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Impact of reading habit on white matter structure: Cross-sectional and longitudinal analyses

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ABSTRACT

Psychological studies showed the quantity of reading habit affects the development of their reading skills, various language skills, and knowledge. However, despite a vast amount of literature, the effects of reading habit on the development of white matter (WM) structures critical to language and reading processes have never been investigated. In this study, we used the fractional anisotropy (FA) measure of diffusion tensor imaging to measure WM microstructural properties and examined cross-sectional and longitudinal correlations between reading habit and FA of the WM bundles in a large sample of normal children. In both cross-sectional and longitudinal analyses, we found that greater strength of reading habit positively affected FA in the left arcuate fasciculus (AF), in the left inferior fronto-occipital fasciculus (IFOF), and in the left posterior corona radiata (PCR). Consistent with previous studies, we also confirmed the significance or a tendency for positive correlation between the strength of reading habit and the Verbal Comprehension score in cross-sectional and longitudinal analyses. These cross-sectional and longitudinal findings indicate that a healthy reading habit may be directly or indirectly associated with the advanced development of WM critical to reading and language processes. Future intervention studies are needed to determine the causal effects of reading habits on WM in normal children.

Introduction

There is tremendous variation in the amount of time people spend reading (Chateau and Jared, 2000). It has been pointed out that printed content contains more declarative knowledge and vocabulary than speech or television (Hayes and Ahrens, 1988; Stanovich, 1993). Many cross-sectional and longitudinal studies have reported the importance of a healthy reading habit in children's verbal development. Numerous studies have shown the positive effects of reading habit; these include better orthographic and phonological word recognition processes (Chateau and Jared, 2000), better vocabularies, increased general knowledge (Stanovich and Cunningham, 1992), improved oral language skills (including comprehension, spelling, and reading) (Mol and Bus, 2011), greater academic achievement (Mol and Bus, 2011), and improved verbal fluency measures (Stanovich and Cunningham, 1992).

Previous neuroimaging studies have investigated the neural basis of reading ability in normal subjects and subjects with developmental dyslexia (for review, see Ben-Shachar et al., 2007). According to this review, these studies have shown the importance of the structural property of white matter (WM) in reading ability, especially that in the left posterior and superior corona radiata (left PCR and left SCR, respectively) areas. However, other WM structures such as the left inferior fronto-occipital fasciculus (IFOF), which is important for the semantic aspects of language (Dick and Tremblay, 2012), orthographic processing (Vandermosten et al., 2012) and also phonological processing (Vandermosten et al., 2015), were also found to be important for reading ability (Odegard et al., 2009). Further, a recent study showed the left arcuate fasciculus (AF)'s was important for phonological awareness, which is important for the reading ability (Vanderauwera et al., 2015). Furthermore, a longitudinal study have shown that the development of reading ability was correlated with that of WM structural property in WM bundles, such as the left AF and left inferior longitudinal fasciculus (ILF), which are thought to be critical for language (Dick and

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Tremblay, 2012; Yeatman et al., 2012). Another longitudinal study demonstrated that changes in the structural properties of the left AF and SCR between kindergarten and Grade 3 predicted individual differences in reading ability at Grade 3 (Myers et al., 2014). However, whether these developmental changes in WM simply reflect individual differences in the speed of neural development (i.e., early or late maturation) and whether other factors may affect this neural development are not known.

These psychological studies of reading habit and WM structural studies of reading ability lead to the following hypothesis: reading habit affects the development of WM structural property in the areas thought to be critical for reading and/or language, namely left PCR, left SCR, left IFOF, left AF, and left ILF (Fig. 1). However, despite these previous studies, no studies have investigated the influence of reading habit on the development of WM structural property, which has therefore become the purpose of this study. Given that these WM structures play important roles in reading and language, both of which are of scientific and social interest, it is important to investigate the extent of plasticity caused by daily reading habits.

For this purpose, we employed cross-sectional analyses to identify associations between reading habit and WM structural property. And then we also analyzed longitudinal associations between reading habit and changes in WM structural property a few years later using a longitudinal design.

To measure WM structural property, the fractional anisotropy (FA) measure of diffusion tensor imaging (DTI) (Le Bihan et al., 2001) was used.

Methods

Subjects

All subjects were healthy Japanese children and the details related to their initial recruitment (pre-experiment) were described elsewhere (Taki et al., 2010). As described previously (Takeuchi et al., 2015b; Taki et al., 2013a), in brief, we successfully collected brain magnetic resonance (MR) images from subjects who did not have any history of malignant tumors or head traumas involving loss of consciousness, developmental disorders, epilepsy, psychiatric diseases, or weak eyesight. We stipulated that only right-handed children could participate in the study in an advertisement used for subject recruitment and also confirmed that all subjects were right-handed using the self-report questionnaire, the "Edinburgh Handedness Inventory"(Oldfield, 1971). As per the Declaration of Helsinki (1991), written informed consent was obtained from each subject and his/her parent prior to MR scanning after a full explanation of the purpose and procedures of the study was provided. Approval for these experiments was obtained from the Institutional Review Board of Tohoku University. A few years (3 years in average) after the pre-experiment, post-experiment was conducted and part of the subjects from the pre-experiment also participated in this post-experiment (subjects who participated in the post-experiment were limited to the subjects who participated in the pre-experiment). For the precise data of intervals between the pre-experiment and post-experiment, see Table 1. Due to the availability of the subjects and the MRI, intervals varied among subjects.

Overall, for the cross-sectional behavioral analyses, effective data were obtained from 296 subjects (145 boys and 151 girls; mean age, 11.3 $\pm$ 3.1 years; range, 5.6–18.4 years), and cross-sectional behavioral analyses were performed with these data. Furthermore, for the longitudinal behavioral analyses, effective data were obtained from 234 subjects (122 boys and 112 girls; mean age, 14.2 $\pm$ 3.1 years; range, 8.4–21.7 years), and longitudinal behavioral analyses were performed with these data. Because diffusion weighted images were obtained from only portion of all the subjects, cross-sectional imaging analyses were performed in 253 subjects (121 boys and 132 girls; mean age, 11.6 $\pm$ 3.1 years; range, 5.7–18.4 years). And longitudinal imaging analyses were performed in 200 subjects (102 boys and 98 girls; mean age, 14.5 $\pm$ 3.0 years; range, 8.4–21.3 years).

Assessments of psychological variables

Of the psychological variables described in this subsection, only the IQ data were obtained both in the pre- and post-experiment (together with the MRI data). All other variables in this subsection were obtained only in the pre-experiment.

In both the pre- and post-experiments, we measured the Full Scale intelligence quotient (IQ). For this, we used the Japanese version of the Wechsler Adult Intelligence Scale-Third Edition (WAIS-III) for subjects aged 16 years or older. And we used the Wechsler Intelligence Scale for Children-Third Edition (WISC-III) for subjects younger than 16 years (Azuma et al., 1998). The tests were administered by trained examiners (Fujita et al., 2006). We calculated the Verbal Comprehension subscore (which is the main target of this study) along with the Full Scale IQ, Perceptual Organization subscore, Working Memory subscore, and Processing Speed subscore for each subject from their WAIS/WISC scores. The correlations between subscales of WAIS-III

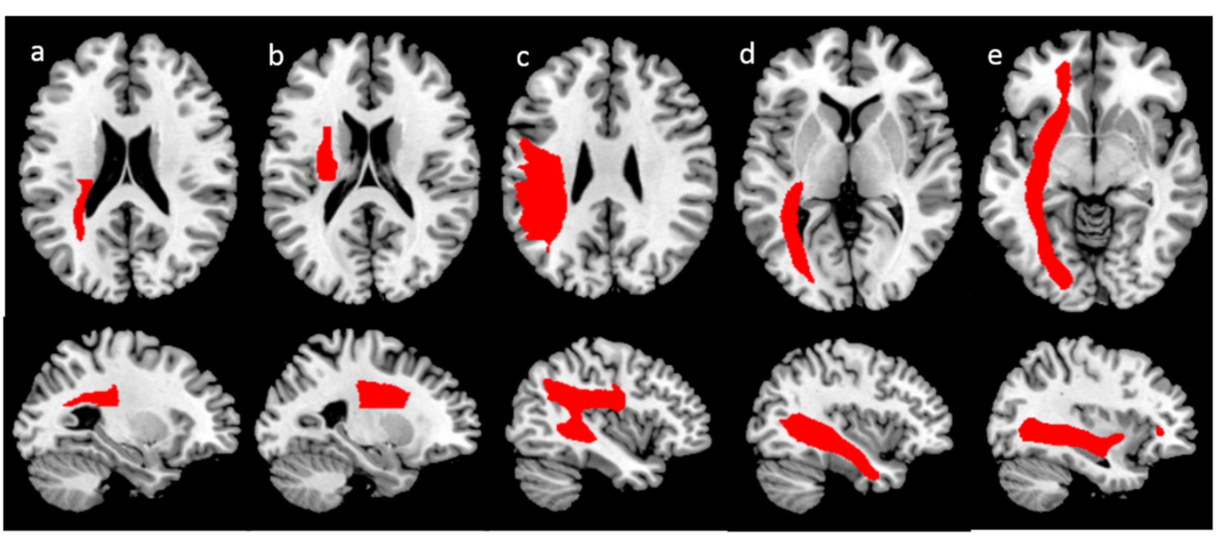

Fig. 1. Regions of interest in the brains of children that are related to reading habit Regions of interest indicated in red were presented; (a) left posterior corona radiata, (b) left superior corona radiata, (c) left arcuate fasciculus, (d) left inferior longitudinal fasciculus, and (e) left fronto-occipital fasciculus.