Published in final edited form as:

Neuroreport. 2014 March 26; 25(5): 347–352. doi:10.1097/WNR.0000000000000121.

Reading skill and structural brain development

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Abstract

Reading is a learned skill that is likely influenced by both brain maturation and experience. Functional imaging studies have identified brain regions important for skilled reading, but the structural brain changes that co-occur with reading acquisition remain largely unknown. We investigated maturational volume changes in brain reading regions and their association with performance on reading measures. Sixteen typically developing children (5-15 years old, 8 male, mean age of sample = 10.06 ± 3.29) received two magnetic resonance imaging (MRI) scans, (mean inter-scan interval = 2.19 years), and were administered a battery of cognitive measures. Volume changes between time points in five bilateral cortical regions of interest were measured, and assessed for relationships to three measures of reading. Better baseline performances on measures of word reading, fluency and rapid naming, independent of age and total cortical gray matter volume change, were associated with volume decrease in the left inferior parietal cortex. Better baseline performance on a rapid naming measure was associated with volume decrease in the left inferior frontal region. These results suggest that children who are better readers, and who perhaps read more than less skilled readers, exhibit different development trajectories in brain reading regions. Understanding relationships between reading performance, reading experience and brain maturation trajectories may help with the development and evaluation of targeted interventions.

Keywords

Reading; Imaging; Brain Structure; Development

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Statement of Conflicts: None Declared

Introduction

Reading is a learned ability specific to humans. Skilled reading relies upon the integration of multiple brain regions, and recruitment of and communication among these regions likely strengthen over time. Functional imaging studies have identified left hemisphere frontal, temporal and parietal regions that are activated during reading tasks [1], and cross sectional studies have reported variations in brain structure in similar areas in children as a function of reading skills [2]. However, the ways in which developmental changes in brain structure relate to reading acquisition in children remain largely unknown. Given the negative individual and societal implications associated with illiteracy in both children and adults, furthering our understanding of these changes as they relate to typical brain development is necessary, and may be useful for the development of targeted reading interventions.

Learning to read is a protracted developmental process supported by the parallel development of multiple cognitive and linguistic skills, including fluency, accuracy, and phonological awareness [1, 3]. These skills begin to emerge prior to the onset of fluent reading and are refined as one continues to learn, such that learning to read is likely a facilitator and an outcome of other developmental processes, including brain maturation.

Brain maturation involves dynamic changes in gray and white matter [4, 5]. These changes are regionally and temporally specific, such that gray matter volume decreases and white matter volume increases between childhood and adolescence occur earlier in more primitive brain regions and later in phylogenetically newer ones [6, 7]. Cortical changes in the left perisylvian language regions show a unique developmental pattern where cortical thickening occurs much later than that of the more dorsal regions of the frontal and parietal lobes [4-7]. These changes are thought to reflect variations in synaptic density and myelination, both of which are influenced by environmental and genetic factors, and characterize neural plasticity throughout development [6]. Longitudinal imaging studies have related regionally specific patterns of cortical maturation to general intellectual functioning, specific cognitive functions, and skill learning [5, 8-9]. In the context of reading and literacy, these findings have important implications, but specific relationships between acquisition of reading skill and the simultaneous structural brain changes in children are still not well understood [1]. Given that cortical maturation, IQ and reading are influenced by environmental experience throughout development, and that some brain regions are likely more integral than others in learning to read, a developmental reading model that includes brain maturation is warranted.

Only a handful of imaging studies have investigated relationships between brain structure and reading skill in children. Cross-sectional studies of impaired readers report reduced gray matter volumes in bilateral fusiform and right hemisphere supramarginal regions [10], and a longitudinal study of typically developing children suggests that those with greater thickening of inferior frontal cortical regions demonstrate improved phonological skills [9]. The inferior parietal cortex has also been implicated in reading, given its location along the visual pathway and its pattern of activation during reading tasks. DTI studies of reading have consistently revealed relationships between white matter and reading, with higher fractional anisotropy and larger white matter fiber bundles in temporo-parietal and frontal regions being associated with better reading [2].

Here, we used longitudinal structural magnetic resonance imaging to study whether maturational volume changes in brain regions implicated in reading are associated with reading performance in typically developing children. We hypothesized that more efficient reading-related skills would be associated with volume change within bilateral canonical reading regions (inferior frontal, inferior parietal, superior temporal, supramarginal and fusiform).

Materials and Methods

Participants

Sixteen typically developing adolescents (8 m/8 f, 5-15 years, mean age of sample=10.1 $\pm$ 3.3 years) were recruited as a part of a larger study at the University of California, Los Angeles. Participants had no history of neurological impairment, psychiatric disability, learning disability, language impairments, developmental delay, or significant exposure to prenatal teratogens such as alcohol. Participants were right-handed, native English speakers. Participants and their parents gave their informed consent to participate in this study, which was approved by the Institutional Review Board of the University of California, Los Angeles. Table 1 depicts the demographic details of all participants.

Neurocognitive Data Collection

Participants were administered a comprehensive battery of standardized cognitive measures that included the rapid letter naming subtest of the Comprehensive Test of Phonological Processing (CTOPP) [11], the fluency subtest of the Gray Oral Reading Test (GORT) [12], the word reading score of the Wide Range Achievement Test, 3rd Edition [13], and the Wechsler Intelligence Scale for Children, Fourth Edition (WISC-IV) [14]. These measures were selected from the larger neurocognitive battery as they were thought to represent the most distinct reading skills: the efficient access and retrieval of letters held in long-term memory (CTOPP rapid letter naming), the ability to quickly and accurately read text (GORT fluency), and correctly pronouncing real, printed words (WRAT reading). Prorated IQ Scores were calculated using the Vocabulary, Block Design, Similarity and Matrix Reasoning subtests. One participant was missing GORT Fluency data, and two were missing IQ data. Demographic data are presented in Table 1.

Image Acquisition and Processing

Structural imaging data were obtained on a Siemens 1.5T Sonata Scanner using a 12-channel head coil. Two to four high-resolution sagittal T1-weighted images were collected for each participant using the following parameters: TR= 1900 ms; TE= 4.38 ms; flip angle, 15; matrix size, 256 $\times$ 256; voxel size, 1 $\times$ 1 $\times$ 1 mm; acquisition time, 8 min 8s. Detailed image processing procedures have been described previously [16]. Briefly, pre-processing and segmentation of cortical gray matter regions on structural images were conducted using automated brain segmentation software (Freesurfer 5.1, <http://surfer.nmr.mgh.harvard.edu>) [16]. MPRAGE acquisitions for each participant were averaged to enhance signal to noise ratio (SNR), then motion-corrected, and non-brain tissue (skull, orbits) was removed. A blinded expert user (EK) manually edited skull-stripped images if extraction was poor. Images were then run through Freesurfer's recon-all longitudinal stream [17]. Gray/white

matter boundaries were automatically defined; any errors were manually corrected, but were mostly restricted to topological deficits. Volume measurements were calculated for five bilateral brain regions (supramarginal, inferior frontal, inferior parietal, superior temporal and fusiform), as well as measures of total brain, total cortical gray matter, and total white matter volumes. Freesurfer parcellation methods are summarized by Desikan et al. (2006) [24]. Relevant to our work, the inferior parietal cortex is defined by the supramarginal gyrus (rostral boundary) and the lateral occipital cortex (caudal boundary), and sits just below the superior parietal cortex. The rostral and caudal boundaries of the supramarginal gyrus were the posterior portion of superior temporal cortex and the anterior portion of the superior parietal cortex, respectively. The pars opercularis, the pars triangularis and the pars orbitalis were summed to define the inferior frontal gyrus, with the rostral portion of the inferior frontal sulcus as the rostral boundary, and the precentral gyrus as the caudal boundary. The rostral portion of the superior temporal sulcus and the caudal portion of superior temporal gyrus bound the superior temporal gyrus. Boundaries for the fusiform gyrus were the rostral portion of the collateral sulcus and most posterior portion of the lateral occipital cortex. See Figure 2 for visualization of our regions of interest.

Statistical Analyses

Statistical analyses were conducted in R v. 2.15.2. Annualized brain volume changes were calculated for each individual by subtracting the volume of gray matter at time 1 from the volume of gray matter in the same region at time 2 and divided by the inter-scan interval. Relationships between age at time 1 and annualized volume change, age at time 1 and behavioral reading performance, and between behavioral reading performance and Prorated Full Scale IQ were assessed with correlation analyses.

We used separate linear models to test our hypotheses that regional annualized volume changes are associated with better baseline reading performance. In each model, baseline reading score for each reading measure was entered as the predictor of brain volume change, with age at time 1 and total gray matter volume change utilized as covariates. A significance threshold of $p < 0.05$ was used for all tests. This analysis was repeated for time 2 scores, where separate linear models were used to explore whether time 2 scores were associated with volume change in the same regions. As follow-up analyses, we (1) entered participants' prorated IQ scores into each model as an additional covariate, and (2) examined the relationship between prorated IQ and regional cortical volume changes, controlling for age, and total cortical volume change.

Results

There were no significant relationships between rapid naming, word reading and fluency (GORT) at time 1 and prorated full-scale IQ. All reading scores were stable across the two scans, ($r > .65$), though baseline raw scores were significantly correlated with age at time 1. Age at time 1 also demonstrated a significant relationship with volume (change) in the left inferior parietal region. No other cortical regions had significant volume change-age correlations.

Better baseline performance on the WRAT Reading subtest was associated with volume reduction in the left inferior parietal cortex ($p=.005$), controlling for age and total cortical volume change. Similarly, better baseline scores on both the GORT Fluency ($p=.020$) and CTOPP Rapid Letter subtests ($p=.035$) were associated with volume decrease in the left inferior parietal cortex and better baseline performance on the CTOPP Rapid Letter subtest ($p=.037$) was associated with volume decrease in the left inferior frontal gyrus (see Figures 1 and 2, and Table 2).

Time 2 GORT fluency scores were associated with volume reductions in the left fusiform cortex ($p=.032$). In addition, time 2 WRAT word reading scores were associated with volume reduction in the left inferior parietal region, and time 2 scores on the rapid naming subtest of the CTOPP were associated with volume decrease in bilateral inferior frontal regions ($p=.010$, left; $p=.004$, right), and the left inferior parietal region ($p=.027$). Entering prorated IQ into the models resulted in similar patterns for all regions (i.e., volume decrease with increased score), but results did not reach significance, perhaps due to reduced statistical power associated with an additional predictor variable. Regional volume changes, controlling for age and total cortical volume change, however, were not significantly associated with IQ.

Discussion

This longitudinal MRI study investigated structural brain changes that co-occur with reading acquisition in typically developing children, and is the first longitudinal report to our knowledge to identify a specific relationship between cortical volume and this subset of reading skills in typically developing children. As hypothesized, we found that volume reductions in the left inferior parietal and frontal regions are characteristic of children who perform better on tests of rapid naming, word reading and fluency, regardless of age.

The longitudinal design of this study provides more power and further insight into the neuroanatomical correlates of typical reading development compared to previous cross-sectional studies. Most work to date reveals altered structural profiles in impaired readers, including reduced left hemisphere volumes in adults with dyslexia [19]. In this sample, we find an overall maturation pattern of volume decreases in canonical left hemisphere reading regions associated with better performance on three reading measures (fluency, word recognition, and rapid naming). These results complement previous findings of larger volume decreases being related to higher intelligence in subjects both with and without prenatal alcohol exposure [15], and findings of varying developmental trajectories in children of differing intelligence [8], and show that cognitive abilities may be more strongly related to trajectories of structural brain changes than volume at any one time point. Understanding trajectories of brain development and how they relate to cognitive maturation is critical for developing and evaluating targeted therapies to improve reading skill.

Though the nature of its exact functional role remains a topic of investigation, the pattern of cortical maturation described in this report supports the important role of the inferior parietal cortex in reading by suggesting that maturation in this region is associated with proficiency on tests of fluency and rapid naming. Likewise, the current report highlights the importance

of the left inferior frontal gyrus (IFG, Broca's area, BA 44/45) in reading. Imaging findings suggest variable activation patterns in the left IFG in children with dyslexia [18], and there is evidence that white matter connections between posterior and frontal anterior reading regions are disrupted in dyslexic readers [19]. To the extent that the volume decreases seen here are indicative of cortical maturation, our findings further inform the developmental trajectories of these regions by suggesting that the abnormal activations observed in this region for impaired readers might not just be a product of abnormal morphology, but also of altered overall maturation of these regions during childhood and adolescence.

It is possible that the overall decrease in volume over time is more generally due to overall intelligence, however, raw reading scores in this sample showed no relationship to intellectual ability, and IQ alone was not predictive of volume change. Thus, while we know that general intelligence and age may contribute to overall brain maturation [8, 20], and that IQ may have a unique relationship with academic achievement [21] future studies should more closely examine the relationship of IQ to regional and global maturation as it relates to specific skills.

Future studies with larger samples will be needed to replicate the present results, given the relatively small sample studied here. Further, investigations with a smaller age range would be helpful in order to narrow the longitudinal brain changes over two years to more specific aspects of reading. Nonetheless, the results reported are consistent with our *a priori* hypotheses and are quite robust for a relatively small sample (e.g., $p = 0.005$ for left inferior parietal cortex). Additionally, the longitudinal design provides greater power than a comparable cross-sectional study with a similar sample size. Future studies with increased sample size will be able to use the current results as a foundation to more closely investigate the variables, such as IQ, that may contribute to these structural changes as they relate to the evolutionarily newer skill of reading. Certainly, understanding the nature of experience's influence on brain development and cognition remains a critical goal, given previous findings of cortical change in response to intervention [22] and the effects of socioeconomic status on regions important for linguistic skill [23].

Conclusions

In conclusion, this longitudinal study demonstrates relationships between three components of skilled reading (rapid naming, word reading, and fluency) and cortical volume change in typically developing children. Specifically, decreases of volume in the frontal and parietal cortical regions over time were associated with better behavioral performance on rapid naming, word reading and fluency. Future longitudinal studies of cortical maturation and reading are needed to further our understanding of more suitable interventions for reading impairment. These results may be of help in future targeted therapies.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

This research was supported by the following organizations: National Institutes of Mental Health (NIMH) (5 R01MH087563-04), and the Eunice Kennedy Shriver National Institute of Child Health and Human Development (NICHD)(7 R01HD053893-05).

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Figure 1.

Relationships between baseline reading scores and regional volume changes were significant in four regions: (A) GORT Fluency predicts volume change in the left inferior parietal cortex. (B) WRAT Reading predicts volume change in the left inferior parietal cortex. (C) & (D), CTOPP score predicts volume change in the left inferior parietal and left inferior frontal regions. Note: residualized scores shown; total cortical gray matter change is residualized out of volume change; age at time 1 is residualized out of reading scores. Higher scores indicate better performance on the GORT and WRAT tests; lower scores are indicative of better performance on CTOPP.

Figure 2.

Brain regions demonstrating significant correlations between annual volume decreases and baseline reading scores are shown as colored regions. Grey regions were tested, but showed no significant correlations; white regions were not tested. In the left inferior frontal gyrus (red), better reading scores on the CTOPP were associated with larger volume decreases. In the left inferior parietal cortex (striped blue/green/red), better reading skills on all three measures (CTOPP (red), GORT (green), WRAT (blue)) were associated with larger volume decreases. Note: the presence of three colors in this region denotes it's persistent involvement in these reading skills and is not indicative of smaller regions of the cortex being differentially involved in reading.

Table 1

HR for Major CVD, Total CVD, CHD, Stroke, and MI by *COMT* SNPs rs4680 (val158met) and rs4818
Among Women Exclusively Allocated to Placebo

End Point*	Events	HR [95% CI]; <i>P</i> Value	
		rs4680 [†]	rs4818 [‡]
Age-adjusted models		n=5811	n=5795
Major CVD	135	0.66 [0.51–0.84]; 0.0007	0.67 [0.51–0.86]; 0.0022
Total CVD	204	0.77 [0.63–0.93]; 0.0075	0.70 [0.57–0.87]; 0.0010
CHD	126	0.81 [0.63–1.04]; 0.1030	0.69 [0.53–0.90]; 0.0068
Stroke	59	0.76 [0.53–1.09]; 0.1400	0.80 [0.55–1.17]; 0.2580
MI	53	0.60 [0.41–0.90]; 0.0130	0.59 [0.39–0.91]; 0.0162
Fully adjusted models [‡]		n=5136	n=5120
Major CVD	116	0.65 [0.50–0.85]; 0.0016	0.69 [0.52–0.91]; 0.0095
Total CVD	174	0.73 [0.59–0.91]; 0.0042	0.69 [0.55–0.87]; 0.0016
CHD	108	0.73 [0.56–0.96]; 0.0248	0.65 [0.38–0.87]; 0.0038
Stroke	50	0.76 [0.51–1.12]; 0.1669	0.79 [0.52–1.20]; 0.2764
MI	47	0.53 [0.35–0.82]; 0.0047	0.58 [0.37–0.91]; 0.0168

CI indicates confidence interval; CHD, coronary heart disease; CVD, cardiovascular disease; HR, hazard ratio; and MI, myocardial infarction.

* Major CVD, the primary Women's Health Study outcome is a composite of MI, stroke, or death from cardiovascular causes. Total CVD, is a composite of revascularization procedures (percutaneous transluminal coronary angioplasty and coronary bypass graft) in addition to events in the primary outcome. CHD is a composite of nonfatal MI or fatal CHD plus revascularization procedures.

[†] rs4680 coded allele=G(val), reference allele=A(met); rs4818 coded allele=G, reference allele=C.

[‡] Fully adjusted Cox models were adjusted for standard cardiovascular risk factors: age, systolic blood pressure, diastolic pressure, low-density lipoprotein-cholesterol, high-density lipoprotein-cholesterol, triglycerides, family history of myocardial infarction, family history of diabetes mellitus, smoking, and the use of hormone replacement therapy. Observations with incomplete data were not included in the analysis.

Table 2

Linear Regression of Baseline Raw Scores on Change in Gray Matter Volume Controlling for Age and Total Cortical Gray Matter Volume Change.

Regions	B0 GORT	B1 GORT	R2 GORT	B0 WRAT	B1 WRAT	R2 WRAT	B0 CTOPP	B1 CTOPP	R2 CTOPP
Left FF	-150.7	-7.2	.39	116.9	-13.5	.21	-670.1	7.5	.19
Left IFG	-87.1	-5.9	.45	402.6	-23.2	.45	-1625.0	22.2 *	.54
Left IFP	433.1	-17.1 *	.58	1466.2 *	-63.0 **	.64	-2327.0	36.6 *	.52
Left SMG	-689.5	-.8	.27	-666.0	-3.3	.28	-1406.0	9.4	.31
Left STG	566.4 *	-5.4	.56	652.3	-7.8	.45	31.6	6.6	.46
Right FF	1059.2 *	-7.9	.42	1282.3 *	-24.6	.39	656.0	4.7	.32
Right IFG	-59.6	-5.1	.33	226.5	-14.2	.27	-1110.0	14.9	.39
Right IFP	255.5	-5.4	.36	859.3	-36.5	.49	-876.5	14.7	.36
Right SMG	-1117.0 *	-1.2	.31	-1333.0 *	12.6	.33	-719.3	-5.3	.31
Right STG	1066.0 *	-6.2	.47	1279.0 *	-11.7	.45	1046.4	.22	.43

FF= Fusiform Gyrus, IFG=Inferior Frontal Gyrus, IFC=Inferior Parietal Cortex, SMG=Supramarginal Gyrus, STG=Superior Temporal Gyrus.

* =p<.05,

** = p<.01.