Neural activation dependent on reading speed during covert reading of novels

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We measured the dependence of activation on reading speed with fMRI in a wide range that spanned two orders of magnitude. We used four trained subjects who were capable of a technique of rapid reading, and another four who were untrained, to investigate the neural mechanism during the covert reading of novels. This revealed that activation decreased for trained subjects during extremely rapid reading in the left superior and middle temporal gyri or near Wernicke's area, and in Broca's area. These results suggest that the trained subjects read sentences with fewer phonological processes. The decrease in activation might also be due to fewer semantic and syntactic processes, although the subjects understood the story lines in the novels. *NeuroReport* 15:239–243 © 2004 Lippincott Williams & Wilkins.

Key words: Broca's area; Covert reading; fMRI; Novel; Phonology; Rapid reading; Wernicke's area

INTRODUCTION

Neural activation during reading has been investigated through a variety of experimental tasks. Characters and words were visually presented to measure activation for visual form, phonology, and lexico-semantic processes [1,2], while tasks with sentences required the addition of a syntactic process. Event-related potential (ERP) and MEG studies showed that semantic incongruity induced an N400 component, while syntactic incongruity induced other components such as N125, P600, and ELAN [3–6]. PET and fMRI studies have compared neural activation during comprehension of sentences with different syntactic complexities such as object relative clauses *vs* subject relative clauses, center-embedding sentences *vs* right-branch sentences, and left-branch sentences *vs* center-embedding sentences (in Japanese) [7–12]. Activation was also measured when subjects read sentences with syntactical errors [13–15]. These results showed that activation increased in Broca's area as task demands on the syntactic process increased, while activation in Wernicke's area was considered to be related to the semantic process because it was independent of syntactic difficulties [12]. Varying task demands were intended to isolate activation of the syntactic process in these experiments.

Reading speed is an alternative parameter for varying task demands in the reading of sentences. Apart from word experiments where the rate was varied for word presentation [16,17] and inner speech [18], no neuroimaging data related to the speed of reading sentences have been reported. Although the method of varying reading speed cannot isolate activation for a specific process component, we can measure changes in neural activation using the same reading materials under natural reading conditions.

In this report, we measured neural activation during covert reading of novels, i.e. reading them without vocalization, with fMRI. We used well-trained subjects who were capable of a technique of extremely rapid reading [19] and untrained subjects who were not to vary the reading speed over a wide range.

MATERIALS AND METHODS

Subjects: Four subjects who were trained to be capable of a technique of rapid reading (one male and three females) with a mean ($\pm$ s.d.) age of 37 ± 4 years and four untrained subjects (four males) with a mean age of 29 ± 13 years participated in the experiments. They consented after being informed on what the experiment involved, and answered the Edinburgh Handedness Inventory [20]. All were right-handed (mean laterality quotient 73 ± 25 for trained subjects and 76 ± 25 for untrained subjects), and native speakers of Japanese. This study was approved by the Ethics Committee for Human and Animal Research of the Communications Research Laboratory.

Stimuli and tasks: We used several novels written by Natsume Soseki, a well known Japanese novelist. These were Kokoro (Heart), Higansugimade (To the spring equinox and beyond), Michikusa (Grass on the wayside), and Nowaki (Autumn wind) (Aozora-bunko; http://www.aozora. gr.jp). A novel was chosen for each participant so that the subject either had not read it or had read it several years before the experiment. They were written in a mixture of kanji, hiragana, and katakana characters (three Japanese writing systems: morphograms (the first) and syllabograms (the last two)), where the characters were arranged in 19 rows and 23 columns, from top to bottom, and from right to left, as is the usual style for Japanese novels printed in paperback. Characters were presented on a screen, which was placed 1.6 m away from subjects. Their size represented a visual angle of $0.46 \times 0.46^\circ$, which was slightly larger than the typical size when books are physically read in hardcopy form. Luminance was $0.75\,cd/m^2$ for the characters and $160\,cd/m^2$ for the background.

The subjects were instructed to covertly read the sentences both at an ordinary speed and rapidly under the test conditions. They turned pages by pressing a button, which was monitored to record the reading speed. The procedures for the control conditions were the same as for the test conditions except that characters were replaced by pseudo-characters, which were prepared by deforming katakana characters. Subjects were instructed to pursue the pseudo-characters with their eyes and turn pages in the same manner and at a similar speed as reading sentences under the test conditions. Since subjects could not read pseudo-characters, the control conditions required only the visual form process. Neural activation under the control conditions was subtracted from that under the test conditions so that the difference did not include activation related to visual form process.

Data acquisition: An MRI system (Siemens AG, Vision) with a magnetic field of 1.5 T was used in the experiments. Thirty-two axial-slice data were measured to cover the subject's whole cerebral cortex in each scan with the echo-planar imaging method (TR: 4 s, TE: 55 ms, and FA: 90°). The slices had a thickness of 4 mm and no gaps, and consisted of 64×64 pixels with sizes of 4×4 mm. We conducted two kinds of experimental run: a two-condition run that consisted of five periods, with each period including 12 consecutive scans for each of the test and control conditions, and a three-condition run that consisted of four periods, with each period including 12 consecutive scans for two test and control conditions, whose sequences were randomized. All subjects executed two-condition runs to contrast ordinary-speed reading *vs* pseudo-character pursuing, and to contrast rapid reading *vs* pseudo-character pursuing. Some of the subjects also executed a three-condition run contrasting ordinary-speed reading, rapid reading, and pseudo-character pursuing conditions. We found that activation obtained from runs under the three conditions did not systematically differ from activation obtained from runs under the two conditions. Since some subjects confused reading speed during the three-condition runs, almost all analyzed data were taken from the two-condition runs.

T1 structural images with a voxel of $1\times 1\times 4$ mm (thickness) and others with a cubic voxel of $1 \times 1 \times 1$ mm were taken from each subject to superimpose activation data on them. Eye movement was measured during the execution of tasks with a measuring instrument (NAC Inc., MRI-EMR-NC).

Data analysis: The fMRI data were analyzed with SPM99 software (The Wellcome Department of Cognitive Neurology, London; http://www.fil.ion.ucl.ac.uk/spm); realigned for motion correction, coregistered to T1-structural images, spatially filtered with a full-width half-maximum value of 8 mm, temporally filtered with a time constant of twice the fundamental periods of a time course for low-frequency-cutoff and a typical hemodynamic response delay (6 s) for high-frequency-cutoff, and underwent a statistical test. The difference in activation between test and control conditions was detected at a significance level of $p < 0.001$ (uncorrected for multiple comparison), while neglecting small clusters with < 4 active voxels (spatial extent threshold value, $k = 4$).

To quantitatively evaluate the dependence of activation on reading speed in Wernicke's area and Broca's area, fMRI signal intensity was averaged over voxels included in the volume of interest (VOI), which centered on an active voxel with the highest z value, and had a radius of 1 cm. We then evaluated the mean and s.d. across scans for the relative VOI signals, which were the VOI signal values divided by the intensity averaged over the whole brain.

RESULTS

There was a distinct difference in eye movement for rapid reading between trained and untrained subjects; the trained subjects moved their eyes almost horizontally, while the untrained subjects moved their eyes vertically and horizontally along the same sequence as the characters were arranged (Fig. 1). All trained subjects had decreased vertical eye movements in common during rapid reading, while eye movements at ordinary speed were similar for trained and untrained subjects.

Activation was observed in the inferior frontal gyrus (IFG), precentral gyrus (preCG), anterior temporal area (aT), near the posterior superior temporal sulcus (pSTS) or in the superior and middle temporal gyri (STG and MTG), and in the fusiform gyrus (FuG; Fig. 2). Activation in these areas was observed for almost all subjects, and was wider in the left hemisphere than in the right. Additional activation was observed in the left insula for one trained subject during rapid reading and one untrained subject during ordinary-speed reading, and in the parietal areas near the intraparietal sulcus (IPS) or in the superior parietal lobule (SPL) for three trained subjects during rapid reading, where the activation occurred in both hemispheres for two trained subjects, and in the right hemisphere for one trained subject. Activation near the left pSTS or in Wernicke's area and in the left IFG or Broca's area decreased in trained subjects during rapid reading (upper and middle of Fig. 3), where the trained subjects demonstrated an interval between turning pages of < 10 s/page, or a reading speed of > 40 characters/s, which could not be attained by untrained subjects. The VOI signals in Wernicke's area and those in Broca's area obtained from eight subjects were correlated (bottom of Fig. 3) and produced a correlation coefficient of 0.74.

DISCUSSION

Although the reading speed was extremely fast, trained subjects comprehended the content so that they provided a synopsis of the novels with emotion, except for one subject,

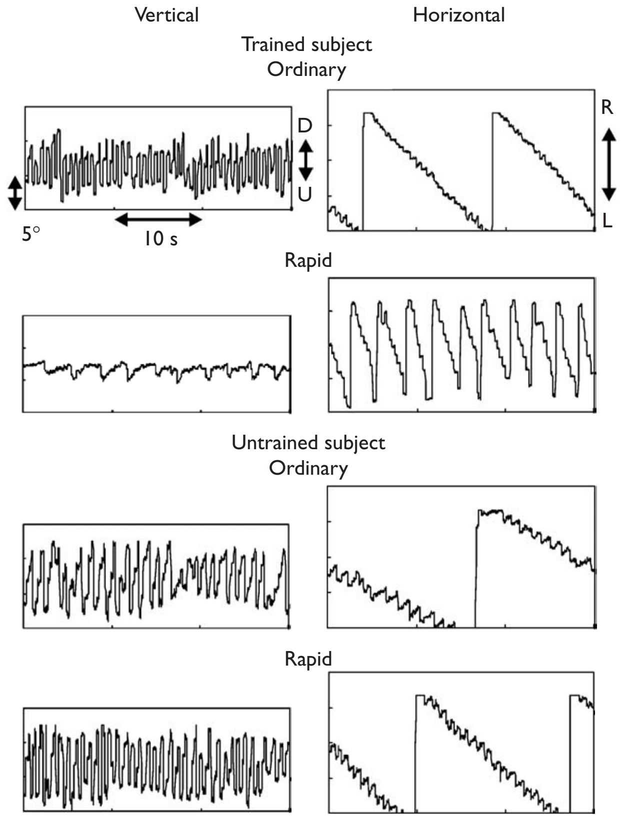

Fig. 1. Vertical and horizontal eye movements during covert reading of novels at an ordinary speed and rapidly for a trained subject (upper) and an untrained subject (lower). The symbols, U, D, L, and R denote up, down, left, and right directions.

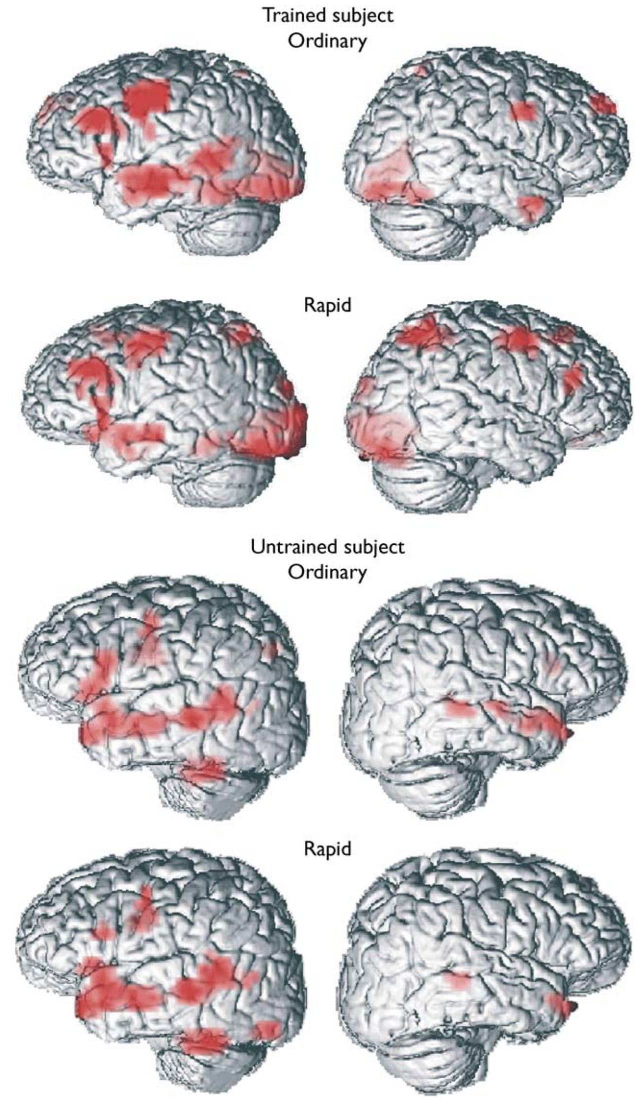

Fig. 2. Neural activation during covert reading of novels at an ordinary speed and rapidly for a trained subject (upper) and an untrained subject (lower).

S3, who had the highest speed but had difficulty in talking about the detailed synopsis, although she reported that she had comprehended the stories.

Activation decreased in Wernicke's and Broca's areas as reading speed increased for trained subjects and these had a high correlation coefficient (0.74). A previous EEG study [19] revealed that a β-wave component recorded at a posterior temporal scalp electrode (T5) had a tendency of being smaller under rapid-reading conditions than under pursuing-symbol conditions for subjects who had mastered the same rapid-reading training as the present trained subjects had, while this component was larger in rapid reading than in pursuing symbols for beginners. The present decrease in activation in Wernicke's area is consistent with the decrease in the previous β-wave component.

Previous reports revealed that activation increased in Wernicke's and Broca's areas when the stimulus presentation rate was increased for word comprehension tasks [16,17] and when the speech rate was increased for an inner speech task [18]. An increase in activation was observed at rates of < 60 or 100 words/min, i.e. 1 or 2 words/s in these studies. However, a decrease in activation in the present study was observed for a reading speed of > 40 characters/s or about 10 words/s if we assume several characters correspond to one word on average. Thus, the reading speed differed by more than one order. In other words, the previous and present results implied that activation increased as the processing speed increased in the low-speed range, but that activation decreased as the processing speed increased in the high-speed range. The decrease in neural activation is considered to reflect a strategy of extremely rapid reading in trained subjects. In addition, vertical eye movements decreased for trained subjects during rapid reading, although activation in the parietal areas suggested that trained subjects directed visuo-spatial attention to reading materials [21]. The decreased vertical eye movements also suggested another strategy, i.e. rapidly reading sentences without pursuing them with the eyes along each column line. In this regard, a previous fMRI study showed that neural activation related to auditory frequency discriminations decreased after the training in the STG of both hemispheres, which included the STS and the planum temporale (PT) or Wernicke's area [22]. The present results agree with the previous results in that activation in Wernicke's area may be changed by training. Recently, the training of non-linguistic sequence tasks was reported to improve syntactic comprehension ability for aphasic patients [23]. This suggests a plasticity of the language

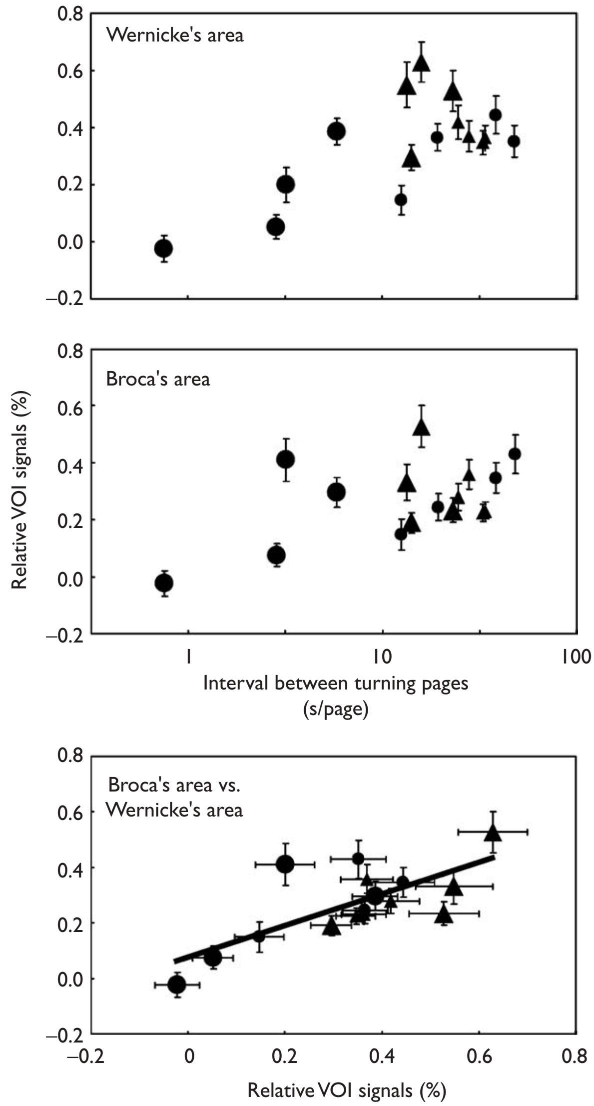

Fig. 3. Relative VOI signals in Wernicke's area (upper) and Broca's area (middle) *vs* interval between turning pages, and relative VOI signals in Broca's area (vertical) *vs* those in Wernicke's area (horizontal) for eight subjects (bottom). Small and large solid circles denote the data during ordinary-speed and rapid reading for trained subjects; triangles denote data for untrained subjects, and error bars denote a positive and a negative s.d. The thick line represents a regression line.

system. The present decrease in activation in trained subjects may reflect such the plasticity. The previous character and word experiments demonstrated that activation in Wernicke's and Broca's areas was related to a phonological process such as phonological transformation, analysis, and inner speech [1,2], and that activation in these areas and in the left inferior parietal areas depended on the task demands of inner speech [18,24]. Furthermore, experimental evidence has been reported that supports a connectionist model in which these areas constitute a neural network for a phonological loop of working memory [25]. The previous fMRI studies reported the functional roles of sub-areas in Wernicke's area, i.e. speech perception for the STS and phonetic analysis or processing of complex sounds for the PT [26,27]. Thus the present findings, i.e. a correlated decrease in Wernicke's and in Broca's areas, suggest that the phonological process, such as phonological transformation and accompanying inner speech, was reduced during rapid reading in trained subjects. However, since Wernicke's area has also been reported to be related to the semantic aspects of comprehension [12], while Broca's area has been reported to be related to syntactical process [7–15], we cannot deny the possibility that the present decrease in activation also implies reading taking place with fewer semantic and syntactic processes. Nevertheless, the high correlation coefficient between activation in Wernicke's and Broca's areas seems to support greater contribution from a single phonological process.

CONCLUSIONS

The present study revealed that neural activation decreased in Wernicke's and Broca's areas for a reading speed of > 10 words/s. This suggests that reading was executed with fewer neural processes such as phonology in the high-speed range. This finding is in contrast to the previous reports where activation increases as the speed increases in the low-speed range. The reduced neural activation, as well as the decreased vertical eye movements, was considered to reflect a strategy that enabled extremely rapid reading.

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