-Hb concentration changes in the right ch10 were significantly lower in those who rated their proficiency a 4—good (p = 0.004), and a 5—very good (p = 0.015) during silent reading, compared with those who rated it with a 1—very poor ($\chi^2$ = 26, $p < .001$). Also, in the left ch16, the values of oxy-Hb concentration changes were significantly lower in those who rated their proficiency a 4—good (p = 0.004) and a 5—very good (p = 0.015) during silent reading compared with those who rated it a 1—very poor ($\chi^2$= 29.1, $p < .001$) (Fig.9).

Meanwhile, the values of oxy-Hb concentration changes were significantly lower among those whose self-reported proficiency rating was 4—good (p = 0.016) during oral reading compared with those who rated it a 1—very poor ($\chi^2$= 22, $p < .001$) in the right ch10. The same trend in oxy-Hb changes was seen in the left ch16 among those who rated it a 4—good (p = 0.016) and a 5—very good (p=0.036) during oral reading compared with those whose rating was 1—very poor ($\chi^2$ = 21.0, $p < .001$) (Fig. 10).

## DISCUSSION

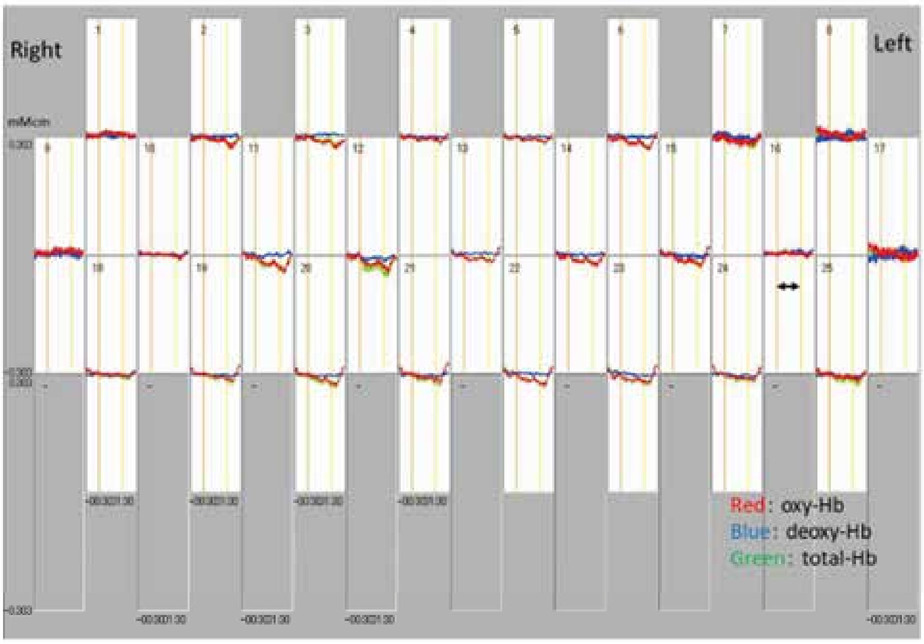
The characteristics of NIRS include the following : 1) It is non-invasive and is widely used in studies of brain function from neonates to schoolchildren (6-10) ; 2) High temporal resolution measurements can be made every 0.1 second, and changes in brain function can be observed over time by measuring oxy-Hb concentration and other parameters (8, 10) ; 3) The device is small and portable, allowing testing at any location, such as the bedside ; 4) The device does not interfere much with the subject's behavior, allowing measurement to be taken in a position similar to that observed in daily life, and is quiet. These features allow for the evaluation of brain function in children and the conduct of clinical research to elucidate the pathology of various neurodevelopmental disorders, such as autism spectrum disorder and attention-deficit/hyperactivity disorder, thus helping in the development of treatment methods (7, 8, 10).

Broca's area has a left-right localization and is generally left hemisphere dominant (12, 18). In this study, left lateral prefrontal cortex (ch16) activity was significantly greater during oral reading compared with the right side. There have been no previous reports comparing brain activity during oral and silent reading using NIRS. The activity in Broca's area, which is



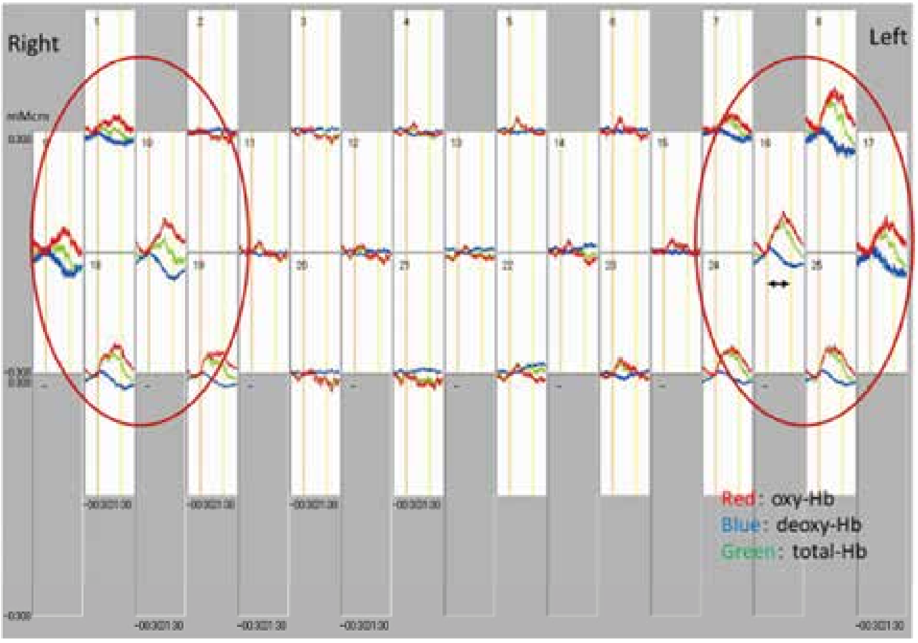

*The story was read silently for the time indicated by the ↔ symbol. Oxy-Hb levels were elevated in the left and right lateral prefrontal cortex, mainly in ch16 and ch10. The degree of increase was slightly greater on the left side.*

Fig 2. Trend graph during silent reading (Typical example of a person who had difficulty with silent reading)



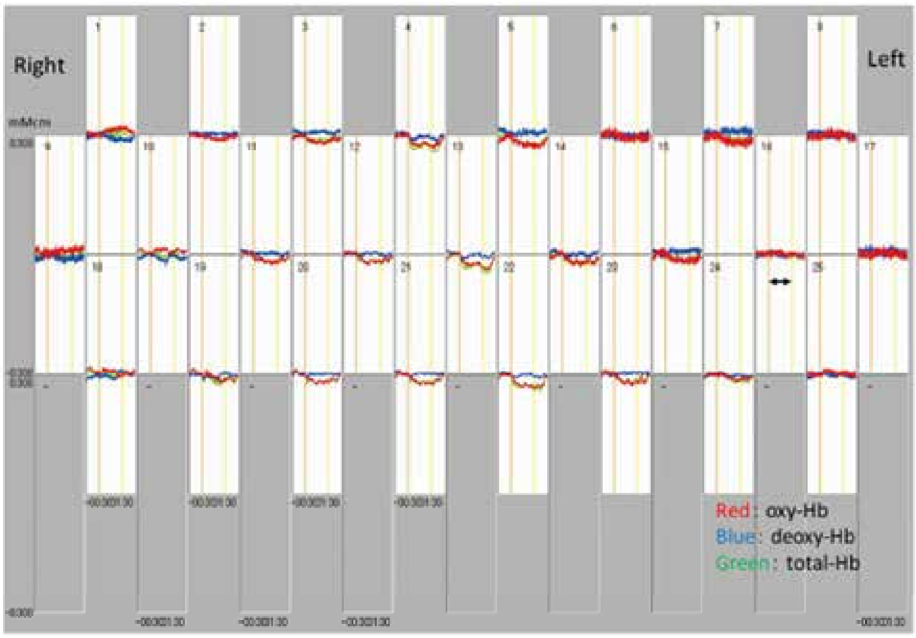

*The story was read silently for the time indicated by the ↔ symbol ; No significant increase in oxy-Hb concentration was observed in the bilateral prefrontal cortex.*

Fig 3. Trend graph during silent reading (Typical example of a person who demonstrated the most ease in silent reading)




*The story was read aloud for the time indicated by the ↔ symbol, and elevated levels of oxy-Hb were found in the left and right lateral prefrontal cortex, mainly in ch16 and ch10. The degree of increase was slightly greater on the left side.*

Fig 4. Trend graph during oral reading (Typical example of a person who had difficulty with oral reading)




*The story was read aloud for the time indicated by the ↔ symbol ; No significant increase in oxy-Hb concentration was observed in the bilateral prefrontal cortex.*

Fig 5. Trend graph during oral reading (Typical example of a person who was very good at oral reading)

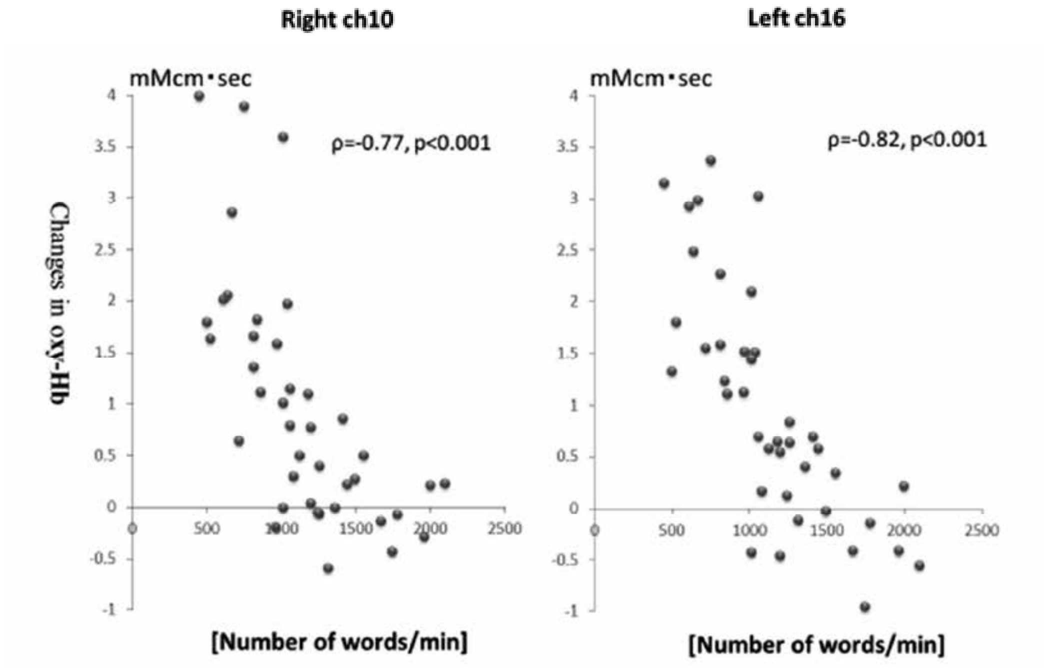



Fig 6. Correlation between the changes in oxy-Hb concentration and silent reading speed

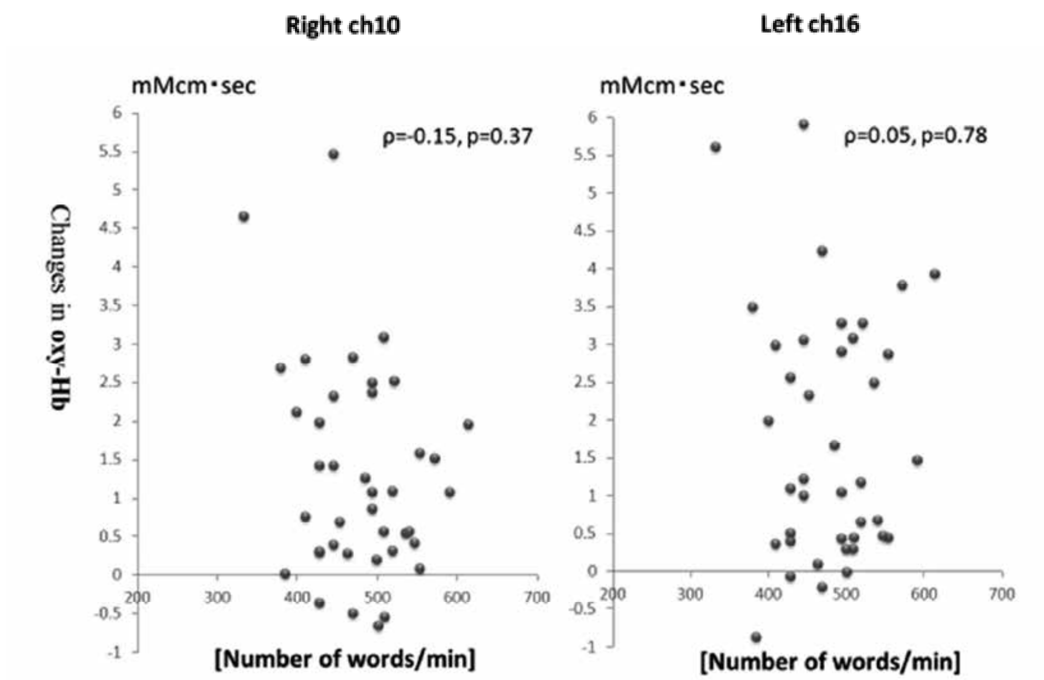
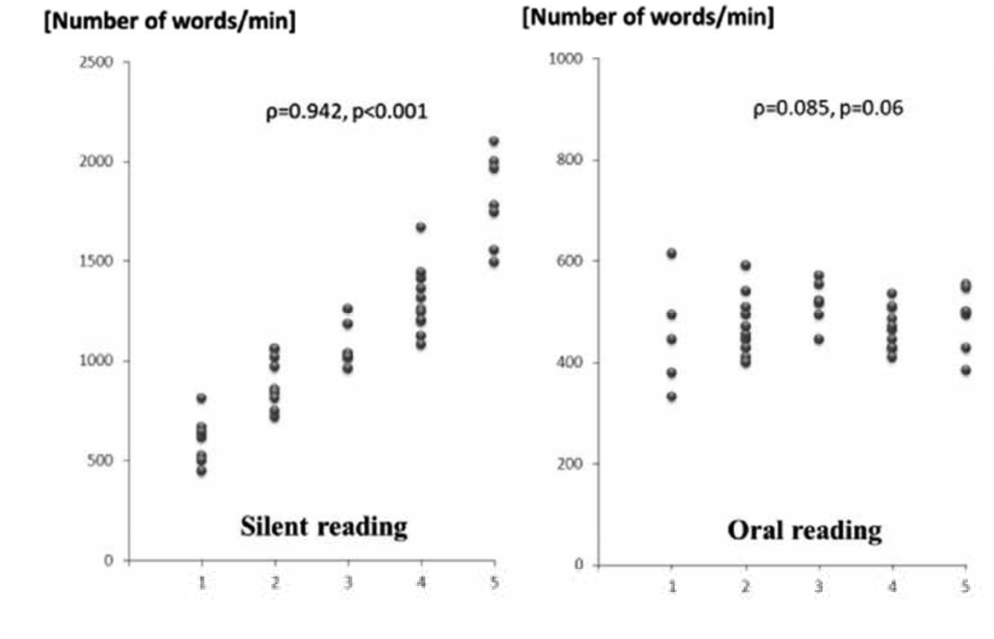
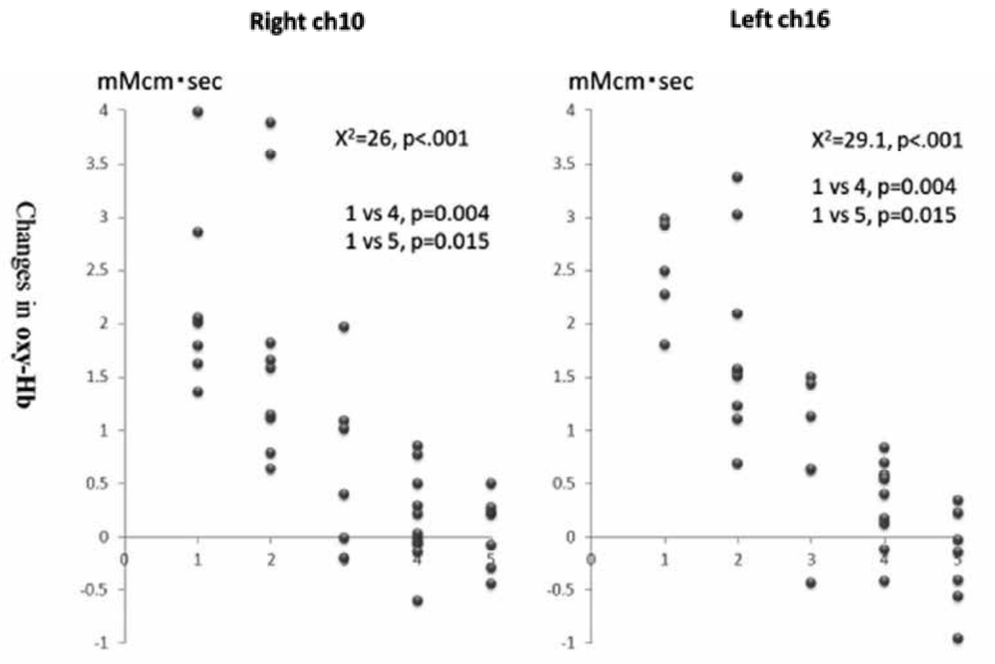



Fig 7. Correlation between changes in oxy-Hb concentration and oral reading speed



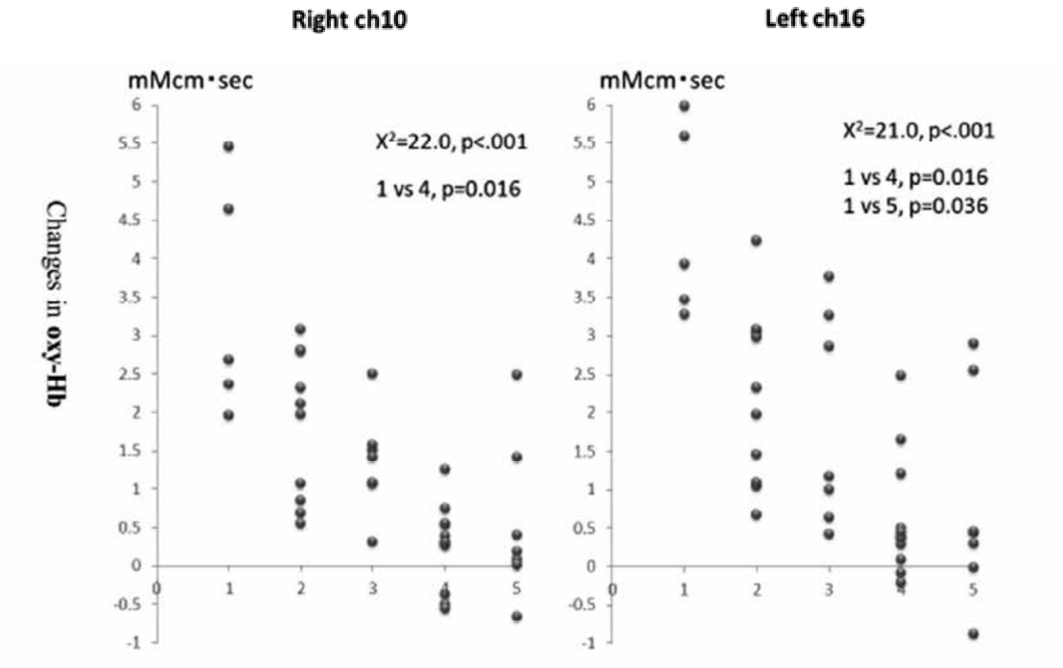

*Self-reported reading proficiency was rated on a 5-point Likert scale : 1 = very poor, 2 = poor, 3 = fair, 4 = good, and 5 = very good.*

Fig 8. Correlation between reading speed and self-reported reading ability




*Self-reported reading proficiency was rated on a 5-point Likert scale : 1 = very poor, 2 = poor, 3 = fair, 4 = good, 5 = very good.*

Fig 9. Relationship between changes in oxy-Hb concentration during silent reading and self-reported reading proficiency




*Self-reported reading proficiency was rated on a 5-point Likert scale : 1 = very poor, 2 = poor, 3 = fair, 4 = good, 5 = very good.*

Fig 10. Relationship between changes in oxy-Hb concentration during oral reading and self-reported reading proficiency

involved in articulation and pronunciation, would be expected to be less than that during oral reading because typically developing persons do not require vocalization during silent reading. In the present study, the amount of change in oxy-Hb concentration during silent reading was significantly lower in the left ch16 than during oral reading. In addition, no significant differences were observed between silent and oral reading in the right lateral prefrontal cortex (ch10). Thus, it was suggested that the NIRS-based oral reading task may be useful in determining the left and right localization of Broca's area.

Reading is known to involve the temporoparietal junction centered on the angular gyrus and inferior parietal lobule, the left occipitotemporal gyrus centered on the fusiform gyrus, and the left lateral prefrontal cortex (Broca's area) (2). The left temporoparietal junction is involved in phonological processing/decoding. The left inferior occipitotemporal gyrus is called the *visual word form area*, and is involved in the identification of written words. The motor center for speech (Broca's area), located in the left lateral prefrontal cortex, is thought to be involved in phonological processing/decoding as well as vocalization and grammatical processing (2).

Shaywitz conducted functional magnetic resonance imaging (fMRI) studies on children with and without developmental dyslexia and reported that the left temporoparietal region is activated in the early stages of reading, whereas the left occipitotemporal gyrus is more activated in proficient readers (2, 19). This suggests that the left temporoparietal region is involved in early reading when decoding letters one by one, while the left occipitotemporal gyrus is involved in skilled reading (chunking) when reading words as a coherent group (2, 18). In children with developmental dyslexia, the left temporoparietal junction and left occipitotemporal gyrus were less active than those in children without developmental dyslexia. In contrast, children with developmental dyslexia had a more active left lateral prefrontal cortex (Broca's area) during silent/oral reading. Broca's area showed greater activity in older children with developmental dyslexia and was considered a compensatory pathway supporting effortful reading (2, 19). In Japanese children with developmental dyslexia, similar findings have been reported in a hiragana reading task after fMRI testing (20, 21).

In our study, we found a positive and significant correlation between silent reading speed and self-reported reading proficiency. Silent reading speed varies widely among individuals and is thought to reflect every individual's reading ability. A significant negative correlation was found between the change in oxy-Hb concentration in the left and right lateral prefrontal cortex (ch16 and ch10) during silent reading and the silent reading speed. Furthermore, students with lower self-reported reading proficiency had significantly greater changes in oxy-Hb concentrations in the left and right lateral prefrontal cortex (ch16, ch10) during silent reading than did students with higher self-reported reading proficiency. The increase in oxy-Hb concentration in the left or right lateral prefrontal cortex during silent reading may reflect effortful reading in students with reading difficulties.

There were few individual differences in oral reading speed, and no correlation was found between the change in oxy-Hb concentration in the left and right lateral prefrontal cortex (ch16, ch10) during oral reading and oral reading speed (letters/minute). However, students with lower self-reported reading proficiency had significantly greater changes in oxy-Hb concentrations in the left and right lateral prefrontal cortex (ch16, ch10) during oral reading than did students with higher self-reported reading proficiency. Thus, the increase in oxy-Hb concentration in the left or right lateral prefrontal cortex observed during oral reading may also reflect effortful reading in students who are poor readers.

NIRS is a non-invasive test that is relatively easy to perform and can be repeated in children. The results of this study suggest that NIRS is useful for evaluating reading function and can be used to aid in the diagnosis of developmental dyslexia in children. In the future, it would be worthwhile to compare brain responses during reading activities in children with developmental dyslexia and typically developing children using NIRS. In addition, it has been reported that brain activity improves when children with developmental dyslexia receive appropriate training from an early age (22). It is expected that NIRS will be used to develop effective training methods.

*Limitations*

More attention is being paid to the left occipitotemporal involvement in developmental dyslexia. Recent brain imaging studies have revealed that many abnormalities in that area have affected axonal directional heterogeneity and reduced activity in word recognition tasks (23-25). In addition, excessive gyrus formation in the auditory cortex of the left temporal lobe and aberrant downstream connectivity have been reported in children with dyslexia (26), suggesting that atypical maturation of the language network is involved in the development of dyslexia (26).

In this study, a significant correlation was found between reading speed and self-reported reading ability in silent reading, whereas no significant correlation was found between reading speed and self-reported reading ability in oral reading. Silent reading speed is considered an objective indicator of silent reading ability ; however, there is no appropriate objective indicator that reflects the ability to read aloud. In future studies, it will be necessary to develop objective indicators that reflect oral reading ability.

Moreover, future studies using NIRS are needed to examine brain activity in regions that include the temporal lobe in healthy children and those with dyslexia. Moreover, NIRS has the disadvantage that it only measures surface brain activity from above the scalp and does not measure activity in basal or deep brain regions. To compensate for this disadvantage, we still need to consider fMRI evaluation in parallel.

## CONCLUSIONS

Evaluation of the reading task by NIRS may be useful for determining the left and right localization of Broca's area. Furthermore, elevated levels of oxy-Hb in the left and right lateral prefrontal cortex during silent and oral reading may reflect effortful reading in struggling readers. The results demonstrate that NIRS is useful for assessing reading function and may be used to diagnose developmental dyslexia in children.

## CONFLICT OF INTEREST STATEMENT FOR ALL AUTHORS

There are no conflicts of interest to declare.

## ACKNOWLEDGMENTS

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