ORIGINAL

Hemodynamics of the left cerebral hemisphere during silent reading : analysis using near-infrared spectroscopy

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Abstract : The purpose of this study was to investigate the hemodynamic activity in the left cerebral hemisphere during silent reading in college students with typical development using near-infrared spectroscopy (NIRS). Sixty college students with typical development participated in this study. In the silent reading task, participants were asked to read a text from Andersen's fairy tale. Then, the change in oxygenated hemoglobin (oxy-Hb) concentration during silent reading of the text was calculated. The number of letters read during the silent reading task was also measured to calculate the silent reading speed. The average trend graph of 60 college students revealed increased oxy-Hb concentration in both the left inferior frontal gyrus (Broca's area) and the left inferior occipitotemporal gyrus during silent reading. A negative correlation was found between the change in oxy-Hb concentration in Broca's area and silent reading speed. A positive correlation was found between oxy-Hb concentration change in the left inferior occipitotemporal gyrus and silent reading speed. The increase in oxy-Hb concentration in Broca's area observed during silent reading may reflect effortful reading in students with reading difficulty. The increase in oxy-Hb concentration in the left inferior occipitotemporal gyrus observed during silent reading may reflect proficiency in reading. Our findings suggest the usefulness of NIRS in assessing reading function and its potential use in the diagnosis of developmental dyslexia. J. Med. Invest. 71 : 267-272, August, 2024

Keywords : *near-infrared spectroscopy (NIRS), left hemisphere, silent reading, developmental dyslexia*

INTRODUCTION

Developmental dyslexia is the core disorder of learning disabilities (1, 2). According to the American Psychiatric Association's DSM-5 classification, developmental dyslexia is classified as a reading disorder within the category of specific learning disorder (1). Individuals with developmental dyslexia face significant challenges in reading letters, despite having average or above-average intelligence, which can interfere with their academic progress.

The underlying mechanism of this disorder is that individuals with developmental dyslexia struggle to automatically link letters to their corresponding sounds (3). This impairment stems from deficits in phonological processing, the ability to recognize and manipulate the sounds that make up words. As a result, individuals with developmental dyslexia have difficulty in decoding, thus investing significant effort and time to recall the sounds of letters. This extends to processing larger units like words and phrases (i.e. chunking), leading them to rely on a character-by-character reading approach.

Several brain regions are known to be critical for reading, including the left temporoparietal junction (centered on the supramarginal gyrus and the angular gyrus), the left inferior occipitotemporal gyrus (centered on the fusiform gyrus), and the left inferior frontal gyrus (3) (Fig. 1). Among these, the left temporoparietal junction plays a key role in phonological processing and decoding written words, while the left inferior occipitotemporal gyrus, also known as the visual word form area, is essential for word-form recognition. The motor language area (Broca's area) in the left inferior frontal gyrus is thought to play a supportive role in phonological processing and decoding, alongside its role in speech and grammatical processing (3).

To gain initial insights into the pathology of developmental dyslexia, we used near-infrared spectroscopy (NIRS) to analyze hemodynamic activity in the left cerebral hemisphere of college students with typical development during silent reading. This investigation aimed to explore the association between reading speed and hemodynamic activity in the left cerebral hemisphere.

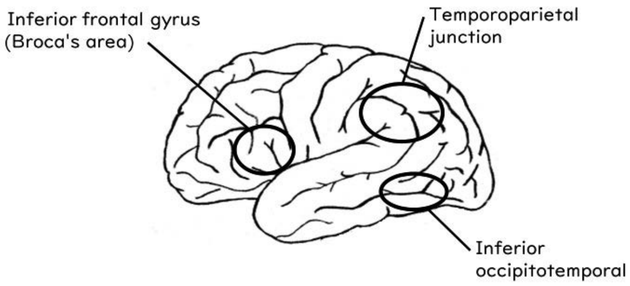

Fig. 1. Neural systems for reading

SUBJECTS AND METHODS

Sixty college students (30 men, 30 women) with typical development participated in this study. Their average age was 20.5 ± 1.8 years, and all were right-handed. NIRS data collection occurred between July 2022 and March 2024.

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A 24-channel NIRS probe (Hitachi Medical Corporation, ETG-4000) was positioned over the left cerebral hemisphere, maintaining a 3 cm source-detector separation, with the lowest center position at T3, maintaining a 6 cm separation between probe 12 and probe 16, as illustrated in Figure 2. In the silent reading task, participants were asked to read a text from Andersen's fairy tale silently for 60 seconds. The text included both kanji and kana characters, with ruby annotations providing pronunciation guidance for all kanji characters. Before each reading task, participants completed a 60-second rest task where they silently repeated the vowels 'A-I-U-E-O.' The silent reading task and rest task were performed twice in total. To calculate changes in oxygenated hemoglobin (oxy-Hb) concentration during the silent reading task, the data from both silent reading trials were combined and averaged to obtain an additive mean waveform. Participants were instructed to read silently and accurately at their usual reading pace. Silent reading speed (letters/min) was calculated based on the number of letters read during the task.

This study was approved by the Ethics Review Committee for Life Science and Medical Research at the University of Tokushima Hospital (Approval number : 1671). All participants were informed about the purpose and methods of the study, and their written consent was obtained.

STATISTICAL ANALYSIS

Differences between men and women in silent reading speed and the change in oxy-Hb concentration were analysed using the Mann-Whitney test. The correlation between silent reading speed and the change in oxy-Hb concentration was assessed using Spearman's rank correlation coefficient. Statistical analysis was performed with IBM SPSS Statistics for Windows (version 21.0 ; Armonk, NY : IBM Corp.). The significance level was set at $p < 0.05$.

RESULTS

No gender differences were found in silent reading speed or the change in oxy-Hb concentration. The maximum silent reading speed was 1240 letters/min and the minimum silent reading speed was 253 letters/min (median : 596 letters/min). The gender ratio of the 30 participants whose reading speed was faster than the median was 14 males : 16 females. The gender ratio of the 30 participants whose reading speed was slower than the median was 16 males : 14 females.

With probe placement as shown in Figure 2, ch-13, ch-14 and ch-16 are likely to correspond to the left inferior frontal gyrus (Broca's area), while ch-1 is likely to correspond to the left inferior occipitotemporal gyrus (4). Averaging NIRS trend graphs of all 60 participants during silent reading showed increased oxy-Hb concentration in the Broca's area (ch-13, ch-14 and ch-16) and the left inferior occipitotemporal gyrus (ch1), as illustrated in Figure 3.

Figures 4 and 5 illustrate typical trends in oxy-Hb concentration for participants with slow and fast silent reading speeds, respectively. The student with a slow reading speed (281 letters/min) exhibited a marked increase in oxy-Hb concentration in the left inferior frontal gyrus (Broca's area) during silent reading, with minimal increase in the left inferior occipitotemporal gyrus (ch-1). Conversely, the student with a fast reading speed (1118 letters/min) showed an increase in oxy-Hb concentration in the left inferior occipitotemporal gyrus (ch-1), while the increase in the left inferior frontal gyrus (Broca's area) was minimal.

A negative correlation was observed between the change in oxy-Hb concentration in the Broca's area (ch-13) and the reading speed during silent reading (ρ=-0.51, $p<0.001$). Similar findings were observed in ch-14 and ch-16 (ch-14 : ρ=-0.41, $p<0.01$, ch-16 : ρ=-0.43, $p<0.01$)(Fig. 6). This indicates that slower reading speeds were associated with a greater increase in oxy-Hb concentration in Broca's area during silent reading. In contrast, a positive correlation was observed between the change in

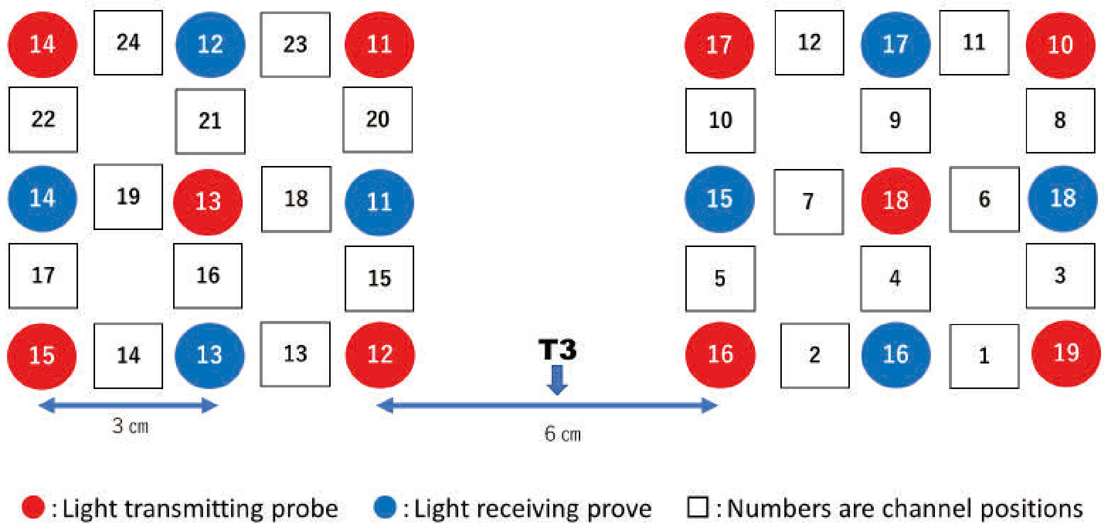

Fig. 2. Arrangement of the light transmitting probes and light receiving probes
Ch-13, ch-14 and ch-16 are likely to correspond to the left inferior frontal gyrus (Broca's area), while ch-1 is likely to correspond to the left inferior occipitotemporal gyrus.

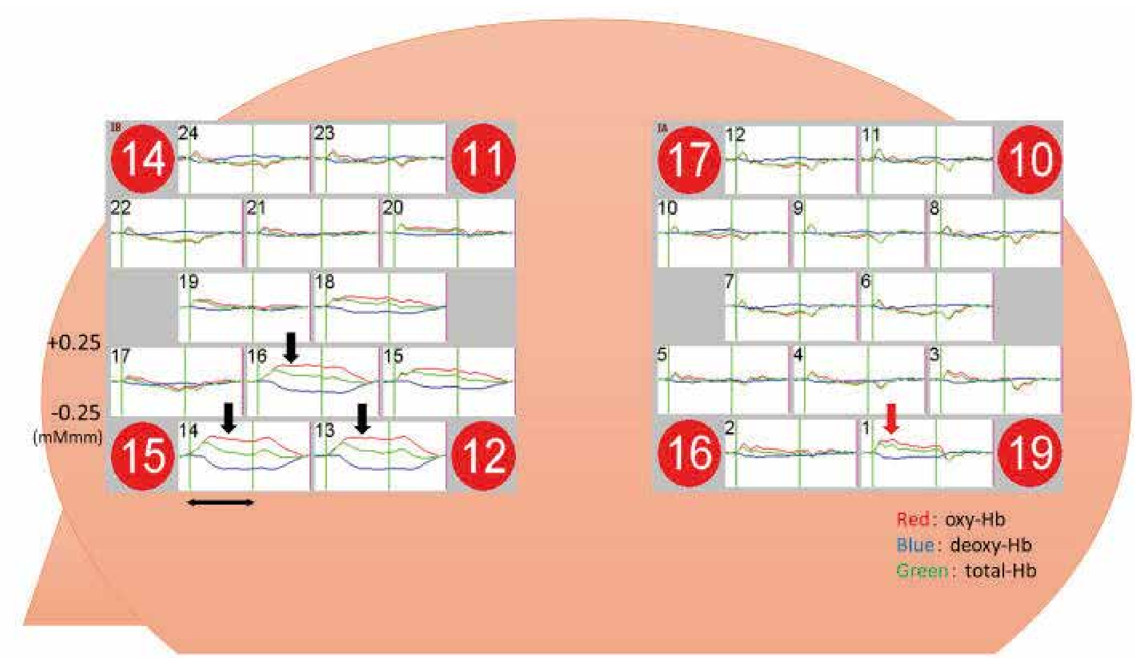

Fig. 3. Averaging NIRS trend graphs of all 60 participants during silent reading
In lateral view, the probes were attached to the left cerebral hemisphere. The story was read silently for the time indicated by the ↔ symbol. Elevated levels of oxy-Hb concentration in the Broca's area (ch-13, ch-14 and ch-16 : ↓) and the left inferior occipitotemporal gyrus (ch1 : ↓) were observed.

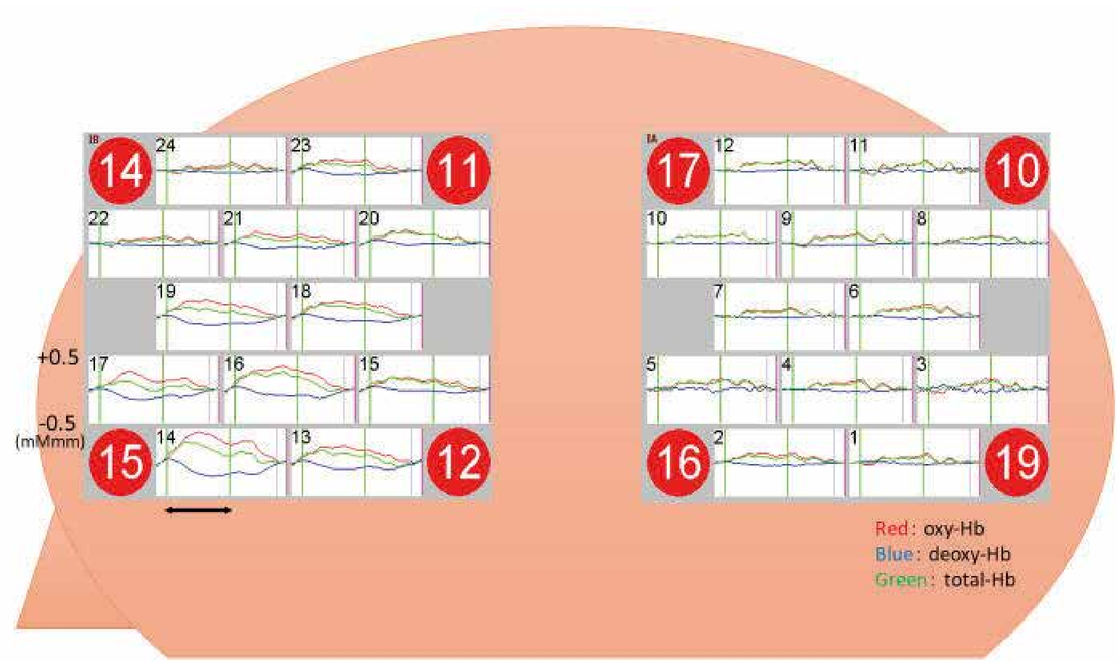

Fig. 4. Trend graph during silent reading (Typical example of a person who demonstrated a slow reading speed)
In lateral view, the probes were attached to the left cerebral hemisphere. The story was read silently for the time indicated by the ↔ symbol. Marked increase in oxy-Hb concentration in the Broca's area was observed, with minimal increase in the left inferior occipitotemporal gyrus (ch-1).

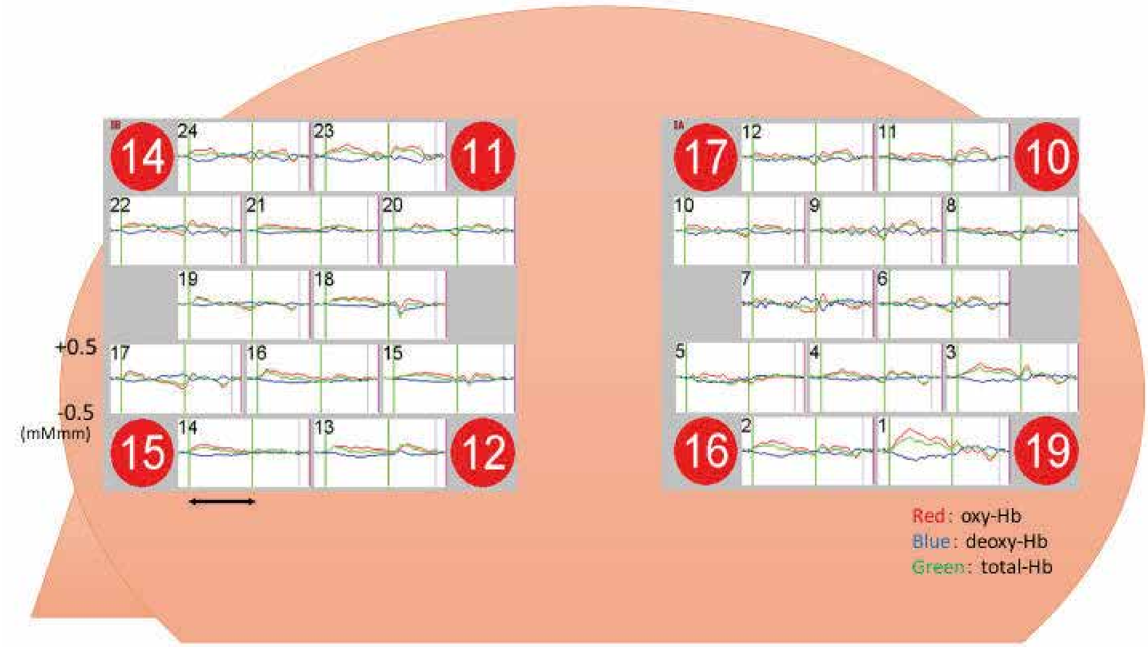

Fig. 5. Trend graph during silent reading (Typical example of a person who demonstrated a fast reading speed)
In lateral view, the probes were attached to the left cerebral hemisphere. The story was read silently for the time indicated by the ↔ symbol. Marked increase in oxy-Hb concentration in the left inferior occipitotemporal gyrus (ch-1) was observed, while the increase in the Broca's area was minimal.

oxy-Hb concentration in the left inferior occipitotemporal gyrus (ch1) and reading speed during silent reading ($\rho=0.46$, $p<0.001$) (Fig. 7). In the more posterior ch3, the correlation between the change in oxy-Hb concentration and reading speed was weak ($\rho=0.28$, $p<0.05$) (Fig. 7).

DISCUSSION

A number of studies have been conducted using functional MRI with the aim of elucidating the pathophysiology of developmental dyslexia (5-13). Shaywitz *et al*. used functional MRI to study brain activity in children with and without dyslexia (14). Their findings revealed greater activation in the left temporoparietal region during the early stages of reading, while the left inferior occipitotemporal gyrus was more active in proficient readers. Based on this, they hypothesized that the left parietotemporal region plays a role in early reading stages of phonological processing, where letters are decoded one by one, while the left inferior occipitotemporal gyrus likely becomes more active during proficient reading (chunking), when words are recognized as whole units. In contrast, children with dyslexia exhibited less activity in the left parietotemporal junction and the left inferior occipitotemporal gyrus compared to those without dyslexia. Interestingly, the left inferior frontal gyrus and the right hemisphere showed increased activity in older dyslexic children, suggesting that these regions may represent compensatory pathways to support effortful reading (14).

Our study revealed a negative correlation between the change in oxy-Hb concentration in the left inferior frontal gyrus (Broca's area) and the reading speed during silent reading (letters/min). The increase in oxy-Hb concentration in the left inferior frontal gyrus (Broca's area) observed during silent reading may reflect effortful reading in students with reading difficulty.

In the early stages of reading, as discussed earlier, they primarily use the left temporoparietal region for decoding individual letters. As they get used to it, the left inferior occipitotemporal gyrus (visual word form area) becomes more active, allowing them to recognize words and phrases as whole units (chunking), which eventually enables them to read accurately and quickly. Shaywitz *et al*. used functional MRI to show strong activation in the left inferior occipitotemporal gyrus of proficient readers (14). Our NIRS study replicated this finding, revealing activity in the same brain region. Furthermore, we observed a positive correlation between the change in oxy-Hb concentration in the left inferior occipitotemporal gyrus and the speed of silent reading. These findings suggest that the increase in oxy-Hb concentration in this region during silent reading may reflect proficiency in reading.

Our findings suggest the usefulness of NIRS in assessing reading function and its potential use in the diagnosis of developmental dyslexia. It has been reported that appropriate training improves brain activity in children with dyslexia (15, 16). Notably, NIRS offers several advantages : it is minimally invasive, relatively easy to administer, and suitable for repeated use in children. Future research using repeated NIRS measurements could provide valuable insights into the relationship between the temporal development of children's reading skills and cerebral hemodynamics. Additionally, NIRS holds promise for the development of effective training methods for developmental dyslexia.

LIMITATION OF THE PRESENT STUDY

Women are considered to be better than men on issues related to language skills (17, 18). Developmental dyslexia is also more common in men than in women (1). In the present study, no gender differences were found in reading speed or NIRS findings.

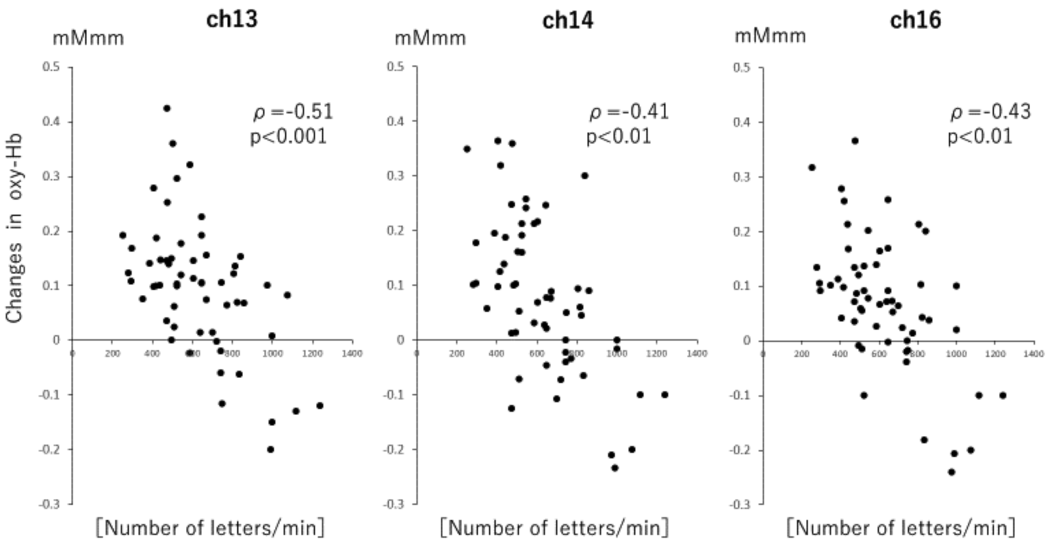

Fig. 6. Correlation between the changes in oxy-Hb concentration and silent reading speed in the left inferior frontal gyrus (Broca's area)

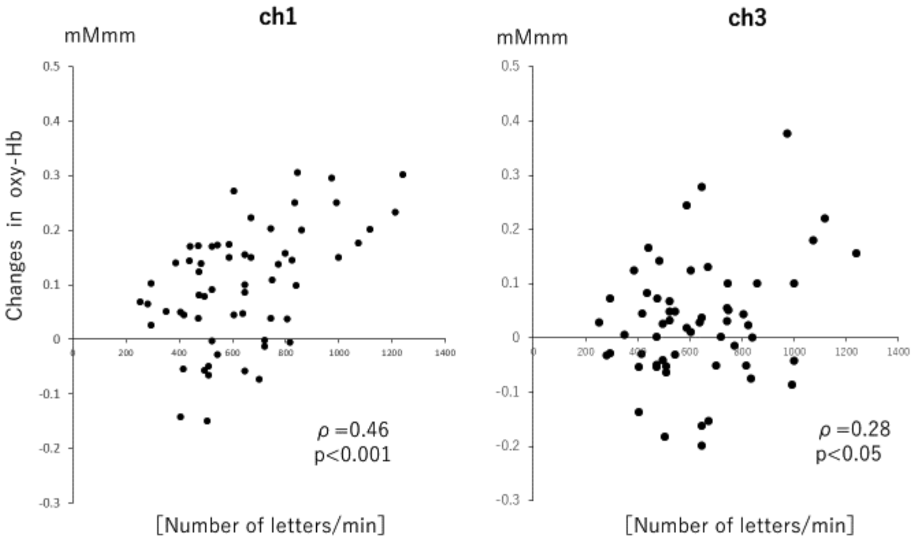

Fig. 7. Correlation between the changes in oxy-Hb concentration and silent reading speed in the left inferior occipitotemporal gyrus (ch-1) and ch-3

This may be due to the fact that the subject of this study was university students who had been selected and enrolled through a common examination. It is considered necessary to invite more members of the public to participate in future studies to examine gender differences in reading ability and brain responses during reading activities.

Decoding accuracy and reading speed or fluency are considered important in the diagnosis of developmental dyslexia (1). In the present study, the focus was also on reading speed. However, future research needs to be designed to include assessment of reading comprehension as well, because impaired reading comprehension is also an important symptom of learning disability.

NIRS is used to measure only activity of the brain surface through the scalp, thus limiting its ability to measure activity at the base of the brain or in the deeper brain regions. Therefore, NIRS cannot accurately assess activity in the medial part of the occipitotemporal gyrus (fusiform gyrus) that plays a central role as a visual word form area. To address this, we recommend considering complementary functional MRI evaluations for a more comprehensive picture of brain activity.

CONFLICT OF INTEREST STATEMENT FOR ALL AUTHORS

There are no conflicts of interest to declare.

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