

Brain Basis of Phonological Awareness for Spoken Language in Children and Its Disruption in Dyslexia

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Phonological awareness, knowledge that speech is composed of syllables and phonemes, is critical for learning to read. Phonological awareness precedes and predicts successful transition from language to literacy, and weakness in phonological awareness is a leading cause of dyslexia, but the brain basis of phonological awareness for spoken language in children is unknown. We used functional magnetic resonance imaging to identify the neural correlates of phonological awareness using an auditory word-rhyming task in children who were typical readers or who had dyslexia (ages 7–13) and a younger group of kindergarteners (ages 5–6). Typically developing children, but not children with dyslexia, recruited left dorsolateral prefrontal cortex (DLPFC) when making explicit phonological judgments. Kindergarteners, who were matched to the older children with dyslexia on standardized tests of phonological awareness, also recruited left DLPFC. Left DLPFC may play a critical role in the development of phonological awareness for spoken language critical for reading and in the etiology of dyslexia.

Keywords: child, dyslexia, fMRI, phonological awareness, reading

Young children learn to speak naturally and effortlessly because they are equipped with psychological processes and neural systems that have evolved over time to engender language in humans. Conversely, reading acquisition is a recent cultural invention that demands years of explicit instruction and effort. Beginning readers must learn to relate auditory language to print through “phonological awareness,” the concept that spoken words are composed of discrete sounds (phonemes) that can be mapped onto letters or syllables (graphemes). Phonological awareness ability in prereaders predicts later success in learning to read in both alphabetic and non-alphabetic languages (Ziegler and Goswami 2005), although the precise relation between phonological awareness and reading acquisition may differ across orthographies (Goswami and East 2000). A deficit in phonological awareness is thought to be a common etiology of dyslexia (Bradley and Bryant 1978; Wagner and Torgesen 1987), a difficulty in learning to read despite adequate intelligence and reading instruction that affects 5–17% of children (Shaywitz 1998; Wolf 2007). Here, we used functional magnetic resonance imaging (fMRI) to discover the neural correlates of phonological awareness using auditory language tasks in children who are typically developing readers and children with dyslexia.

Most neuroimaging studies examining phonological awareness in children have presented words visually rather than

aurally and asked children to perform tasks that require phonological awareness after accessing the phonological form of the printed word. Rhyme detection tasks, in which children decide whether or not 2 visually presented words or letters rhyme, have been frequently used to identify the neural circuitry associated with phonological awareness. These rhyming tasks are commonly used for 3 reasons: rhyming judgments require phonological awareness of the constituent sound parts of words or letter names; rhyming is one of the earliest phonological awareness tasks that children master (Anthony et al. 2003); and rhyming is an effective predictor of later reading success for young children (Bradley and Bryant 1978; MacLean et al. 1987; Goswami and East 2000; de Jong and van der Leij 2002; Ziegler and Goswami 2005).

Functional neuroimaging studies of phonological awareness using tasks with visually presented materials have revealed left hemisphere regions that are engaged in phonological analysis of printed letters and words. These regions change in activation as children develop into better readers and are differentially engaged in children with dyslexia. In typically developing children, regions engaged during phonological awareness tasks with print include left inferior frontal gyrus, superior temporal gyrus, middle temporal gyrus, and fusiform gyrus (Temple et al. 2001; McCandliss and Noble 2003; Booth et al. 2004; Shaywitz et al. 2004; Cao et al. 2006; Hoeft et al. 2006; Bitan et al. 2007; Shaywitz et al. 2007; Bolger et al. 2008a, 2008b; Bitan et al. 2009). Activations in left posterior temporal and parietal regions increase with age and reading proficiency (Hoeft et al. 2006; Bitan et al. 2007; Shaywitz et al. 2007), but these activations are often reduced in children with dyslexia relative to age- or ability-matched typical readers (Temple et al. 2001; Shaywitz et al. 2002; Cao et al. 2006; Hoeft et al. 2007). Effective reading remediation for dyslexia is associated with increased activation in left posterior temporal and parietal regions (Simos et al. 2002; Temple et al. 2003; Shaywitz et al. 2004; Meyler et al. 2008). Electrophysiological (evoked response potential [ERP]) studies report that children as young as 7 years of age show a “rhyming effect” or a greater N400/N450 response for visually presented nonrhymes as compared with rhymes (Grossi et al. 2001; Khateb et al. 2007). This ERP rhyming effect appears aberrant in children with dyslexia (Ackerman et al. 1994; Lovrich et al. 2003).

Examining the neural correlates of phonological awareness using auditory tasks is important because it is phonological

awareness for the sounds of language, in the auditory or spoken modality, that underlies typical reading acquisition and is disrupted in dyslexia. Prior imaging studies, which examined phonological awareness using visual tasks, focused on the consequences of dyslexia on reading performance, whereas an imaging study examining phonological awareness using auditory tasks involves no reading and focuses on the putative cause of dyslexia. Indeed, the atypical brain responses in dyslexia for visually presented words during a task that demands phonological awareness reflects not only phonological analyses but also multiple processes related to reading such as orthographic analysis and word recognition. An auditory task provides a more direct measure of phonological awareness.

A few neuroimaging studies have compared typical and dyslexic readers' brain activations in response to auditory tasks that involve phonological awareness, such as word or nonword rhyming. These studies did not, however, attempt to isolate phonological awareness because their baseline tasks involved tones or visual letters and symbols (Corina et al. 2001; Booth et al. 2004; Raizada et al. 2008). Therefore, it is difficult to know if activation differences, which varied across studies, were related to phonological awareness or one of many other aspects of auditory language processing. Precise identification of the neural correlates of phonological awareness for auditory tasks requires a contrast where stimulus properties such as modality and meaningfulness are held constant, and only the demand for phonological awareness is varied.

Here, we directly investigated the neural correlates of phonological awareness by examining brain activation via fMRI in conditions that held auditory language perception constant but varied demands on phonological awareness. Children listened to pairs of words and made judgments about the words in 2 conditions. For the phonological awareness task, they judged whether pairs of words did or did not rhyme (Rhyme condition: "cat" and "bat" rhyme; "cup" and "pen" do not rhyme). For the control task, they judged whether pairs of words were or were not identical (Control condition: "dog" and "dog" are identical; "rat" and "pan" are not identical). Stimuli (auditory words) were similar across the 2 tasks, but the rhyme task demanded phonological awareness and analysis, whereas the control task placed minimal demands on phonological awareness.

We conducted a 2-part study. The goal of Experiment 1a was to discover the neural correlates of phonological awareness in the auditory modality in typical readers ages 7–13. The goal of Experiment 1b was to compare the neural correlates of phonological awareness in children with dyslexia relative to a group of typically reading age- and IQ-matched controls and also to a performance-matched control group of younger kindergarten children with typical language abilities. Because a deficit in auditory phonological awareness is thought to be a leading cause of dyslexia, we hypothesized that we would see differences between the age-matched typical and dyslexic groups despite the fact that no reading was involved in the experimental tasks. We examined a group of typically developing kindergarteners, ages 5–6, who were matched to the dyslexic children on IQ and performance on a standardized measure of auditory phonological awareness. Children this young are rarely involved in fMRI studies, but this is the age when children begin to learn to read. Inclusion of this younger group allowed us to examine whether any activation differences in the older dyslexic readers either reflected a de-

velopmental delay or were a direct consequence of the level of phonological awareness. In either of these cases, the 5- to 6-year-olds would resemble the older children with dyslexia in their patterns of activation. If the 5- to 6-year-olds exhibited patterns of activation different from those of older dyslexic children, then any atypical activation in the children with dyslexia may be more related to the etiology of dyslexia than a developmental delay or the level of phonological awareness.

Materials and Methods

Participants

All participants were part of a larger study of reading and language and met eligibility criteria including: native English speaker, normal hearing, no history of cognitive or motor developmental difficulties or brain injury, no current regimen of medication affecting the nervous system, and at least average verbal IQ scores (Kaufman Brief Intelligence Test [KBIT-2] verbal standard score > 85). This study was reviewed and approved by Massachusetts Institute of Technology (MIT)'s and Tufts University's institutional review boards, and parents and child participants completed informed consent and assent forms, respectively. Participants were divided into 4 groups.

Typically Developing Readers

This group included 17 typically developing, right-handed children in grades 1–5 (ages 7–13, mean = 9.2, standard deviation [SD] = 1.1; 8 females). All children were good readers (Woodcock Reading Mastery Test-Revised/Normative Update [WRMT-R NU] Reading Cluster standard score > 100 [composite score of Word ID, Word Attack, and Passage Comprehension]) with no history of language, reading, or other developmental difficulties (Table 1). All typically developing readers, ages 7–13, who completed the brain imaging session successfully were included in this group (data from 3 additional children could not be used due to motion artifacts).

Children with Dyslexia

This group included 12 children with dyslexia (age 7–13, mean = 9.0, SD = 1.5; 4 females). All children with dyslexia had a history of reading difficulty, were evaluated and diagnosed with dyslexia independently by an accredited clinician before the study, and were receiving intensive reading remediation, which included phonological awareness training. Further criteria for inclusion in this group included a standard score below the 25th percentile on at least 2 reading and/or phonological awareness subtests (WRMT-R NU: Word Identification, Word Attack, and Passage Comprehension; Comprehensive Test of Phonological Processing [CTOPP]: Elision, Blending, Nonword Repetition; Table 2). In this group, 11 children were right handed; one child

Table 1

Participant information: typically developing readers (Experiment 1a)

Experiment 1: typical readers	Mean ± SD
N	17
Age (months)	110.7 ± 12.8
Behavioral measures	
KBIT Verbal IQ Standard Score	114.4 ± 11.0
WRMT Reading Cluster ^a Standard Score	116.3 ± 11.2
CTOPP Phonological Awareness Composite ^b Standard Score	107.8 ± 13.3
CTOPP Phonological Awareness Composite ^b Raw Score (maximum = 40)	29.9 ± 6.0
CTOPP Nonword Repetition Standard Score ^c	9.4 ± 2.9
CTOPP Nonword Repetition Raw Score (maximum = 18)	10.1 ± 3.2
In-scanner task performance	
Accuracy (% correct)	
	Rhyme
	Control
	82.5 ± 13.2
	94.0 ± 5.3
RT (ms)	
	Rhyme
	Control
	3847 ± 516
	3659 ± 432

^aComposite of standardized Word Identification, Word Attack, and Passage Comprehension subtests; data not available for Kindergarteners.

^bComposite of Elision and Blending Words.

^cThis subtest standard score is based on a mean of 10 rather than 100. Scores of 8–12 are considered to be in the average range.

was left handed but showed typical left hemisphere language dominance as assessed with a separate semantic decision task in the scanner. All children with dyslexia who completed the brain imaging session successfully were included in the study (data from 2 additional children could not be used due to motion artifacts).

Age-Matched Controls

A subset of typically developing readers was selected as an age- and verbal IQ-matched control group ($n = 12$, mean = 9.0, SD = 1.2; 6 females) for a direct comparison to children with dyslexia (Table 2).

Kindergarten Controls

This group was comprised of kindergarteners ($n = 10$; ages 5–6, mean = 5.9, SD = 0.4; 3 females) with at least average language ability and no family history of reading difficulties. The kindergarteners were younger than the children with dyslexia but were matched for verbal IQ and on raw scores for phonological awareness ($P > 0.15$, nonsignificant [NS]; Table 2 [CTOPP raw scores for Elision and Blending]). Only kindergarteners who performed at an above-chance level during practice trials underwent fMRI scanning; the excluded children did not reliably perform the rhyme task. Twenty kindergarteners completed the brain imaging session successfully. Data from 4 of these children were excluded due to motion artifacts, and data from 6 other children were not included because their IQ and/or phonological awareness performance did not match that of the children with dyslexia.

Behavioral Measures

Participants completed standardized measures of cognitive, language, and reading abilities, including the KBIT-2 (Kaufman and Kaufman, 1990), the CTOPP (Elision, Blending Words, and Nonword Repetition subtests; Wagner et al. 1999), and the WRMT-R NU (Word ID, Word Attack, and Passage Comprehension subtests; Woodcock 1998). Parents also completed a questionnaire detailing their child's previous and current language, reading, cognitive, and motor development, as well as any family history of learning difficulties.

Group demographics and behavioral measures are reported in Table 1 (all typical readers, Experiment 1a) and Table 2 (children with dyslexia, age-matched controls, and kindergarteners, Experiment 1b). Age-matched typical readers scored significantly higher than dyslexic readers on standardized measures of reading (WRMT-R NU Reading Cluster; Word ID, Word Attack, and Passage Comprehension subtests) and phonological awareness (CTOPP Elision, Blending, Nonword Repetition subtests) (independent-samples t -tests, 2 tailed, all at significance level of $P < 0.001$). The 2 groups did not differ significantly on verbal IQ ($P = 0.07$), although typical readers had a higher mean verbal IQ than children with dyslexia (Table 2). Kindergarteners were ability matched to older

children with dyslexia (Table 2). Their scores did not differ significantly on verbal IQ ($P = 0.15$) or on raw phonological awareness (CTOPP Elision and Blending subtests) ($P = 0.33$). Thus, on phonological awareness measures, children with dyslexia scored equally with kindergarteners who were on average 3 years younger (Table 2).

Phonological Awareness Imaging Tasks

During fMRI scanning, participants completed 3 block conditions: a phonological awareness task (Rhyme task), a control task (Match task), and fixation (Rest). The Rhyme task required participants to listen to a pair of words, segment the words' phonological form into constituent parts, identify the ending (i.e., the rime), and decide if the endings were identical or not (e.g., "cat" and "bat" rhyme; "cup" and "pan" do not). The Match task required participants to listen to a pair of words and decide if the 2 word forms were identical or not (e.g., "dog" and "dog" are identical; "rat" and "pan" are not). During both tasks, children heard pairs of words and made a yes/no decision about the pairs. There were equal numbers of "yes" and "no" trials for both the rhyme and match tasks. "Yes" and "no" responses were randomized across blocks to preclude participants from making assumptions about the distribution of "yes" and "no" trials during each block. Auditory words were similar across the 2 tasks, but only the rhyme task demanded phonological awareness and analysis, whereas the control task placed minimal demands on phonological awareness.

Stimuli

All stimuli were real monosyllabic words matched within and across conditions (Rhyme and Match) for concreteness, written and verbal frequency, and number of letters and phonemes (data from MRC Psycholinguistic database; one-way analysis of variance (ANOVA), $P > 0.05$, NS, within each condition; ad hoc t -tests comparing the conditions were also nonsignificant, $P = 0.53$ or greater). To ensure that all young participants were likely to be familiar with the task items, the words were selected in consultation with experts in early reading development and dyslexia at the Center for Reading and Language Research at Tufts University. All words were recorded by the same female speaker. The words were then filtered and normalized to 80 dB, using Adobe Audition 1.5 software. The mean duration of Rhyme stimuli was 554 ms, and the mean duration of Match stimuli was 532 ms; there was no significant difference between word duration across the 2 conditions ($P > 0.05$, NS). Stimuli were presented via Presentation software (Neurobehavioral Systems Inc., Albany, CA).

Procedure

Children completed task training and practice outside the scanner with a set of stimuli different from those used during scanning. Children

Table 2

Participant information: age-matched controls, children with dyslexia, and kindergarten children (Experiment 1b)

	Age-matched controls (mean ± SD)	Children with dyslexia (mean ± SD)	Kindergarten (mean ± SD)	t Values: dyslexia vs. age matched	t Values: dyslexia vs. kindergarten	
<i>N</i>	12	12	10			
Age (months)	108.2 ± 14.4	108.5 ± 18.0	70.6 ± 5.0	0.05, NS	6.42***	
Behavioral measures						
KBIT Verbal IQ Standard Score	111.7 ± 8.6	104.7 ± 9.1	114.9 ± 15.0	1.94, NS	1.98, NS	
WRMT-R NU Reading Cluster ^a Standard Score	113.6 ± 10.9	92.3 ± 7.4	—	5.53***	—	
CTOPP Phonological Awareness Composite ^b Standard Score	108.0 ± 12.7	89.3 ± 9.4	117.4 ± 12.9	4.12***	5.92***	
CTOPP Phonological Awareness Composite ^b Raw Score (maximum = 40)	30.2 ± 5.5	19.2 ± 5.6	20.1 ± 7.5	4.93***	0.33, NS	
CTOPP Nonword Repetition Standard Score ^c	10.2 ± 2.9	6.8 ± 2.8	9.1 ± 3.0	2.88**	1.82, NS	
CTOPP Nonword Repetition Raw Score (maximum = 18)	11.1 ± 3.2	7.3 ± 3.5	7.2 ± 3.6	2.72*	0.09, NS	
In-scanner task performance						
Accuracy (% correct)	Rhyme	83.3 ± 9.9	77.4 ± 9.2	73.9 ± 13.1	1.68, NS	1.67, NS
	Control	95.1 ± 3.6	87.1 ± 15.8	86.6 ± 12.1	1.63, NS	1.12, NS
RT (ms)	Rhyme	3908 ± 589	4092 ± 725	4362 ± 425	0.65, NS	1.03, NS
	Control	3730 ± 497	3935 ± 745	4020 ± 398	0.74, NS	0.31, NS

^aComposite of standardized Word Identification, Word Attack, and Passage Comprehension subtests; data not available for Kindergarteners.

^bComposite of Elision and Blending Words.

^cThis subtest standard score is based on a mean of 10 rather than 100. Scores of 8–12 are considered to be in the average range.

* $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$, 2-tailed t -test; all other t -tests NS at threshold of $P = 0.05$.

then participated in a practice fMRI scan during which they helped experimenters scan a plush stuffed animal just prior to their own scan.

During each trial, 2 words were played in sequence via pneumatic headphones. While listening to the words, participants saw a white fixation cross on a black background on the mirror screen in front of them. Participants were instructed to respond as quickly as possible via button press (yes or no) whether or not the 2 words rhymed or matched (as appropriate in each condition). During each trial, the first word was played at the beginning of the trial, and the second word was played 2 s later. A question mark (2 s) concluded each 6-s-long trial. This was a block design with 4 trials per each 24-s block, 6 blocks per condition. Participants also viewed a fixation cross for a Rest condition (6 blocks, each 24 s). Audio-recorded instructions preceded each condition. The order of trials, blocks, and conditions was randomized. For school-aged typical readers (ages 7–13) and children with dyslexia, Rhyme and Match conditions occurred within the same 14-min run. Also, as part of a larger study, typical readers (ages 7–13) and children with dyslexia completed visual rhyme and visual match control tasks with visually presented word stimuli included in the same run (6 blocks of each). All participants completed 2 additional tasks during the scanning session (a semantic and an orthographic task) as part of a larger study, with the order of all tasks randomized. Rhyme and Match conditions were separated into two 4-min runs for kindergarteners (ages 5–6) because we thought that they would have a difficult time switching between tasks, and there were no additional visual tasks.

Image Acquisition

Image acquisition was performed on a Siemens 3T MAGNETOM Trio, A Tim System (Siemens Medical Solutions, Erlangen, Germany) using a commercial 12-Channel Matrix head coil (Siemens Medical Solutions). Head immobilization was achieved using foam pads. Automatic slice prescription, based on alignment of localizer scans to a multisubject atlas, was used to achieve a consistent head position across subjects. Blood oxygenation level-dependent measurements were performed using a gradient-echo T_2^* -weighted EPI sequence. Thirty-two 4-mm thick slices with interslice gap = 0.8 mm were positioned parallel to the AC-PC line. The imaging parameters were time repetition = 2 s, time echo = 30 ms, flip angle = 90° , bandwidth = 2520, echo spacing = 0.47, field of view = 192×192 , matrix size = 64×64 . Prior to each scan, 4 images were acquired and discarded to allow longitudinal magnetization to reach equilibrium.

fMRI Data Analysis

Statistical analysis was performed with SPM2 statistical parametric mapping software (Wellcome Department of Cognitive Neurology, London). After image reconstruction, each subject's data were realigned to the first functional volume. For kindergarteners, who completed the task in 2 runs, all images were normalized to the mean image from the first run. Extensive artifact detection was then conducted (see below). Sessions were normalized by using the mean functional volume and resampled to fit Montreal Neurological Institute stereotaxic space, which is a valid normalization for children ages 7 and older (Burgund et al. 2002). Spatial smoothing was done with a Gaussian filter (4 mm, full-width, half-maximum). Each subject's data were high-pass filtered at 128 s and analyzed using a fixed-effects model.

Data were visually inspected and reviewed for artifacts using custom software (<http://web.mit.edu/swg/software.htm>). For all subjects, the mean signal intensity for each individual volume and the average mean signal intensity for all volumes in a functional imaging run were calculated. Individual volumes with mean signal intensity ≥ 3 SD from the overall mean signal intensity of the run were excluded from subsequent statistical analyses. Additionally, movement parameters calculated by SPM2 realignment were used to exclude volumes with potential artifacts on an individual subject level. The difference series between subsequent scans was calculated for both translational and rotational movement. Using the derivative of the motion parameters allowed for the identification of volumes in which subjects were moving their heads excessively, resulting in data artifacts. Volumes were excluded if the norm of rotational movement [$=\sqrt{(x^2 + y^2 + z^2)}$] exceeded 0.5 mm and/or if the norm of rotational movement

[$=\sqrt{(\text{pitch}^2 + \text{roll}^2 + \text{yaw}^2)}$] exceeded 0.01 radians. Participants were excluded from the study if more than $\frac{1}{4}$ of their volumes were deemed as artifacts according to these criteria or if the task > rest contrast images failed to exhibit well-defined bilateral auditory activation at $P < 0.05$ (due to excessive motion or imaging equipment malfunction).

An independent-samples t -test revealed no significant differences in the numbers of excluded volumes between conditions or the comparison groups (children with dyslexia mean number of excluded volumes = 11.5, age- and IQ-matched typical readers mean = 10.8; $P = 0.87$; rhyme mean = 1.79, match mean = 0.96, $P = 0.21$). In order to double-check the integrity of the findings, we ran an analysis of covariance (ANCOVA) with covariates for motion outliers and session orders. The ANCOVA results were nearly identical to the t -tests; hence, we report the t -test statistics.

Group Analyses

Experiment 1a: Brain Basis for Phonological Awareness for Spoken Language in Typically Developing Readers

To examine activations for linguistic processing (Match > Rest) and phonological awareness (Rhyme > Match) in typically developing readers (ages 7–13), we conducted 2 one-sample t -tests (block design analyses, cluster-level corrected for multiple comparisons at $P < 0.05$, height threshold $P < 0.001$, extent threshold (ET) > 25).

Experiment 1b: Brain Bases of Phonological Awareness for Spoken Language in Children with Dyslexia

To examine activations for linguistic processing (Match > Rest) and phonological awareness (Rhyme > Match), we conducted one-sample t -tests for each group, and a 2-sample t -test comparing directly the matched children with versus without dyslexia (block design analyses, cluster level corrected for multiple comparisons at $P < 0.05$, height threshold $P < 0.001$, extent threshold > 25 voxels). Activation for the kindergarteners was examined in regions of interest (ROI) analyses restricted to a 10-mm sphere around the peak activation in the region of difference between the typical readers and children with dyslexia and evaluated with a one-tailed t -test between conditions ($P < 0.05$). We did not compare the kindergarteners directly with the older groups because scans were conducted differently for the kindergarteners.

Results

Experiment 1a: Brain Basis of Phonological Awareness for Spoken Language in Typically Developing Readers

Behavioral Results

Typical readers (ages 7–13) were significantly more accurate ($t_{(15)} = 3.6$, $P < 0.01$) and significantly faster ($t_{(15)} = 3.9$, $P < 0.01$) on the match task than the rhyme task (Table 1). Children's accuracy on the rhyme task correlated significantly with their performance on the CTOPP standardized composite score of Elision and Blending (Pearson correlation $r_{(15)} = 0.63$, $P < 0.01$). For one participant, in-scanner data were unavailable due to a technical error, but the child successfully completed task training and the child's performance accuracy was monitored throughout the scanning procedure so as to ensure that the child understood the task and was following the instructions.

Imaging Results

For linguistic processing of spoken language (Match > Rest contrast), typically reading children showed activation in bilateral superior temporal gyri, left insular, right insular cortex/frontal gyrus, medial frontal, and bilateral occipital/cuneus regions (Fig. 1a and Table 3). For explicit phonological analysis of spoken language (Rhyme > Match contrast),

children showed greater activation only in left dorsolateral prefrontal cortex (DLPFC) (Fig. 1b and Table 3).

Results for Experiment 1b: Brain Bases of Phonological Awareness for Spoken Language in Children with Dyslexia

Behavioral Results

There were no significant differences in accuracy or reaction time between the children with dyslexia and the age-matched controls (12 age and IQ-matched subset of the 17 typical readers) or between children with dyslexia and kindergarteners (Table 2). Participants' performances were analyzed with separate mixed-measures ANOVAs (2 conditions x 3 groups) for accuracy and for reaction time. The ANOVAs revealed a significant main effect of accuracy (Match more accurate than Rhyme; $F_{1,28} = 34, P < 0.01$) and a significant main effect of reaction time (Match faster than Rhyme; $F_{1,28} = 17, P < 0.01$).

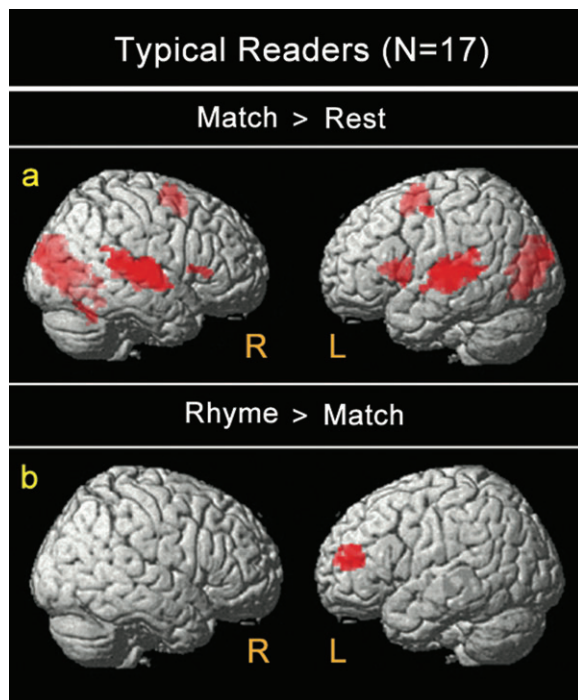


Figure 1. Brain activation for typically developing readers (Experiment 1a) during (a) Match > Rest and (b) Rhyme > Match.

Table 3

Experiment 1a: activation for Match > Rest and Rhyme > Match in all typical readers (Montreal Neurological Institute [MNI] coordinates; cluster-level corrected for multiple comparisons at $P < 0.05$, height threshold $P < 0.001$, extent threshold > 25 voxels)

Brain region groups	Hemisphere	x	y	z	t	Volume (voxels)
All typical readers (n = 17)						
Match > Rest						
Insular cortex/anterior inferior frontal gyrus	L	-38	12	2	7.92	265
	R	26	-52	0	6.66	45
Posterior superior temporal gyrus	L	-46	-20	6	10.70	1291
	R	46	-30	10	10.97	1481
Occipital/cuneus	Bilateral	8	-80	8	15.80	2101
Medial frontal gyrus/SMA region	Bilateral	-4	6	58	8.26	329
Cerebellum	R	30	-58	-26	6.05	85
Rhyme > Match						
DLPFC	L	-30	48	12	6.09	251

There were no significant interactions between groups ($P > 0.01$).

There were no significant correlations between children's in-scanner performance and CTOPP phonological awareness scores (neither for each group separately nor for all groups combined, $P > 0.05$), perhaps due to the smaller sample sizes. In-scanner performance was not recorded for 2 participants with dyslexia due to a technical error.

Imaging Results

Children with dyslexia versus age-matched controls. For the Match > Rest contrast, typically reading age-matched controls and children with dyslexia showed activation in bilateral superior temporal gyri, left insular, right insular cortex/frontal gyrus, medial frontal, and bilateral occipital/cuneus regions (Fig. 2a,b and Table 4). Relative to age- and IQ-matched controls, children with dyslexia showed greater activation in a right temporoparietal region that included superior temporal, middle temporal, and angular gyri (Table 4 and Fig. 2c; $x = 48, y = -64, z = 24, \text{volume} = 62 \text{ voxels}, t = 4.5$). The difference between groups in this region reflected a combination of decreased activation for Match relative to Rest (a deactivation

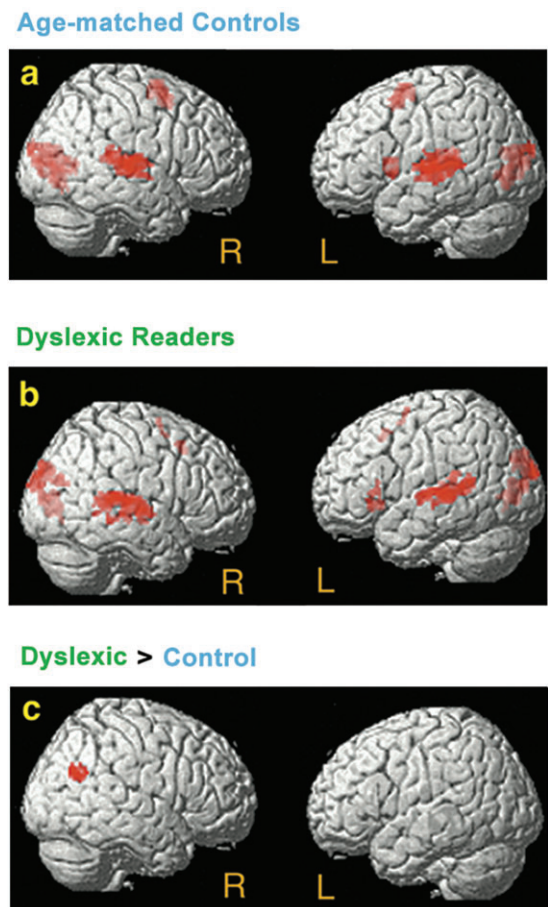


Figure 2. Activation for Match > Rest (Experiment 1b). (a) Typically reading age-matched controls (n = 12) and (b) children with dyslexia (n = 12) showed activations in bilateral superior temporal gyri, left insular cortex/frontal gyrus, medial frontal, and bilateral occipital/cuneus regions. (c) Children with dyslexia exhibited significantly greater right temporoparietal activation as compared with age-matched controls.

from rest) in typically reading children and an increased activation in children with dyslexia (Figure 3). There were no greater activations in typical readers as compared with children with dyslexia for this control task ($P > 0.001$).

Typically reading children showed greater activation only in DLPFC for the Rhyme relative to the Match task (Table 4). Children with dyslexia did not show any statistically significant group activation for Rhyme > Match (Fig. 4b,e). When age-matched typical and dyslexic readers were compared directly, the typical readers showed significantly greater activation than the dyslexic readers in left DLPFC (Figs 4c,f and 5; $x = -32, y = 48, z = 12, ET = 71, t = 5.3$). In the left DLPFC region of group difference, all 12 typical readers showed activation, but only 1 of 12 children with dyslexia

showed activation (Fig. 5, Fig. 6). Markedly reduced activation in left DLPFC exhibited by dyslexic readers could not be attributed to a general reduction in activation; across the whole-brain, dyslexic readers on average activated more voxels (mean = 9966, SD = 10 816) than typical readers (mean = 6038, SD = 4232) for the Rhyme > Match contrast, although this difference was not significant ($P = 0.25$). The difference between groups in this region reflected increased activation for the Rhyme relative to the Match task in the typically developing readers and slightly decreased activation for the Rhyme relative to the Match task in the dyslexic readers (Fig. 7). Finally, whole-brain analyses did not reveal any greater activation for Match > Rhyme in either experimental group ($P > 0.001$).

Table 4
Experiment 1b: activation for Match > Rest and Rhyme > Match in age-matched controls ($n = 12$) and children with dyslexia ($n = 12$) (Montreal Neurological Institute [MNI] coordinates; cluster-level corrected for multiple comparisons at $P < 0.05$, height threshold $P < 0.001$, extent threshold > 25)

Brain region groups	Hemisphere	x	y	z	t	Volume
Age- and IQ-matched controls ($n = 12$)						
Match > Rest						
Insular cortex/anterior inferior frontal gyrus	L	-38	10	2	7.28	64
Posterior superior temporal gyrus	L	-48	-20	8	8.71	756
	R	58	-18	10	11.24	597
Occipital/cuneus	Bilateral	8	-80	8	15.44	938
Medial frontal gyrus/SMA region	Bilateral	-4	6	56	13.28	294
Insular cortex/anterior inferior frontal gyrus	L	-32	22	6	6.27	87
Posterior superior temporal gyrus	L	-58	-12	4	9.59	534
	R	60	-22	8	11.29	711
Occipital/cuneus	L	-6	-96	24	7.20	79
	R	14	-94	26	6.76	480
Medial frontal gyrus	R	4	18	46	5.97	39
Rhyme > Match						
DLPFC	L	-32	48	14	6.10	52
Children with dyslexia ($n = 12$)						
Insular cortex/anterior inferior frontal gyrus	L	-32	22	6	6.27	87
Posterior superior temporal gyrus	L	-58	-12	4	9.59	534
	R	60	-22	8	11.29	711
Occipital/cuneus	L	-6	-96	24	7.20	79
	R	14	-94	26	6.76	480
Medial frontal gyrus	R	4	18	46	5.97	39
Rhyme > Match						
No significant activations						

Kindergarteners. We examined activation in kindergarteners in the right inferior parietal region that exhibited a difference between age-matched typical and dyslexic readers during the Match task (Match > Rest; ROI was a 10-mm sphere around peak activation of the region shown in Fig. 2c). Kindergarteners exhibited significant deactivation in this region (Match > Rest mean = 0.50; $t_{(9)} = 2.6; P < 0.05$) that was similar in magnitude to the older typical readers and dissimilar to the pattern of activation exhibited by the dyslexic readers (Fig. 3). We also examined activation in kindergarteners in the left DLPFC region that exhibited a difference between age-matched typical and dyslexic readers during the phonological awareness Rhyme contrast (Rhyme > Match; ROI was a 10-mm sphere around peak activation of the region shown in Fig. 4c). Kindergarteners exhibited significant activation in this region (Rhyme > Match mean = 0.54, $t_{(9)} = 2.0, P < 0.05$) that was similar in magnitude to the older typical readers and dissimilar to the pattern of activation exhibited by the dyslexic readers (Fig. 6).

Discussion

Brain Bases of Phonological Awareness for Spoken Language

The present study investigated brain regions that participate in phonological awareness for spoken language, an essential ability for learning to read in typical readers and one that is compromised in dyslexia. The greater demand on phonological awareness incurred by an auditory rhyming task relative to an auditory verbal control task resulted in increased activation in a left DLPFC region in typically developing readers but not in children with dyslexia. Matched typical readers (ages 7–12) showed significantly greater activation in left DLPFC region than did dyslexic readers (ages 7–13). Further, younger children ages 5–6, who were matched to the older dyslexic children for phonological awareness, exhibited greater left DLPFC activation during the Rhyme than the Match task in the same region and at the same magnitude as typically developing readers in the age-matched group. These findings indicate that left DLPFC may play a critical function in phonological awareness in typical development and that children with dyslexia do not engage this region for phonological processing.

Convergent lines of evidence indicate that the reduction of left DLPFC activation for phonological awareness in dyslexia is related to the cause of dyslexia. First, brain differences between the groups are unlikely to be secondary to reading difficulty because they occurred on an auditory nonreading task. Second,

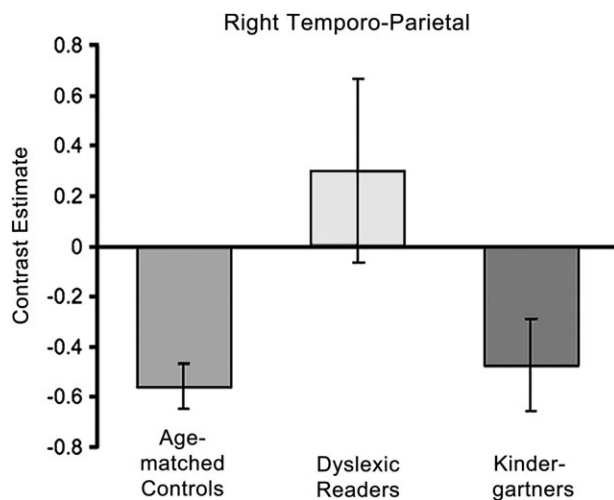


Figure 3. Mean contrast estimates for right temporoparietal region of difference between children with dyslexia and age-matched controls for Match > Rest (Experiment 1b). Kindergarteners showed deactivation similar in magnitude to typical readers. Error bars represent the standard error of the mean.

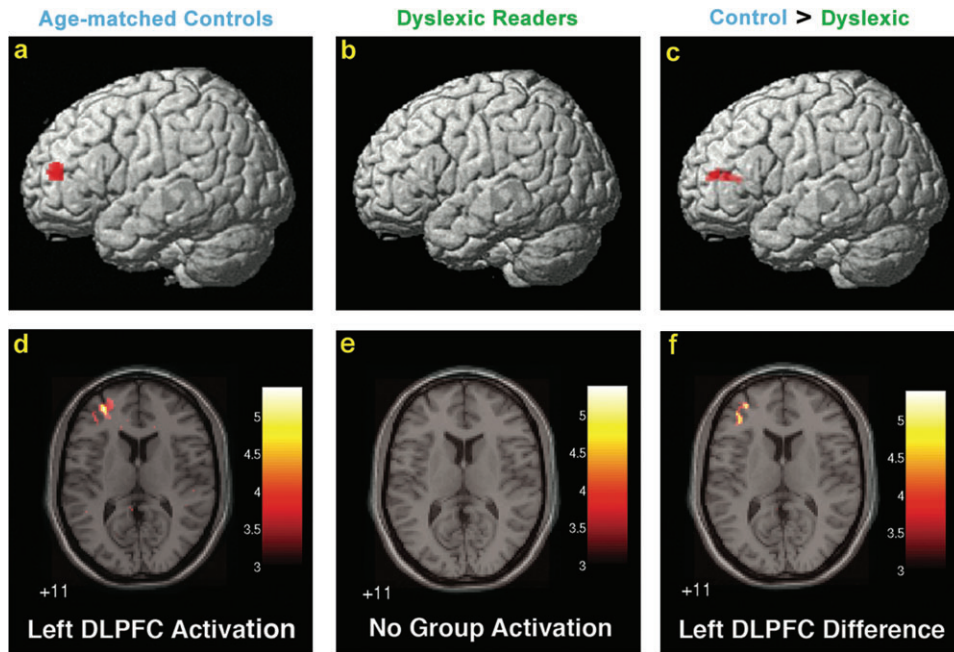


Figure 4. Activation for Rhyme > Match (Experiment 1b). Lateral (top row—*a*, *b*, and *c*) and axial views (bottom row—*d*, *e*, and *f*). (*a*, *d*) Age-matched controls ($n = 12$). (*b*, *e*) Children with dyslexia ($n = 12$). (*c*, *f*) Children with dyslexia exhibited significantly less activation in left DLPFC as compared with age-matched controls.

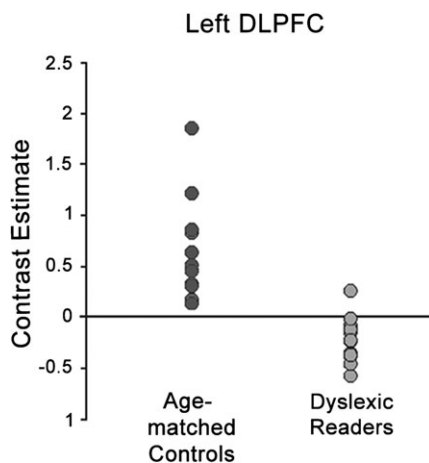


Figure 5. Mean contrast values for each typically reading age-matched control child and each child with dyslexia in the left DLPFC region of difference between the 2 groups for Rhyme > Match. All 12 age-matched controls showed activation, but only 1 of 12 children with dyslexia showed activation (Experiment 1b).

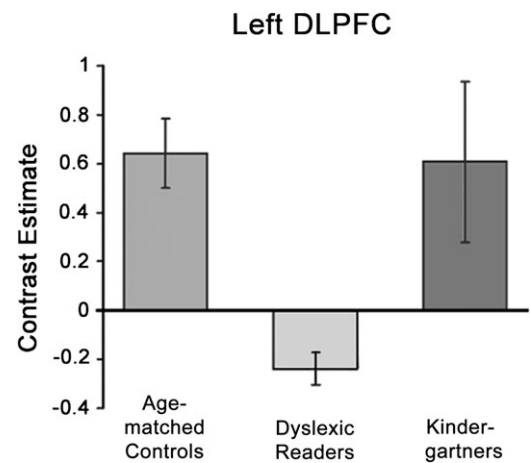


Figure 6. Mean contrast estimates for left DLPFC region of difference between children with dyslexia and age-matched controls for Rhyme > Match (Experiment 1b). Kindergartners showed activation similar in magnitude to typical readers. Error bars represent the standard error of the mean.

brain differences cannot be due to differential task difficulty or time on task because children with and without dyslexia performed similarly on the in-scanner phonological awareness and control tasks (although the children with dyslexia performed worse on standardized tests of phonological awareness). Third, the reduction of activation in left DLPFC in dyslexic readers cannot reflect reduced overall activation because overall brain activation was not significantly different between groups. Fourth, the reduction of DLPFC activation in children with dyslexia cannot be ascribed to delayed maturation or absolute level of phonological awareness because younger children who were matched on phonological awareness to children with dyslexia exhibited activation in left

DLPFC. Rather, the reduction in left DLPFC activations appears to be associated with the weakness in phonological awareness that was present in this group of dyslexic children and that frequently precedes and predicts how well a child learns to read.

The dyslexic readers in this study exhibited the substantial weakness in phonological awareness that is thought to be a common cause of dyslexia. This weakness was evident in their poor scores on a standardized test of phonological awareness (CTOPP), which were significantly lower than age- and IQ-matched typical readers and equal to kindergartners who were, on average, about 3 years younger than the dyslexic readers. The dyslexic children, however, were not significantly

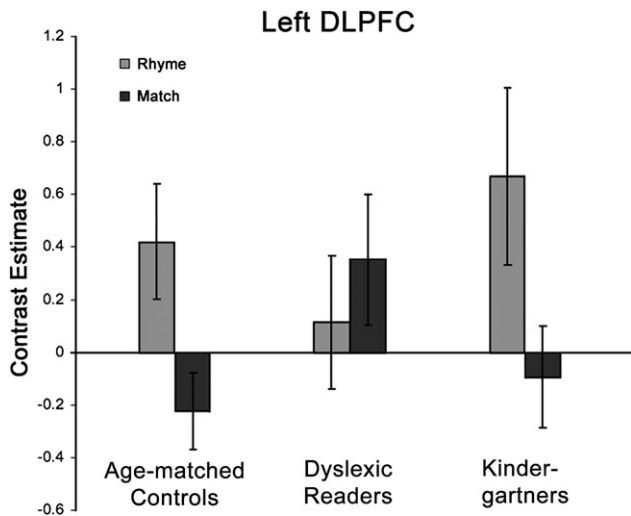


Figure 7. Mean contrast estimates for Rhyme > Rest and Match > Rest in the left DLPFC region of difference between children with dyslexia and age-matched controls for Rhyme > Match contrast (Experiment 1b). Age-matched controls and kindergartners showed a similar pattern of greater activation for Rhyme than Rest and greater activation for Rest than Match conditions. Children with dyslexia showed a reverse pattern of greater activation for Match than both Rhyme and Rest. Error bars represent the standard error of the mean.

impaired on their rhyme performance in the scanner, so it is unlikely that the marked reduction of left DLPFC activation is simply a consequence of poor scanner task performance. The dyslexic children did score 6 percentage points lower than the age-matched control group on the in-scanner rhyme task, and perhaps, this difference would become significant in a larger sample, but they also performed 3.5 percentage points better than the kindergartners who exhibited left DLPFC activation. The similarity between groups on in-scanner performance may reflect the relationship between age and performance on a rhyme detection task. Rhyme detection performance is a basic measure of phonological awareness and is useful in predicting future reading performance in kindergartners. As children mature, their performance on this task improves and other, more challenging measures of phonological awareness become better predictors of reading success (Cardoso-Martins 1995; Duncan and Johnston 1999; de Jong and van der Leij 2002; Anthony et al. 2003; Castles and Coltheart 2004). Thus, it appears that children develop strategies to become accurate on basic phonological awareness tasks such as rhyme detection but that strategy may be different in children with versus without dyslexia.

Typically developing children appear to consistently engage left DLPFC when performing an auditory phonological awareness task relative to the control word-matching task. We did not observe any significant group activation for the rhyme task relative to the control task in the dyslexic readers. This lack of significant activation suggests that children with dyslexia may develop a variety of strategies associated with a variety of neural systems to support phonological awareness when the left DLPFC is not engaged and that no common brain regions are consistently recruited by the dyslexic children. This “re-routing” of neurological resources away from left DLPFC for phonological awareness in dyslexia may potentially be related to compensatory brain mechanisms observed for the control task. Although these alternative strategies and neural pathways

can support performance on a relatively easy rhyme task, they did not support age-level performance on more demanding tests of phonological awareness administered behaviorally in the CTOPP Elision, Blending Words, and Nonword Repetition subtests.

The left DLPFC location of activation for auditory phonological awareness was somewhat unexpected given that visually presented tasks that tap phonological awareness are typically associated with more posterior regions and inferior frontal cortex. Other studies, however, have implicated the left middle frontal gyrus (MFG) in language-related or auditory tasks and also reported reduced MFG responses in dyslexia. First, unlike typical readers, children with dyslexia did not show left MFG activation during the auditory perception of rapidly (relative to slowly) changing nonspeech stimuli, but they did show increased left MFG activation after remediation with a program focused on improving rapid auditory processing (Gaab et al. 2007). These findings suggest that left MFG may support both verbal and nonverbal auditory processes important for reading acquisition. Second, dyslexic readers had poor performance for a visually presented verbal working memory task and decreased MFG activation (although more posteriorly in Brodmann area 6; Vasic et al. 2008). Third, a phonological awareness study that used pictures rather than printed words found increased activation in left inferior/middle and superior frontal gyri but not in posterior brain regions (Katzir et al. 2005), suggesting that phonological awareness without print engages the frontal lobe, whereas the engagement of left posterior regions may reflect the integration of printed and auditory information during reading (Pugh et al. 2000; Booth et al. 2004; Shaywitz et al. 2007). Finally, although prior studies of phonological awareness have focused on left inferior frontal and posterior temporal activation, many of these studies also found left MFG activation for the same tasks (e.g., Poldrack et al. 2001; Burton and Small 2006; Bolger et al. 2008a, 2008b). The sole left DLPFC activation in the present study, however, must be interpreted cautiously because other relevant regions may not have been identified due to the nature of the task contrast or limited statistical power. It is unlikely that phonological awareness for speech depends upon a single brain region rather than a network of brain regions.

Previous studies of phonological awareness have typically asked participants to examine visually presented information (pictures or text), translate this visual information into language, and then perform phonological or other types of spoken language-related analyses (Temple et al. 2003; Shaywitz et al. 2004; Katzir et al. 2005; Hoefl et al. 2007; Bolger et al. 2008a, 2008b). These studies have implicated different regions, specifically a network of posterior left-hemisphere regions, including posterior temporal and parietal regions as being important for reading due to their engagement for tasks involving phonological analysis of print and their reduced engagement in dyslexic readers (Pugh et al. 2000; Temple et al. 2001; Shaywitz et al. 2002; Shaywitz et al. 2004; Cao et al. 2006; Hoefl et al. 2006, 2007; Shaywitz et al. 2007). Moreover, such studies have found positive correlations between children’s growing phonological awareness competence and brain activations in these posterior left hemisphere regions, including posterior temporal, temporoparietal, and temporo-occipital regions (Temple et al. 2003; Turkeltaub et al. 2003; Frost et al. 2009). The present findings suggest that the prior

imaging studies addressed the interaction between phonological awareness and reading of print.

Role of Verbal Working Memory in Phonological Awareness

The present findings suggest an important role of left DLPFC, a region that has been typically associated with verbal working memory (Baddeley 2003; Curtis and D'Esposito 2003; D'Esposito 2007), in phonological awareness. This finding speaks to the relationship between phonological awareness and literacy. Researchers have called into question the notion that children's performance on phonological awareness tasks is a pure reflection of their ability to perceive and manipulate the sounds of words (Castles and Coltheart 2004). Instead, phonological awareness tasks may invoke a broader set of cognitive or metaphonological abilities, including sound manipulation, phonetic, and lexical word knowledge, and verbal working memory (Castles and Coltheart 2004). Strong correlations between verbal working memory and phonological awareness performance suggest that verbal working memory is a critical component of the ability to perform phonological awareness, reading, and spelling tasks in typical readers (Rohl and Pratt 1995).

Perhaps phonological awareness for rhyming tasks demands verbal working memory as children have to inhibit their typical analysis of speech for meaning and instead explicitly focus their analysis on the phonetic constituents of speech. Left DLPFC activation is consistently observed during timed phonological verbal fluency tasks, in which participants are asked to generate as many words as possible that start with a particular sound (cf., Klumpp and Deldin 2010). Similar to phonological verbal fluency, this goal-directed manipulation of auditory-verbal information during rhyming may require support from processes subserved by left DLPFC, a dysfunction in left DLPFC that prevents children from engaging those processes may lead to dyslexia. This hypothesis would be consistent with behavioral research that has shown that children with dyslexia may have trouble operating upon or working with phonological units of language, rather than perceiving or forming phonological representations (Ramus and Szenkovits 2008). Thus, these neuroimaging findings converge well with a large body of behavioral investigations into the nature of phonological awareness showing that children's ability to complete a phonological awareness task, in typical reading and dyslexia, places a critical demand on verbal working memory capabilities (Ramus et al. 2003; Castles and Coltheart 2004; Ziegler et al. 2009).

Brain Bases of Linguistic and Auditory Processes in Dyslexia

During the verbal control Match task, children with dyslexia showed greater activation in right temporoparietal neocortex as compared with typical readers. The location of this right hemisphere activation is nearly homologous to area Spt, a left-hemisphere region within the Sylvian fissure at the parietal-temporal boundary. Area Spt is thought to be critical for the sensory-motor integration of speech or the mapping of phonological representation onto motor output (Hickok and Poeppel 2007). Right temporal and parietal hyperactivation has been observed in reading studies of dyslexia and has been viewed as a compensatory neural mechanism elicited by the greater processing and attention demand that reading imposes

on children with dyslexia (Simos et al. 2002; Shaywitz and Shaywitz 2005). Here, we observed that typical children, including kindergarteners, tended to suppress this region during auditory word matching, whereas dyslexic children engaged this region during auditory word matching. This suggests that an atypical reliance on right posterior cortex for phonological processing in dyslexia may be a compensatory mechanism related to the impaired phonological processing frequently observed in dyslexia (Wagner and Torgesen 1987).

Limitations of Present Study

These findings may be interpreted with caveats regarding the design of the experiment. Some children with dyslexia may have a selective deficit in perceiving speech in a noisy environment (Ziegler et al. 2009). The present study employed continuous fMRI scanning (scanner noise was present throughout the experiment), and it is thus possible that the observed left DLPFC activation differences between typical readers and children with dyslexia were confounded with each group's ability to perceive words in the noisy scanner environment. Some support for the validity of our left DLPFC group differences comes from another study with sparse fMRI design (no noise during auditory stimulus presentation) showing that children with dyslexia show a reduced left MFG activation during the auditory perception of rapidly (relative to slowly) changing nonspeech stimuli (Gaab et al. 2007). Another caveat of the study is that the school-age children (ages 7-13) were exposed to both auditory and visual rhyming tasks, which may have created a contextual influence of the visual tasks onto the processing of the auditory task. The present interpretation is supported, however, by the similarity of the results across school-age and kindergarten children, who were only exposed to the auditory conditions. Nevertheless, further in-depth investigations into auditory language abilities in dyslexia using silent imaging (including studies using magnetoencephalography, ERP, functional near-infrared spectroscopy, and silent fMRI designs) are warranted.

Conclusions

Learning to read requires a translation from spoken to visual language and depends upon phonological awareness as a bridging mechanism. Phonological awareness, which precedes and predicts reading acquisition, may depend upon the developmental integrity of left DLPFC, an important region for goal-directed verbal processing. In the present study, children with dyslexia showed under-recruitment of left DLPFC, which does not appear to be related simply to phonological awareness proficiency or reading experience because DLPFC activation was present in kindergarteners with equal phonological awareness proficiency and far less reading experience. Thus, typical development of left DLPFC may empower children to work with spoken language units in a manner that facilitates reading acquisition, whereas atypical development or under-recruitment of left DLPFC may render reading acquisition difficult for children who are later characterized as having dyslexia.

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