Enhanced Visual Form and Visuo-Spatial Processes in Japanese Speed-Reading Experts:
A Preliminary Analysis

Hiromitsu Miyata[1, 2*], Shigeru Watanabe[3], Kazuhiro Ueda[4],
Toyofumi Sasaki[5], Yasuyo Minagawa[3]

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[Author Affiliation]
1. Japan Society for the Promotion of Science; 2. Graduate School of Human Relations, Keio University; 3. Faculty of Letters, Keio University; 4. Graduate School of Arts and Sciences, The University of Tokyo; 5. NBS Japan Society of Speed Reading Education. *Present Affiliation: Japan Institute of Lifelong Learning; Human Innovation Research Center, Aoyama Gakuin University

[Contact]
Hiromitsu Miyata
Japan Institute of Lifelong Learning
1-20-10 Nishi-shimbashi, Minato-ku, Tokyo 105-0003, JAPAN
miyatahiromitsu1981@gmail.com

日本認知科学会
事務局
〒464-8601 愛知県名古屋市千種区不老町
名古屋大学 大学院教育発達科学研究科内
Tel / Fax: 052-789-2654
jcss@jcss.gr.jp

Abstract

Studies on reading have suggested involvement of multiple neurocognitive processes. It is a challenge to elucidate how such processes may change through training to achieve extraordinary cognitive performance such as speed-reading. The Park-Sasaki method of speed-reading involves systematic visual training that is based on meditative techniques. Experts in this method reportedly can read Japanese sentences faster than 10,000 characters per minute with comprehension. The present study examined cerebral hemodynamic responses (near-infrared spectroscopy) of 16 Park-Sasaki speed-reading experts and 18 untrained adults while they rapidly read Japanese contemporary novels on a computer screen and looked at figures composed of meaningless symbols on a computer screen (control). In addition to enhanced activities in bilateral occipital areas responsible for visual information processing, speed-readers showed significant increase in oxygenated hemoglobin changes (1) around left middle/inferior occipital/temporal areas and (2) around right middle/inferior parietal areas when speed-reading sentences. The former (1) suggested relatively enhanced visual form processes and use of neural pathways typically used to read kanji, and the latter (2) confirmed enhanced visuo-spatial processes associated with speed-reading. Untrained participants showed less apparent hemodynamic changes observed in the bilateral occipital areas and around left middle/inferior occipital/temporal areas when reading sentences, which suggested use of visual form processes. In addition, eye-tracking data confirmed that speed-readers used horizontal eye movements during measurement, in the same ways as they do in the training.

Keywords: speed-reading (速読), visual form processes (視覚形態処理), visuo-spatial processes (視空間的処理), hemodynamic changes (血行動態変化), eye movements (眼球運動)

1. Introduction

Behavioral and neuroimaging studies have suggested involvement of multiple neurocognitive processes associated with reading (for an overview see Dehaene, 2009; Wolf, 2008). When reading characters and words, visual form processes start around 100 milliseconds, followed by phonological and semantic processes from around 200 milliseconds. Syntactic processes are also involved when reading sentences (Fujimaki et al., 1999). In addition, regarding reading of Japanese, the dual route hypothesis proposes that two neural pathways for processing characters are present (Iwata, 1984; Kawamura, 2007; Sakurai, 2007). One is a dorsal pathway for processing kana, a kind of phonogram, which involves brain regions around the left angular gyrus. The other is a ventral pathway for processing kanji, a kind of morphogram, which involves areas around the posterior part of the left inferior temporal cortex. Behavioral data suggested that kanji is processed more quickly than kana (Kato et al., 2008).

Whereas ordinary reading speeds of Japanese adults are around 500 to 700 characters per minute, trained speed readers are reportedly capable of reading more than 10,000 characters per minute while maintaining comprehension (Miyata et al., 2012). Elucidating how processes involved in normal reading may change through training to achieve such extraordinary performance should be quite beneficial in terms of understanding potentials of humans' cognitive plasticity.

A number of speed-reading methods are present both in the West and in Japan; however, psychologists in the West have often regarded speed-reading as at most a form of skimming processes and expressed critical perspectives on their efficacy (Carver, 1990; Just & Carpenter, 1987; McNamara, 2001). In Japan, different speed-reading methods including the Kim method and PhotoReading are present, although little empirical data have been obtained to show their efficacy (Miyata, 2016). The present study included experts of the Park-Sasaki method of speed-reading, which originated in Korea and has been developed in Japan (Sasaki, 1995; Sasaki & Park, 1986). The method involves organized visual training to widen effective visual field, and to smoothly shift attentional focus from one point to another while being instructed not to feel one's own eye movements. All training stages are based on the use of meditative techniques such as *tanden kokyu*, breathing using the inner part of the lower abdomen, progressive muscle relaxation, as well as developing a good sitting posture to form a relaxed and concentrated state of mind. Because contemplative training has been suggested to enhance cognitive processes including attention and inhibition (e.g., Slagter et al., 2011), studying mechanisms of the Park-Sasaki method is interesting in that we can address how higher cognitive processes such as reading may transform as a result of meditation-based training.

Psychophysical and neural correlates of the Park-Sasaki method of speed-reading have been investigated over the past few decades. Some earlier studies using electroencephalogram (EEG) suggested use of fewer phonological processes and employment of visual images in speed-reading (Kawano & Sasaki, 2005; Yokoyama, 1992). Consistent data have been obtained using functional magnetic resonance imaging (fMRI) (Fujimaki et al., 2004; 2009). Fujimaki et al. (2009) showed reduced activity in language-related brain regions during speed-reading, suggesting use of fewer phonological processes, and increased activity in the right intraparietal sulcus, suggesting enhanced visuo-spatial processes. Kato et al. (2005) showed that speed-readers performed better at visual search tasks than untrained participants. Miyata et al. (2012) reported that an advanced speed-reader read Japanese novels 4.7 times faster than untrained individuals, but had similar accuracy on true or false content-related questions after reading through each story once.

These data obtained so far support the notion that speed-reading is made by bypassing phonological processes used in normal reading, while semantic and syntactic processes are maintained to comprehend the text. We could thus hypothesize that visual form processes that start most quickly directly connect to semantic and syntactic processes in speed-reading. In normal reading, visual form processes are suggested to be localized near the left inferior occipital/temporal cortices (Fujimaki et al., 1999), even though Fujimaki et al. (1999) did not involve trainees of speed-reading in their enquiry. Based on these previous findings, we could predict that enhanced activities may be observed around the left inferior occipital/temporal areas while speed-reading as compared with normal reading. Enhanced activities in these areas also seem relevant in relation to the dual route hypothesis; given that kanji is processed more quickly than kana, speed-readers may not use pathways for processing kana but may instead use pathways typically used for processing kanji even when reading the mixture of kanji and kana.

In addition, previous studies on the Park-Sasaki method concur that speed-reading is associated with enhanced visuo-spatial processes, which are necessary in order to follow all the characters at a high speed by using specific eye movement strategies acquired through training. Assuming employment of enhanced visuo-spatial processes while simultaneously using visual form processes and kanji-reading pathways, brain areas used for spatial attention such as the right parietal cortex should be activated while speed-reading as well.

Accordingly, the present study primarily aimed to find enhanced activities near left inferior occipital/temporal areas while speed-reading as compared to normal reading. It also predicted that enhanced activities in areas associated with visuo-spatial processing (i.e., right parietal areas) would be confirmed when speed-reading. Cortical activities in bilateral occipital, parietal, and temporal areas were measured using near-infrared spectroscopy (NIRS). With NIRS, it is possible to examine cerebral hemodynamic responses while participants sit in a posture similar to those during normal reading and training in speed-reading. This is a critical advantage because development of a good sitting posture is a crucial part of the Park-Sasaki method to form a desirable mental state (Miyata, 2016). The NIRS data should much better reflect brain activities during speed-reading as compared with the fMRI data (Fujimaki et al., 2004; 2009), because the fMRI unnaturally forces participants to lie down with no body movements and experts naïve to the study could not sufficiently demonstrate their capabilities during measurement. Specifically, Fujimaki et al. (2009) failed to find significant differences in the cortical activations (fMRI) in the left ventral occipital/temporal areas between the speed-reading trainees and untrained readers. The present study expected to obtain more convincing evidence regarding our primary hypothesis, thanks to the use of the NIRS. In addition, eye movement recording was concurrently made in order to confirm that the trained eye movement strategies were used during the NIRS measurement.

2. Methods

2.1 Participants

Thirty-four Japanese healthy adults participated in this study. Sixteen participants (nine females and seven males; age 21–69 years; mean age = 44.8 years; *SD* = 12.2) were experts of the Park-Sasaki method of speed-reading and had participated in the training course for a mean duration of 7.7 years (*SD* = 3.9). The other 18 participants (12 females and six males; age 18–55 years; mean age = 24.8 years; *SD* = 11.9) were either university students or company workers with no training in speed-reading. The Edinburgh Handedness Inventory (Oldfield, 1971) indicated that all were right-handed except that one speed-reader was left-handed and another speed-reader was mixed-handed, and one untrained participant was left-handed. Non-right-handed participants were included in the analysis because their data were consistent with trends observed in the other participants of each group. All participants had normal or corrected-to-normal vision. The Ethics Committee of Keio University approved this study (No. 10013) and all participants gave written informed consent to participate.

2.2 Settings

The experiment took place in a dimly lit, sound-attenuated room. The participants sat in a height-adjustable chair with good posture. A 58-cm (23.0 inch) TFT LCD monitor (FlexScan EV2333W, EIZO, Ishikawa, Japan) was located on a table 57 cm in front of the participant. A response device created by removing unnecessary keys from a numerical keypad (TK-UFHBK, ELECOM, Osaka, Japan) was placed on the participants' thigh. Pressing a button on the keypad corresponded to clicking a mouse button. NIRS recording and eye-tracking were concurrently conducted during the test.

2.3 Materials

The task consisted of sentence blocks and control blocks, written in Microsoft Visual Basic 6.0. A story for each sentence block was selected from a series of Japanese novels (*99-no-namida* [99 tears] by Linda Publishers Co., Ltd., Tokyo, Japan) published between 2008 and 2010 (e.g., Komatsu, 2010). The stories were 7,086–9,707 characters long (mean 9,016 characters). All stories involved relatively easy content about ordinary people and everyday events. All participants declared that they had not previously read these stories. The text appeared at the center of the monitor within an area 20 cm wide and 14 cm high. The display contained an average of 385 characters, in 20 lines (one 'page'). The sentences used a combination of kanji, hiragana, and katakana, and were arranged in a vertical direction from up to down and subsequently from right to left. Each story corresponded to 19–25 pages on the monitor. For the control block, a stimulus composed of circles and arrows appeared in the same area in the center of the monitor. During the instructions of the procedure, another well-known novel, *Hashire Melos* (Run, Melos!) by Osamu Dazai (9,795 characters long), was used.

2.4 Procedure

Before the testing, all participants were instructed to be prepared to maintain relaxed and concentrate state of mind during recording, as in the speed-reading training. Control blocks and sentence blocks, each 40 s long, alternatively appeared five times within the test session. Rest phases were inserted for 30 s in between blocks and at the beginning and the end of the session. The duration of the test session was therefore 12 min and 10 s. NIRS recording and eye-tracking were performed throughout the test session. During the sentence blocks, participants were instructed to read the text presented on the display as quickly as possible while being able to comprehend the story. Each block started with the beginning of a story. After reading through each page once, participants pressed a button to switch the display to the next page. During the control blocks, participants were instructed to look at the circles and arrows in order, using a strategy comparable to that used for the sentence blocks. This control procedure aimed to compare cerebral hemodynamic responses between speed-reading of sentences and no-reading while using comparable eye movements, to uncover hemodynamic changes unique to speed-reading. After reaching the end of the display, participants pressed a button and returned to the initial circle. During the rest phases, no visual stimuli appeared on the monitor and participants were instructed to relax and blink without averting their gaze from the monitor. To reduce artifacts, participants were instructed not to move their head or body and not to speak during the testing session, unless they wanted to terminate the session.

2.5 Measurement

2.5.1 NIRS measurement

Hemodynamic changes in bilateral occipital, inferior parietal, and posterior temporal areas were measured using NIRS (ETG-7000, Hitachi Medical Corporation, Tokyo, Japan). For each hemisphere, eight near-infrared light sources and seven detectors were arranged in a 3 x 5 lattice pattern and embedded in a soft silicon holder to fit the participant's head, resulting in 22 measurement points ("channels") per hemisphere. The arrangement of these 44 channels on the brain surface is depicted in **Figure 1(A)**. A method of virtual

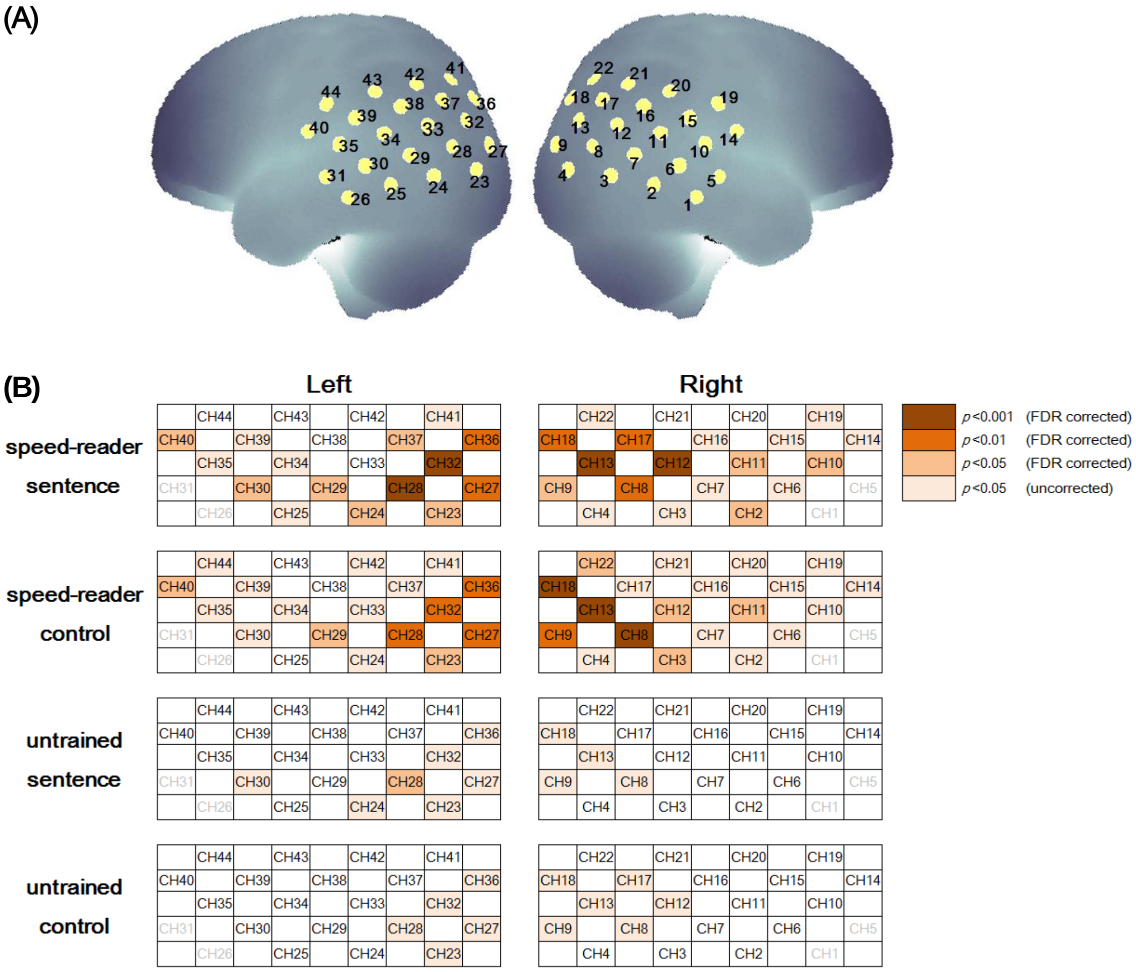

Figure 1 NIRS measurement positions **(A)** and statistical maps **(B)**. **(A)** shows arrangement of the 44 channels. This figure was drawn using the Platform for Optical Topography Analysis Tool (POTATo), developed by Advanced Research Laboratory, Hitachi, Ltd. **(B)** shows *p*-maps of oxygenated hemoglobin increase for speed-readers and untrained participants during sentence blocks (sentence) and control blocks (control). Channels with statistically significant increase in oxygenated hemoglobin (either with or without FDR correction) are marked in red/orange. Channels excluded from analyses are depicted in a pale color. The probe folders and channels are arranged to show a view from the rear of the head.

registration (Tsuzuki et al., 2007) estimated the coordinates of the optodes and channels in the Montreal Neurological Institute space. Based on these coordinates, brain regions were estimated using automated anatomical labeling (Tzourio-Mazoyer et al., 2002). With this method, brain regions associated with each measurement channel can be statistically estimated at a practical level without using the MRI data or 3-D digitizers (Tsuzuki et al., 2007). The holders were placed so that the most anterior optode on the lowest row aligned with T3 and T4, and the five optodes in the lowest row aligned with the horizontal reference curve on the scalp in a balanced manner, according to the international 10-20 system.

2.5.2 Eye-tracking

Eye movements were recorded using an eye-tracking system (Tobii X120 Eye Tracker, Tobii

Technology AB, Danderyd, Sweden) located beneath the display monitor. Calibration of the system was performed before the test session. Tobii X-120 is a binocular eye-tracker composed of two infrared cameras. The recording rate was 60 Hz. The system is non-invasive, tolerates relatively large head movements, and has a measurement accuracy of 0.5°. No devices were attached to the body of the participant. Coregistration of this eye-tracker and NIRS has been demonstrated in our preliminary enquiry. Tobii Studio software (version 1.7.3) was used to set up, execute, and analyze the data.

2.5.3 Data processing

With regard to the NIRS data, concentration of oxygenated (oxy-) and deoxygenated (deoxy-) hemoglobin (Hb) was calculated from the absorbance changes of 780- and 830-mm laser beams sampled at 10 Hz. After the removal of inappropriately fitted channels and blocks with artifacts, data were smoothed with a 5-s moving average. Data from channels 1, 5, 26, and 31 were excluded due to high levels of noise. For both the sentence blocks and the control blocks, the averaged Hb data of the five blocks for each participant were used. Hb data were then normalized to a 5-s baseline period just before the onset of the block. The response peaks for each type of block were evaluated against the baseline period (zero test), as is a common practice to analyze the NIRS data (Minagawa-Kawai et al., 2009). Because the largest peak in the increase in oxy-Hb was observed 8.3–9.0 s after the onset of the block, averaged data of 6–11 s were used as the analysis window.

To uncover overall hemodynamic change patterns in light of our two hypotheses, we first examined channels showing statistically significant increase in oxy-Hb changes against the rest phase. Data for the two groups of participants, i.e., speed-readers and untrained participants, were analyzed separately. There were accordingly four group-block combinations, each referred to as speed-reader-sentence (sentence block for speed-readers), speed-reader-control (control block for speed-readers), untrained-sentence (sentence block for untrained participants), and untrained-control (control block for untrained participants). For each combination, increase in oxy-Hb changes during the task blocks was evaluated against the baseline period just before the start of the blocks.

To create a statistical map containing the 40 analyzed channels, we used a false discovery rate (FDR) method to correct multiple comparisons. In this method, the expected proportions of false positive channels among declared *significant* channels were controlled. We set the threshold at the FDRs of $p < 0.05$, $p < 0.01$, and $p < 0.001$, so that no more than 5%, 1%, and 0.1% of channels were, on average, false positives (Singh & Dan, 2006). Because few channels showed statistically significant increase in oxy-Hb changes for untrained participants, outcomes from zero tests with no FDR correction were also considered in order to better uncover cerebral hemodynamic responses in these participants.

Then, with the intent to more strongly verify our two hypotheses, we directly examined differences in oxy-Hb changes between blocks (i.e., sentence and control blocks) for each group of participants, by using independent samples *t*-tests. We also directly compared increase in oxy-Hb changes between groups (i.e., speed-readers and untrained participants) for each block (independent samples *t*-tests), for channels that had significant increase in oxy-Hb changes in at least one group. Further, in order to better verify our primary hypothesis, correlations were examined between reading speed (sentence blocks) and increase in oxy-Hb changes, by involving all participants from both groups. Channels registered near middle/inferior occipital/temporal cortices (CHs 24, 25, 29, and 30) were considered. Because reading speed turned out to be positively skewed (skewness = 2.17), logarithmically transformed (base 10) values were used for these correlational analyses, to make distributions more normal.

Regarding the eye-tracker data, the number of characters read during the sentence blocks was counted using the "replaying display" function of Tobii Studio software, and was used to calculate reading speed (characters/min). Data were post-processed using Tobii Studio software to obtain the timestamps in milliseconds and coordinate of each gaze fixation. A fixation was identified if the gaze remained stationary within a radius of 0.9 degrees in visual angle; otherwise, the sample was defined as part of a saccade. Our major interest here was to grasp the looking patterns for participants in each group. To visualize the looking patterns, heat maps showing durations of fixations at each part of the control and sentence display were depicted by using the Tobii Studio software. To create the heat maps, all fixations made during the five blocks (40 s x 5 = 200 s in total) for each participant were pooled for the control and sentence blocks, respectively.

3. Results

3.1 NIRS channels with significant hemodynamic responses

3.1.1 Speed-readers

Figure 1(B) shows the NIRS channels that had statistically significant increase in oxy-Hb changes for each group-block combination. For speed-readers, significant increase in oxy-Hb was found in many channels located at the bilateral middle and superior occipital cortices in both the sentence blocks (CHs 8, 9, 13, 18, 23, 24, 27, 28, 32, and 36) ($t[15] = 3.652–6.534$, $p < 0.0012$) and the control blocks (CHs 3, 8, 9, 13, 18, 23, 27, 28, 32, and 36) ($t[15] = 3.741–6.048$, $p < 0.0010$) (Tzourio-Mazoyer et al., 2002; Singh & Dan, 2006). Thus, occipital cortices that are primarily responsible for processing visual information showed significant large hemodynamic responses both when speed-reading sentences and when looking at the figures. Also, channels registered near middle/inferior temporal cortices showed statistically significant increase in oxy-Hb changes during the sentence blocks (CHs 29 and 30: $t[15] = 3.388–3.480$, $p < 0.0021$; CH25: $t[15] = 2.358$, $p = 0.016$, uncorrected) and the control blocks (CH29: $t[15] = 3.419$, $p = 0.0019$; CH30: $t[15] = 1.968$, $p = 0.034$, uncorrected). This was more apparent for the sentence blocks and for the left hemisphere, although some channels from the right hemisphere yielded statistically significant outcomes as well (e.g., CH2: $t[15] = 3.420$, $p = 0.0019$). Thus, significant hemodynamic changes were observed in areas associated with visual form processes and kanji-reading neural pathways. In addition, significant oxy-Hb increase was found in channels near right inferior parietal cortices, more apparently in the sentence blocks (CHs 10, 11, and 12) ($t[15] = 3.464–7.951$, $p < 0.0018$) but also for the control blocks (CHs 11 and 12) ($t[15] = 3.837–4.000$, $p < 0.00081$). This shows that right parietal areas that are suggested to implement visuo-spatial processing exhibited significant hemodynamic responses during speed-reading as well as when using comparable looking strategies to look at the figures.

3.1.2 Untrained participants

For untrained participants, with FDR correction the only significant increase in oxy-Hb changes was observed in CH28 (left middle occipital gyrus) during the sentence blocks ($t[17] = 4.013$, $p = 0.00045$) (**Figure 1[B]**). However, with no multiple comparison corrections, a number of channels located at the bilateral occipital areas showed significant increase in oxy-Hb changes for both the sentence blocks (CHs 8, 9, 13, 18, 23, 24, 27, 28, 32, and 36) ($t[17] = 2.040–4.013$, $p < 0.029$) and the control blocks (CHs 8, 9, 12, 13, 17, 18, 23, 27, 28, 32, and 36) ($t[17] = 1.825–3.438$, $p < 0.043$). These trends show that occipital cortices responsible for processing visual information exhibited increased hemodynamic responses when normal readers read sentences and look at the figures rapidly. For the sentence blocks, CH30, registered near left middle/inferior temporal cortices, also showed significant increase in oxy-Hb ($t[17] = 2.227$, $p = 0.020$). Thus, cortical areas involved in visual word form processes tended to show increased responses when untrained readers read sentences rapidly.

3.2 Comparisons of the NIRS data between blocks

No channels showed statistically significant differences between the blocks, either for speed-readers ($t[15] = -2.673 – 1.624$, $p > 0.017$) (e.g., CH43: $t[15] = -2.673$, $p = 0.017$, uncorrected) or for untrained participants ($t[17] = -2.204 – 2.092$, $p > 0.041$) (e.g., CH21: $t[17] = -2.204$, $p = 0.042$, uncorrected). Thus, for both groups of participants, hemodynamic changes for the control blocks were overall as large as those for the sentence blocks.

3.3 Comparisons of the NIRS data between groups

In the sentence blocks, speed-readers showed significantly greater increase in oxy-Hb than untrained participants in the three channels from the right hemisphere, CH2 (right middle/inferior temporal gyrus; $t[32] = 2.071$, $p = 0.047$), CH11 (right supramarginal/angular gyrus; $t[32] = 3.440$, $p = 0.0016$), and CH12 (right angular/middle occipital gyrus; $t[32] = 2.377$, $p = 0.024$). Because right inferior parietal cortices are involved in these channels, these data show that activities in cortical regions implementing visuo-spatial processing are enhanced in speed-readers than in untrained participants. **Figure 2** depicts grand-averaged NIRS waveforms during the sentence blocks in two channels from the right hemisphere with significant group differences (CH11 and CH12) and two channels from the left hemisphere showing typical hemodynamic change patterns (CH29 and CH32). In the control blocks, speed-readers showed significantly greater oxy-Hb increase than untrained participants in CH11 (right supramarginal/angular gyrus; $t[32] = 2.680$, $p = 0.012$), CH18 (right middle/superior occipital gyrus; $t[32] = 2.063$, $p = 0.047$), and CH40 (left postcentral/supramarginal gyrus; $t[32] = 2.116$, $p = 0.042$). Thus, compared with untrained readers, speed-readers show enhanced activities in areas implementing visual/visuo-spatial processing even when looking at meaningless symbols successively. No significant group differences were found for the remaining channels in either the sentence blocks or the control blocks ($t[32] = -0.925 – 1.758$, all $p > 0.070$).

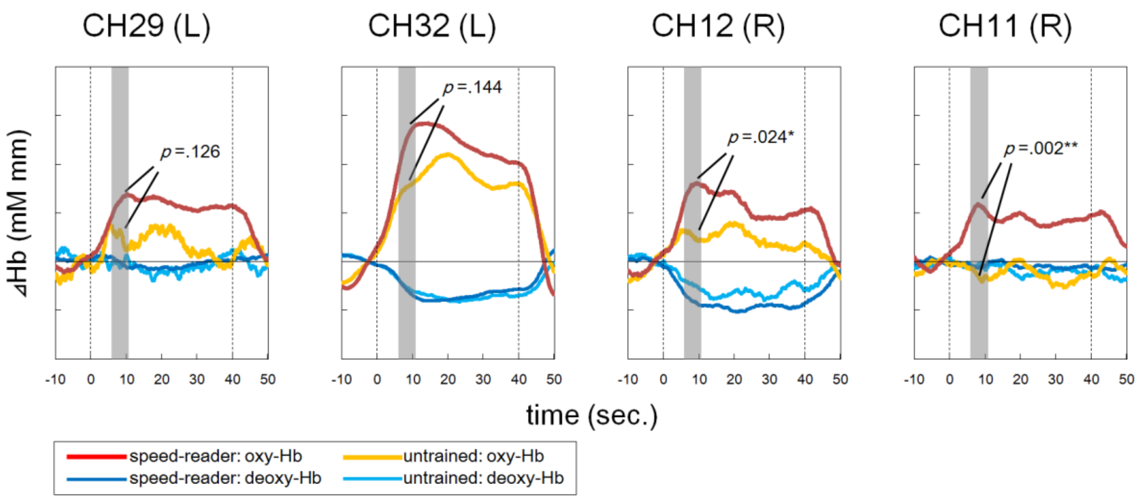

Figure 2 Change in oxygenated and deoxygenated hemoglobin in selected channels averaged across five sentence blocks and then across all participants in the speed-reading group and the untrained participant group. The dotted lines at 0 and 40 s indicate the beginning and the end of the block. Gray-colored areas indicate the analysis window (6–11 s after block onset). *P* values indicate comparisons using *t*-tests between speed-readers and untrained participants of the increase in oxygenated hemoglobin during the analysis window (*: $p < 0.05$; **: $p < 0.01$).

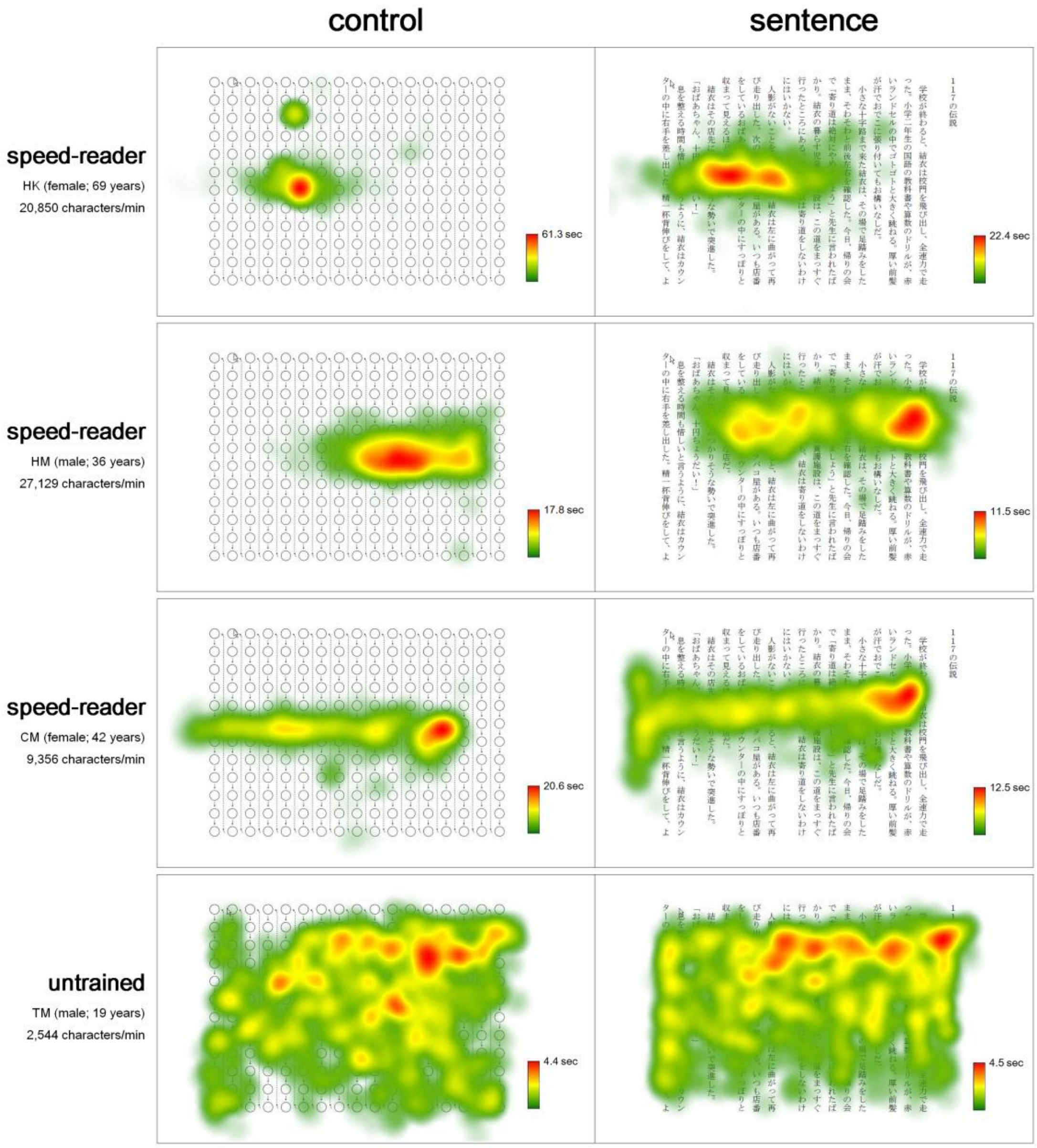

Figure 3 Representative heat maps for three speed-readers and one untrained participant. Color scale indicates fixation time at each area of the stimulus display. Each figure shows pooled data from the five control blocks (left panel) and five sentence blocks (right panel). Figures were created using Tobii studio software (version 1.7.3). The mean reading speed during the sentence blocks is shown for each participant.

3.4 Reading speed and correlations with the NIRS data

During the sentence blocks, mean reading speed was 9414.0 characters/min (*SD* = 6166.2) for speed-readers and 1338.4 characters/min (*SD* = 779.2) for untrained participants (independent samples *t*-test; $t[32] = 5.343$, $p < 0.001$). During the control blocks, speed-readers pressed the button 37.4 times/min (*SD* = 19.2), whereas untrained participants did so 3.4 times/min (*SD* = 0.7; $t[30] = 7.067$, $p < 0.001$). Correlational analyses between reading speed and increase in oxy-Hb changes revealed a statistically significant positive correlation in CH25 ($r_s = 0.378$, $p = 0.014$), though not in the other channels ($r_s = 0.043$–0.136, $p > 0.222$). Thus, participants who read rapidly tended to show greater hemodynamic responses in at least one measurement channel registered near left middle/inferior temporal cortices. **Figure 3** shows typical heat maps illustrating duration of fixations at each part of the monitor. Speed-readers gazed at limited parts of the display, either along a horizontal straight line or almost stopping at a fixed point, whereas untrained participants looked at a large part of the stimulus area.

4. Discussion

Patterns of hemodynamic changes observed for speed-readers are overall supportive of our two predictions. First, speed-readers showed large hemodynamic changes in NIRS channels in broad bilateral middle and superior occipital areas both during the sentence and the control blocks. This suggests that task-relevant activities in occipital areas responsible for processing visual information were enhanced in these experts, both when speed-reading sentences and when looking at the figures. Second, regarding our primary hypothesis, activities around left middle/inferior occipital/temporal areas were observed while speed-reading and less apparently while looking at the control figures. Direct comparisons between speed-readers and untrained participants failed to yield statistically significant differences in hemodynamic responses in these areas. However, by involving all participants, greater hemodynamic changes associated with reading speed were found at least in one channel registered around these areas. These trends are supportive of the view that visual form processes are relatively enhanced and that neural pathways usually used for reading kanji are used associated with speed-reading. Third, in relation to our second prediction, speed-readers showed significant increase in oxy-Hb changes in channels including those near the right middle/inferior parietal cortex, more apparently during the sentence blocks than during the control blocks. Direct comparisons between the groups uncovered greater hemodynamic responses in speed-readers than in untrained participants. Parallel to the preceding studies (Fujimaki et al., 2009; Kato et al., 2005; Miyata et al., 2012), these results support the notion that visuo-spatial processing is enhanced associated with speed-reading.

For untrained participants, weaker statistical trends were found compared with the speed-readers; however, with no correction for multiple comparisons, significant hemodynamic changes were observed in bilateral occipital areas for both the sentence and the control blocks. When reading sentences, significant hemodynamic changes were also found around middle/inferior temporal cortices. These data are consistent with the notion that visual cortices and areas involved in visual form processes were activated in normal readers, more apparently when reading natural sentences than when looking at meaningless symbols.

The eye-tracking data indicated that speed-readers looked at limited parts of the display and did not follow each line as is usually done, both when reading sentences and when looking at the control figures. This gaze pattern is distinctively different from that for the untrained participants, who tended to gaze at larger parts of the stimulus display (**Figure 3**). These are consistent with previous studies on speed-reading (e.g., Fujimaki et al., 2004; 2009; Miyata et al., 2012) and testify to the fact that speed-readers used their trained eye movement strategies during measurement.

There are issues that still require cautious considerations when evaluating these data. First, relatively weak statistical trends were found for the NIRS data in the untrained participants as compared to the speed-readers. With no correction for multiple comparisons, many occipital areas (sentence and control blocks) and middle/inferior temporal areas (sentence blocks) showed significant hemodynamic changes (**Figure 1[B]**). Also, NIRS waveforms for untrained participants showed increase in oxy-Hb changes in multiple channels (**Figure 2**). These data suggest that NIRS signals themselves were recorded and analyzed appropriately. Relatively weak statistical trends could thus be attributed to the variability in neural activities during the rest phases for normal readers. We presented no visual stimuli during the rest phase, because a task such as gazing at a fixation point during the resting period should become another contemplative task for speed-readers (i.e., a similar task is included in the Park-Sasaki training). Thus, the present procedure seems appropriate to record hemodynamic changes in the expert, whereas modified procedures could be desired to better uncover neural activities associated with normal reading. Most studies on neural mechanisms of reading so far have focused on reading of character(s) and/or word(s), with relatively few studies studying neural activities when reading natural sentences (e.g., Fujimaki et al, 2009; Choi et al., 2014). Future research efforts should need to focus on dissociating not only visual form but also phonological, semantic, and syntactic processes from each other associated with everyday reading.

Second, there were relatively weak differences in hemodynamic change patterns observed between the sentence and control blocks. This would suggest that visual form processes and visuo-spatial processes as examined in this study were used both when reading sentences and when looking at the figures by speed-readers. Such views are consistent with the fact that speed-readers are instructed during training to look at the control figures using strategies comparable to those used during speed-reading sentences. Further NIRS studies examining brain areas relevant to phonological, semantic, and syntactic processes may yield greater differences between these blocks.

Another important issue concerns the fact that levels of sentence comprehension were not behaviorally confirmed in the present experiment, except for the explicit instruction to maintain comprehension. Neuroimaging and tests of comprehension so far have been conducted in separate experiments (e.g, Miyata et al., 2012), because conducting these tests simultaneously should impose too much cognitive load to the participants in the current empirical settings. It would be a challenge to combine these approaches in the future studies. Also, demographic and other properties of participants from the two groups were not strictly matched in the present study. It is desirable to control for age, sex, academic background, etc., because differences observed between the groups could be attributed to either of these variables at least at the theoretical level. These further sophistications should help to better understand the mechanisms by which extraordinary cognitive performance such as speed-reading is achieved through training in adult humans.

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