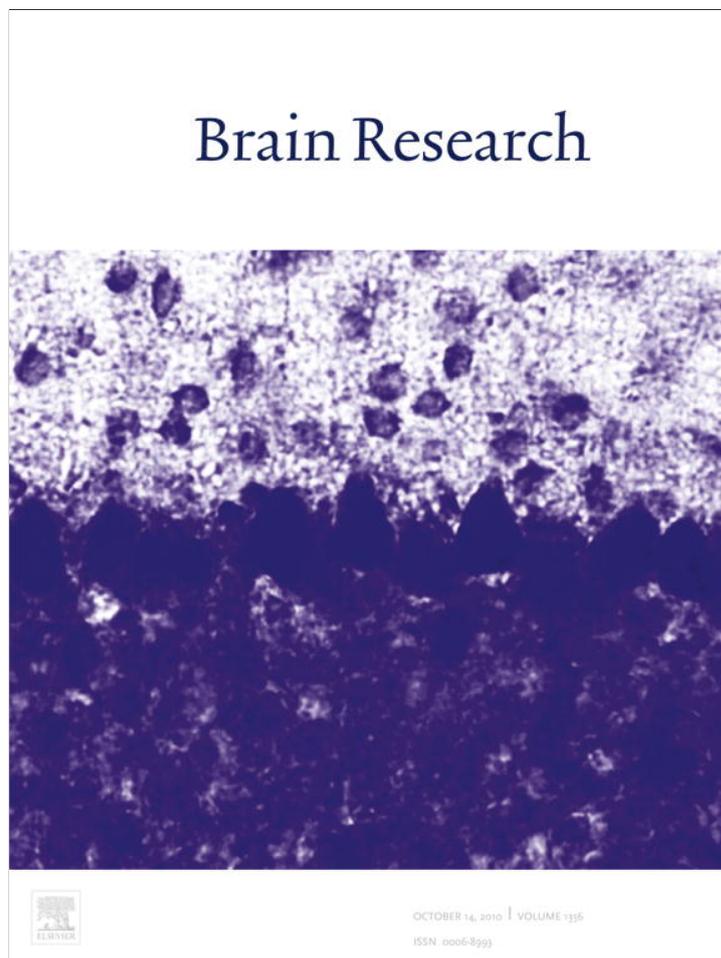


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## Research Report

**Children with reading difficulties show differences in brain regions associated with orthographic processing during spoken language processing**Amy S. Desroches<sup>a</sup>, Nadia E. Cone<sup>a</sup>, Donald J. Bolger<sup>b</sup>, Tali Bitan<sup>c</sup>,  
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## ABSTRACT

We explored the neural basis of spoken language deficits in children with reading difficulty, specifically focusing on the role of orthography during spoken language processing. We used functional magnetic resonance imaging (fMRI) to examine differences in brain activation between children with reading difficulties (aged 9-to-15 years) and age-matched children with typical achievement during an auditory rhyming task. Both groups showed activation in bilateral superior temporal gyri (BA 42 and 22), a region associated with phonological processing, with no significant between-group differences. Interestingly, typically achieving children, but not children with reading difficulties, showed activation of left fusiform cortex (BA 37), a region implicated in orthographic processing. Furthermore, this activation was significantly greater for typically achieving children compared to those with reading difficulties. These findings suggest that typical children automatically activate orthographic representations during spoken language processing, while those with reading difficulties do not. Follow-up analyses revealed that the intensity of the activation in the fusiform gyrus was associated with significantly stronger behavioral conflict effects in typically achieving children only (i.e., longer latencies to rhyming pairs with orthographically dissimilar endings than to those with identical orthographic endings; jazz–has vs. cat–hat). Finally, for reading disabled children, a positive correlation between left fusiform activation and nonword reading was observed, such that greater access to orthography was related to decoding ability. Taken together, the results suggest that the integration of orthographic and phonological processing is directly related to reading ability.

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## 1. Introduction

Reading is a complex task spanning several levels of processing. Both orthography and phonology are central to word reading, which involves translating print into sound. Importantly, phonological abilities have been crucially linked to reading skill, such that phonology has long been considered a core deficit in reading disability (Bradley and Bryant, 1983; Harm and Seidenberg, 2001; Leonard et al., 2001; Pugh et al., 2000; Stanovich, 1988). Indeed, the phonological deficit hypothesis holds that reading difficulties arise as a result of impairments in processing and/or representing phonemes. That is, that under-specified phoneme representations lead to poor development of the grapheme–phoneme correspondences that are essential to reading (Snowling, 1998). Orthographic deficits have also been suggested in reading disability (Badian, 2005; Meyler and Breznitz, 2003); however, the precise basis of such deficits is far from clear. Critically, given that reading involves making connections between orthographic and phonological representations (Foorman, 1994), it may be that the processes mitigating the integration of these two kinds of representations are related to reading failure (Booth et al., 1999, 2000; Plaut and Booth, 2000). Thus, in addition to separately investigating deficits in phonological and orthographic processes in individuals with reading difficulties, there is a need to examine the interactions between these processes.

It is clear that phonology plays a key role in reading, since, as noted above, this process involves relating print to sound. However, the role of orthography in spoken word processing is not obvious — and is far less understood. Despite this opacity, several studies have suggested that orthography does in fact play a distinct role in auditory word processing. For instance, orthographic intrusion has been observed during tasks such as phoneme deletion (Landerl et al., 1996), pseudohomophone priming (Taft et al., 2008), and spoken word recognition (Perre et al., 2009; Ziegler et al., 2003b; Ziegler and Muneaux, 2007). As well, although irrelevant for making auditory rhyme judgments, the orthographic endings of words have been found to influence performance on such rhyme decisions in both adults and children (adults: Donnenwerth-Nolan et al., 1981; Kramer and Donchin, 1987; Rugg and Barrett, 1987; Seidenberg and Tanenhaus, 1979; and children: Cone et al., 2008). Interestingly, given that tasks such as auditory rhyming only require processing in the phonological domain; the findings suggest that orthographic representations are accessed involuntarily during phonological processing. Furthermore, it appears that this influence of orthography on phonology occurs automatically during the time course of processing, and is not merely a consequence of making a response (e.g., Peereman et al., 2009; Perre & Ziegler, 2008; Pattamadilok et al., 2009). Further evidence for this comes from a number of studies by Ziegler and colleagues, who have revealed orthographic consistency effects during spoken word processing. Moreover, using event-related potentials [ERPs] they found that the timing of this effect differed based on where in the word the orthographic inconsistency took place (i.e., early vs. late), providing direct evidence for the on-line integration of orthographic and phonological processes in typical individuals.

With the understanding that orthographic and phonological processes interact during spoken word processing, a handful of

studies have examined whether this integration is impaired in dyslexia; however, these studies have had mixed results. In some studies, when compared to controls, children with dyslexia showed greater orthographic interference effects (e.g., McPherson et al., 1997; Rack, 1985), while others found the opposite: reduced orthographic interference in dyslexic children compared to controls (e.g., Zecker, 1991). These conflicting findings may be attributable in part to age differences in the participants of these studies; however, further research is required to elucidate whether, or under what conditions, children with dyslexia access orthographic representations during phonological processing.

Neuroimaging methods like functional magnetic resonance imaging [fMRI] can provide substantial insight into our understanding of reading development and reading difficulties. Indeed, over a decade of neuroimaging research has provided considerable understanding of the neurocognitive language network, revealing that activation in certain brain areas is related to processing certain kinds of representations. For instance, the left fusiform gyrus (BA 37) has been linked to visuo-orthographic processing. Furthermore, some researchers have proposed that within this area of the left lateral occipital temporal cortex is a region of perceptual expertise for visual word recognition (c.f., the visual word form area, VWFA, see McCandliss et al., 2003 for a review). The fusiform gyrus becomes increasingly attuned to processing visual word forms over development, and that more robust activation in this region is associated with better reading skills (Shaywitz et al., 2002). Another area of the language network, the posterior superior temporal gyrus, Wernicke's area, BA 22, has been found to be related to auditory phonological processing, Démonet et al. (1992); Mesulam, 1998). This area is sensitive to processing auditory phonological information, but not other auditory inputs like tones (Démonet et al., 1992), such that like the fusiform gyrus, this region is selective in the type of information it processes. Of relevance to the present discussion, this selectivity is not always modality specific. That is, during visual word reading, phonological processing is also marked by activity in the superior temporal gyrus (Booth et al., 2002); and during auditory word processing orthographic intrusion is marked by activity in the fusiform gyrus (i.e., for auditory word rhyming, Cone et al., 2008).

Neuroimaging studies of dyslexia have shown disruptions in brain activation in dyslexia related to these processes and brain systems. However, several different patterns have been observed, with some studies showing disruptions in both phonological and orthographic processing (e.g., Shaywitz et al., 1998; Temple et al., 2001), while others find deficits in only one of these processes, for instance, only phonological disruptions, as indicated by underactivation of superior temporal gyrus (Shaywitz et al., 2002; Simos et al., 2000), or only orthographic disruptions, as indicated by underactivation of fusiform gyrus (Aylward et al., 2003; Cao et al., 2006). As we noted with respect to the behavioral evidence, given these mixed results, examining how these processes interact might reveal further insight into the neurocognitive underpinnings of reading disorder.

Indeed, some neuroimaging studies have evaluated deficits in the interaction between orthographic and phonological processing in dyslexia (e.g., Eckert, 2004; Lyttinen et al., 2005). One approach to this has been to measure neural responses

during visual-rhyme judgment, given that both orthographic and phonological representations must be accessed to perform the task (Cao et al., 2006; Hoefft et al., 2006; Simos et al., 2000; Temple et al., 2001, 2003). While these studies have provided valuable insights into deficits underlying dyslexia, since reading is of inherent difficulty for these children, some aspect of the results may be obscured by the nature of their disorder. Therefore, further examination of the degree to which phonological and orthographic processes interact in these children in the auditory modality, promises to offer further evidence regarding the specific nature of their impairment.

### 1.1. The present study

The present study fMRI study employed an auditory rhyme decision task with an orthographic manipulation in order to investigate the role of orthography during phonological processing in children with reading difficulties. We included both a phonological manipulation (rhyming or not rhyming) and an orthographic manipulation, for which the endings of each pair of words were either conflicting (i.e., *pint-mint*, *jazz-has*) or non-conflicting (i.e., *gate-hate*, *press-list*; see Table 1 for examples of all stimulus conditions). If dyslexia is characterized by primary deficits in phonological processing, we would expect differences in activation between typically achieving children and those with reading difficulties in left superior temporal gyrus. However, if children with dyslexia have deficits in the integration of orthographic and phonological representations, we would expect group differences in activation in left fusiform gyrus. Moreover, if activation in left fusiform gyrus during spoken language processing was systematically related to behavioral performance or reading skill this would provide direct evidence of the importance of this region in language processing.

Importantly, activation in the fusiform gyrus during this spoken word rhyming task is suggestive of the automatic activation of orthographic representations during phonological processing. Because of this, we were also interested in evaluating individual differences in this activity based on

specific skill measures and task conditions. First, because nonword reading is one of the constructs most consistently demonstrating differences between typically achieving children and those with reading difficulties (e.g., Griffiths and Snowling, 2002; Rack et al., 1992; Ziegler et al., 2003a), we conducted analyses to explore the relationship between nonword reading ability and fusiform activity. Next, the contrast between conflicting and non-conflicting conditions provides an additional approach to examining how orthography interferes with rhyme judgment. We examined the effect of conflict between orthographic and phonological information by comparing the conflicting versus non-conflicting conditions for the rhyming and for the non-rhyming word pairs separately, comparing conflict between conditions with similar response characteristics (i.e., “yes” or “no” rhyme decision). Given that any fusiform activation during auditory rhyming is suggestive of integration, how individuals perform on these conditions relative to each other (conflicting versus non-conflicting) should provide further insight into the interaction between phonological and orthographic representations.

## 2. Results

### 2.1. Behavioral results

Accuracy and reaction time for typically achieving (TA) children and those with reading difficulties (RD; see Table 2 for standardized test scores) on the lexical (i.e., word) and null trials are reported in Table 3. We calculated a 2 group (TA, RD) × 4 lexical conditions (O+P+, O+P-, O-P+, O-P-) repeated measures ANOVA separately for accuracy and reaction time. Overall, children with RD were significantly less accurate and marginally slower at rhyme judgments than TA children ( $F(1,22)=8.64$ ,  $p<.01$ , and  $F(1,22)=3.52$ ,  $p<.10$ , respectively). There was also a significant main effect of condition for accuracy but not for reaction time ( $F(1,22)=4.47$ ,  $p<.05$ , and  $F(1,22)=.52$ , ns). However, there was no significant interaction between group and condition for accuracy or reaction time ( $F(3,20)=.34$ , ns,  $F(3,20)=.04$ , ns). Follow-up paired t-tests of the main effect of condition in accuracy indicated a significant accuracy difference (Bonferroni corrected for six comparisons,  $p<.002$ ), only between the O+P- and O-P- conditions, with lower accuracy in the conflicting O+P- condition, and additional marginally significant differences ( $p<.05$ ) between the O+P- condition and each of the remaining

**Table 1 – Group mean scaled scores and standard deviations (in parentheses) for standardized tests of achievement for the reading difficulty (RD) and typically achieving (TA) group.**

Standardized Measure	RD	TA
Verbal IQ (WASI)**	96 (12)	108 (10)
Performance IQ (WASI)**	96 (14)	110 (10)
Full-Scale IQ (WASI)**	95 (14)	110 (10)
Word Identification (WJ-III)***	81 (16)	109 (10)
Word Attack (WJ-III)***	79 (12)	107 (9)
Sight Word Efficiency (TOWRE)***	80 (11)	105 (8)
Phonetic Decoding Efficiency (TOWRE)***	76 (13)	102 (13)
Average of four reading tests***	79 (12)	105 (8)
Phonemic Awareness Composite (CTOPP)***	79 (10)	99 (13)

\*\* $p\leq.01$ , \*\*\* $p\leq.001$ , two-tailed. WASI: Wechsler Abbreviated Intelligence Scale; WJ-III: Woodcock Johnson Tests of Achievement – III; TOWRE: Test of Word Reading Efficiency; CTOPP: Comprehensive Test of Phonological Processing.

**Table 2 – Lexical rhyme conditions.**

	Similar orthography	Dissimilar orthography
Similar phonology (rhyming)	O+P+ gate-hate	<sup>a</sup> O-P+ jazz-has
Dissimilar phonology (non-rhyming)	<sup>a</sup> O+P- pint-mint	O-P- press-list

<sup>a</sup> Denotes conflicting conditions, in which phonological information (whether or not the two words rhyme) conflicts with orthographic information (whether or not the two words are spelled the same from the first vowel on).

**Table 3 – Mean accuracy (proportion), reaction time (ms) and their standard deviations (in parentheses) for each group on each lexical condition, average of all lexical conditions and null events.**

		Conflicting		Non-conflicting		All lexical	Null
		O–P+	O+P–	O+P+	O–P–		
Reading difficulties (RD)	Accuracy	.74 (.19)	.68 (.20)	.75 (.21)	.76 (.18)	.73 (.15)	.82 (.17)
	RT	1639 (265)	1670 (389)	1638 (278)	1668 (317)	1654 (288)	1537 (376)
Typically achieving (TA)	Accuracy	.92 (.10)	.78 (.19)	.94 (.07)	.89 (.13)	.88 (.09)	.94 (.11)
	RT	1437 (294)	1459 (221)	1425 (237)	1480 (264)	1450 (241)	1379 (295)

two conditions, O+P+ and O–P+. The lack of a significant interaction between group and condition indicated that the two groups did not differ significantly in the behavioral conflict effect (i.e., neither on O+P– vs. O–P– for “no” responses, nor on O–P+ vs. O+P+ for “yes” responses).

**2.2. Brain activation**

See Table 4 for a description of both the location and intensity of activation for the TA and RD groups. Contrasts between conditions for each subject were performed at the first level, and second level analyses to explore between-group differences were carried out using two-sample t-tests. Between-group differences in activation were examined using a mask of the union of the activation for each of the groups on the rhyming task at a lenient threshold ( $p < .01$ ). Areas of activation reported for all analyses were significant at the voxel level using FDR correction (see Table 4 for exact  $p$ -values for each area), with a minimum cluster size of 15 voxels. For each group, the comparison of all lexical conditions versus null

revealed activation in bilateral superior/middle temporal gyri (see Fig. 1 and Table 4). This activation extended into left supramarginal gyrus in the TA group and into right insula and left inferior parietal lobule in the RD group. Medial frontal activation was also found in both groups, falling in medial frontal gyrus in the TA group and cingulate gyrus in the RD group. Only in the TA group was additional significant activation found in left fusiform gyrus. The only significant group difference in activation between the RD and TA groups for the contrast of the four lexical conditions versus null was greater activation in the TA group than the RD group in left fusiform/inferior temporal gyrus (see Fig. 3). Examination of conflict effects for the rhyming conditions (O–P+ vs. O+P+) and the non-rhyming conditions (O+P– vs. O–P–) revealed no significant activation in either group. There were also no significant group differences in either of the conflicting versus non-conflicting contrasts (O+P– vs. O–P–, or O–P+ vs. O+P+).

It is important to note that although both groups of children had normal to above normal nonverbal IQ; there were significant group differences on this construct. Thus, we

**Table 4 – Regions of activation for the lexical conditions vs. null contrast, separately for the typically achieving and reading difficulties groups of children.**

Region	Hemisphere	BA	Voxels	p-value	x	y	z	t-value
Lexical–null								
Typically achieving group								
Supramarginal gyrus	L	40	829	<.001	–63	–24	15	12.33
Superior/middle temporal gyrus	L	42, 22, 21		<.001	–63	–27	3	
Superior temporal gyrus	L	22		<.001	–54	–15	–3	
Superior temporal gyrus/Heschl’s gyrus	R	22, 42, 41	734	<.001	66	–12	3	10.33
Superior temporal gyrus/Heschl’s gyrus	R	42, 41		<.001	60	–24	12	
Middle temporal gyrus	R	21		<.001	57	–30	–3	
Medial frontal gyrus	L/R	6, 8	55	<.001	0	12	54	6.57
Fusiform gyrus	L	37	16	<.001	–48	–63	–24	5.17
Fusiform gyrus	L	37		<.001	–48	–54	–18	
Reading Difficulties Group								
Middle temporal gyrus	R	21	901	<.001	57	–12	–3	18.39
Superior temporal gyrus/Heschl’s gyrus/insula	R	22, 42, 41, 13		<.001	57	–27	6	
Superior temporal gyrus/Heschl’s gyrus/inferior parietal lobule	L	22, 42, 41, 40	770	<.001	–60	–21	9	9.94
Middle temporal gyrus	L	21		<.001	–63	–12	–3	
Superior temporal gyrus	L	42		<.001	–66	–33	9	
Anterior cingulate cortex	L	32	31	<.001	–6	6	42	5.78
Anterior cingulate cortex	R	32		<.001	3	24	30	
Anterior cingulate cortex	L	32		<.005	–3	18	36	

Note. Reported  $p$ -values are corrected at the voxel level using an FDR correction. For hemisphere, L = left, R = right; BA = Brodmann Area; x, y, z: Montreal Neurological Institute (MNI) coordinates listed only for clusters with volume greater than 15 voxels. All coordinates listed correspond to global maxima within a region (voxels and t-value given) or local maxima within a region (t-value not given).

ran additional analyses to investigate any significant role of nonverbal IQ in our findings. First, for analyses in which significant group differences were found, we ran an identical analysis with nonverbal IQ entered in separately as a covariate. This analysis showed that all of the same regions were significantly active; only the number of voxels activated above-threshold in each of the regions differed between this and the original analysis. Second, we did correlational analyses to explore the relationship between activation in the fusiform and nonverbal IQ scores. Using the extracted beta weights from the fusiform activation observed in our original analyses, we calculated the correlation between IQ scores and activation strength for each group separately and for both groups together on the nonverbal IQ composite, as well as each nonverbal subtask (block design and matrix reasoning). These follow-up analyses revealed that the activity in the fusiform was not correlated with nonverbal IQ (for all analyses, all  $p$ -values  $> .24$ ).

Correlations of brain activation in the four lexical conditions vs. null in left fusiform gyrus<sup>1</sup> with scores on a standardized measure of nonword reading (WJ-III, Word Attack) revealed that the RD group's correlation was significantly positive, while the TA group's correlation failed to reach significance ( $r_{RD} = .66$ ,  $p = .02$ ;  $r_{TA} = .27$ ,  $p = .39$ ; see Fig. 2). However, a statistical comparison of the correlation coefficients between the two groups revealed no significant group difference in this relationship (Fischer's  $Z = 1.08$ ,  $p = .28$ ).

Correlations of brain activation in the four lexical conditions vs. null in left fusiform gyrus<sup>2</sup> with reaction time conflict effect scores for the "yes" responses (calculated by subtracting reaction time to the non-conflicting rhyming condition, O+P+, from the conflicting rhyming condition, O–P+) revealed that the TA group's correlation was significantly positive, while the RD group's correlation failed to reach significance (see Fig. 3, panel D). A statistical comparison of the correlation coefficients between the two groups revealed that the correlation was significantly stronger in the TA group than in the RD group ( $r_{TA} = .63$ ,  $p = .03$ ;  $r_{RD} = -.25$ ,  $p = .43$ ; Fischer's  $Z = .21$ ,  $p = .03$ ). There were no significant correlations between activation in the fusiform gyrus and the conflict effect scores on the "no" responses (i.e., non-rhyming trials).

### 3. Discussion

The goal of the present study was to evaluate the relationship between orthography and phonology during auditory word processing in typically achieving children and those with reading difficulties. Our investigation of the differences in brain activation between these two groups, revealed two key findings. First, the two groups of children showed similar bilateral activation of the superior temporal gyrus during auditory rhyme judgment, providing no evidence that children

with reading difficulties differ in terms of the basic phonological processes subserved by this region (also see Binder et al., 1994). Next, unlike typically achieving children, children with reading disabilities did not show reliable activation of the fusiform gyrus during the auditory rhyming task. Importantly, this finding suggests that while typically achieving children appear to activate orthographic representations automatically and reliably during phonological processing, those with reading difficulties do not.

Orthographic representations appear to be accessed automatically and reliably in typically achieving children during spoken language processing, but not in those with reading difficulties. Comparisons of brain activation during the rhyme decision task revealed neural response in the fusiform gyrus for typically achieving children only, and moreover, that there was a significant difference between the two groups in their activation in this region. Although behavioral measures have been employed to examine orthographic influences in spoken language processing, these have yielded inconsistent findings with respect to children with reading disabilities (e.g., greater vs. smaller consistency effects: McPherson et al., 1997; Rack, 1985; and Zecker, 1991, respectively). Instead, the present study revealed a clear effect where the integration of orthographic and phonological processing is concerned: children with reading difficulties do not show the same automatic access of visual-orthographic representations during auditory phonological processing. This finding both echoes and expands upon a finding that was only briefly discussed in a study by Corina et al. (2001); that is, greater activation in the left occipital cortex for controls compared to dyslexic children. Our study was specifically designed to examine this question using an event-related design and a phonological task in which we explicitly manipulated orthography, whereas the Corina et al. (2001) finding was incidental, nevertheless suggesting that visual processes occur during auditory word processing. Our study is the first to our knowledge to show that children with reading difficulties less automatically activate brain regions implicated in orthographic representations during spoken language processing.

The finding that the automaticity with which orthographic representations are activated during auditory phonological processing can be interpreted within the framework of both interactive activation models of language processing (which suggest that phonology, orthography, and semantics are all interconnected during language processing, Seidenberg and McClelland, 1989) and the Phonological Deficit Hypothesis of reading disability (Snowling, 1998). That is, children with typical reading develop strong interconnections between phonology and orthography, while children with reading difficulties do not. In children with reading difficulties, deficits in processing and representing phonology are related to the impoverished development of the grapheme–phoneme correspondences that are essential to reading. Without this, the connections between phonology and orthography are not strengthened (or possibly not made), rendering them with limited access to orthography during auditory phonological processing.

It is important to note that the present study used a spoken language task with a phonological (i.e., rhyming) judgment to assess the automaticity with which children with reading difficulties access orthographic information during auditory processing. Although auditory rhyming does not require

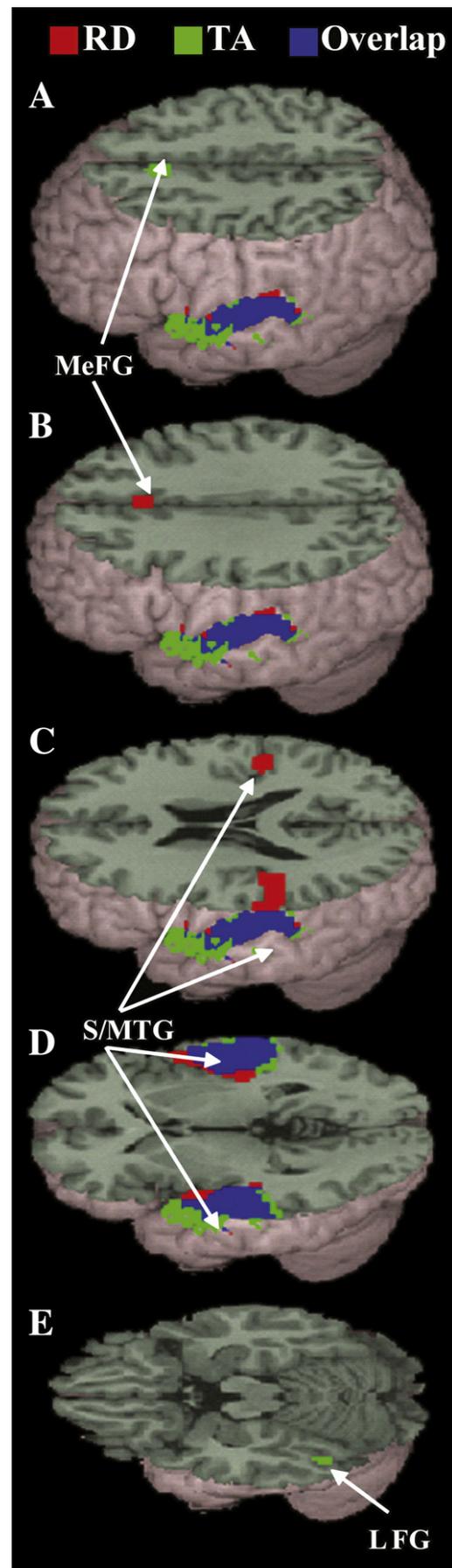
<sup>1</sup> Contrast values extracted from individuals, separately within each group, around the maxima coordinate of significant activation in the TA group only.

<sup>2</sup> Contrast values extracted from individuals, separately within each group, around the maxima coordinate of significant difference between the two groups.

orthographic analysis, further research is needed to determine whether these effects hold in a spoken word processing task without a phonological judgment. Based on evidence from typically achieving individuals that suggests orthography is activated automatically and on-line during spoken word recognition (e.g., using auditory lexical decision and ERPs, Perre & Ziegler, 2008), as well as the fact that by age 8 or 9 auditory rhyme judgment is easy for children, even for those with reading difficulties (e.g., Desroches et al., 2006; Swan and Goswami, 1997), we hypothesize that orthographic effects would be similar across a variety of spoken word tasks.

Although, as a group, the children with reading disabilities did not show reliable activation of orthographic representations during phonological processing, the magnitude of the activation in the fusiform gyrus was related to their reading skill. Using correlation, we found a significant relationship between left fusiform activation and nonword reading score (WJ-III Word Attack, a measure of decoding ability) for children with reading difficulties. As nonword reading scores increased, so did activation in the left fusiform gyrus for children with reading difficulties. Of note, a follow-up analysis of this correlation removing an outlier value still revealed a significant correlation (that was in fact numerically higher,  $r = .73$ ,  $p < .01$  without the outlier vs.  $r = .66$ ,  $p = .02$  with the outlier). This relationship failed to reach significance in the typically achieving children; however, there were no significant differences between the groups in their correlation between left fusiform activation and nonword reading. Importantly, our findings revealed that while children with reading difficulties do not appear to automatically activate their orthographic representations during auditory phonological processing; those with higher decoding abilities do in fact show greater recruitment of a brain region associated with orthographic processing. Therefore, increasing automaticity or efficiency in this phono-orthographic mapping process in children with reading difficulties may be associated with both increasing nonword (decoding) skill and increasingly automatic orthographic processing during spoken language tasks (Van der Leij and Van Daal, 1999; Zecker, 1991).

With respect to typically achieving children, the present findings are consistent with findings from past studies revealing orthographic consistency effects during auditory phonological tasks (e.g., Seidenberg and Tanenhaus, 1979; Perre and Ziegler, 2008), as well as with our own previous finding of activation in the fusiform gyrus during auditory rhyming in a larger group of typically achieving children (Cone et al., 2008). Taken together, the past and present findings suggest that orthographic information is accessed automatically during auditory phonological processing in non-impaired readers,



**Fig. 1** – Main effects of the four lexical conditions versus null, within each group (see Table 4 for coordinates). Activation from the reading difficulty (RD) group in red; for the typically achieving (TA) group in green, and overlap in blue. MeFG = medial frontal gyrus; S/MTG = superior and middle temporal gyri; LFG = left fusiform gyri.

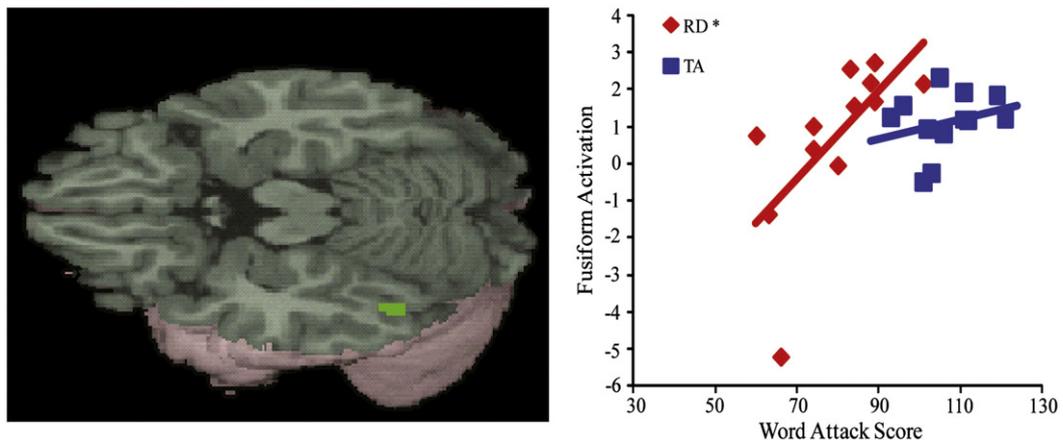


Fig. 2 – Main effects of across four lexical conditions versus null in the TA group in left fusiform gyrus. Scatter plot illustrates correlation within each group between nonword reading score (from the WJ-III Word Attack subtest) and activation in a 6-mm sphere around this cluster maxima (BA 37;  $x=-48, y=-63, z=-24$ ). Asterisk indicates a significant correlation in the RD group.

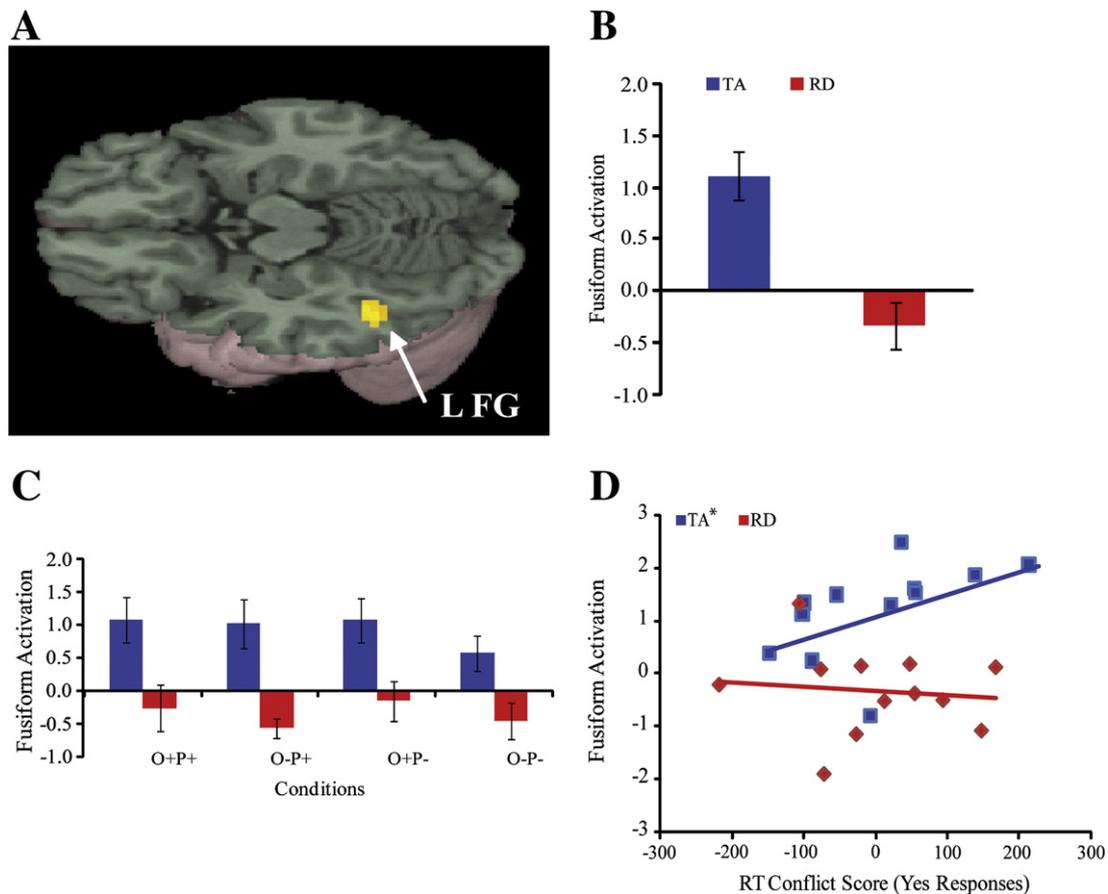


Fig. 3 – Brain image (panel A) illustrates TA greater than RD group difference across four lexical conditions versus null in left fusiform/inferior temporal gyrus (BA 37;  $x=-48, y=-51, z=-15$ ; voxels=22;  $t$ -value=5.01). L FG = left fusiform gyrus. Bar graphs (panels B and C) indicate mean intensity of activation (with standard error bars) for each group (TA in blue and RD in red) in a 6-mm sphere around the above cluster maxima (panel A), across lexical conditions (panel B) and for individual lexical conditions (panel C). Scatter plot (panel D) illustrates correlation within each group between reaction time conflict score for yes responses (conflicting minus non-conflicting reaction time in rhyming conditions: O+P+ minus O-P+) and activation in a 6-mm sphere around the left fusiform gyrus cluster represented in panel A. Asterisk indicates a significant correlation in the TA group.

and also that phonological and orthographic information are highly integrated in these individuals.

We further examined the integration of orthographic and phonological processes by exploring the activation associated with the resolution of conflict between phonological and orthographic representations. Neither group of children showed significant differences in the contrast of the conflicting versus the non-conflicting conditions (O+P– vs. O–P– and O–P+ vs. O+P+), with no significant between-group differences being observed. While comparing these contrasts was not informative for the question at hand, subsequent correlational analyses were useful. A positive correlation was found between activation in the fusiform and the behavioral reaction time conflict effect on rhyming trials (O–P+ vs. O+P+) in the typically achieving children only. Not surprisingly, this effect was significantly stronger for typically achieving children compared to those with reading difficulties, who did not show any evidence of such a relationship. These results further emphasize the claim that children with reading difficulty have less automatic or obligatory phono-orthographic mapping (Meyler and Breznitz, 2003; Van der Leij and Van Daal, 1999; Zecker, 1991).

The correlation between activation in the fusiform and the conflict effect in the typically achieving children indicates that as the influence of conflict on reaction times increased (i.e., greater delays in reaction times for conflicting versus non-conflicting word pairs such as *jazz–has* vs. *gate–hate*), activation in fusiform gyrus also increased. This indicates a close relationship between behavioral and neural influences of orthographic representations during phonological processing in typically achieving children. Consistent with this, we have previously shown that slower reaction times across all lexical conditions result in greater activation in left fusiform gyrus in older (15-year-olds) as compared to younger (9- to 13-year-olds) typically achieving children (Cone et al., 2008).

Notably, the fusiform activation did not vary across the four different lexical conditions in the typically achieving children (Fig. 3, panel C), suggesting that the relationship between fusiform activation and the behavioral conflict effect are not merely a result of the presence of the phono-orthographic conflict. Instead, activation in the fusiform gyrus increased specifically with the degree to which participants' reaction times were affected by the presence of this conflict (Fig. 3, panel D). Increased reaction times are suggestive of more effortful processing; therefore, two possible interpretations follow. First, it might be that individuals who activate orthographic representations more automatically during spoken language processing, are more susceptible to having greater behavioral phono-orthographic conflict effects. Alternatively, it is possible that the typically achieving children in the present study who show greater fusiform activation relative to their other typically achieving peers do so because their phono-orthographic mapping is more effortful or inefficient. Such inefficient mapping might result in greater fusiform activation (Bookheimer et al., 2000), as well as in longer reaction times when an orthographic comparison of the two words conflicts with the task-relevant phonological comparison, possibly due in part to a more effortful/inefficient re-mapping to double-check the phonological rhyme comparison (Seidenberg and Tanenhaus, 1979).

In the present discussion we attribute the observed differences in brain activity to differences in reading level; however, given the discrepancy in nonverbal IQ between the two groups

of children, an alternate interpretation could also be made. Consider the following: given that lower verbal and nonverbal IQ scores relate to a range of abilities including speed of processing, working memory and executive functioning, it could be that lower IQ abilities impede the development of interconnections between representational systems. Under this account, it might be that the IQ discrepancy between groups, coupled with the phonological deficits in children with reading difficulties, drives the observed between-group differences in brain activity. While we cannot discount such an interpretation, we view it as the less likely alternative for several reasons: 1) the findings still hold when additional analyses were performed that partialled for IQ, 2) the activation in the FG was not correlated with IQ for either group on any subtest or composite, and 3) support from a growing body of literature suggesting that nonverbal IQ is often lower in children with reading difficulties, and that IQ is not a significant contributor to their deficits (see Pennington, 2008 for a review; and also D'Angiulli and Siegel, 2003; Dennis et al., 2009; Jiménez et al., 2009; Stanovich, 1991; Snowling et al., 2003; Stuebing et al., 2002; Velluntino et al., 2000).

Finally, with respect to more basic auditory phonological processes, we did not observe any significant differences between the two groups, as indicated by similar activation in bilateral superior temporal cortex (BA 22; also see Binder et al., 1994). However, it is important to note that the findings of the present study do not negate the presence of such deficits. Given that our stimuli were not designed to assess subtle changes in phonemic variation, but rather larger phonological segments (i.e., rhyme), this study may not have had the sensitivity to discern such deficits. Rather, at least at the level of processing pairs of rhyming and non-rhyming words compared to a null control, children with reading difficulties show no deficits compared to typically achieving controls.

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## 4. Conclusion

The current study indicates that during spoken language processing, phonological and orthographic processes are more integrated in typically achieving children compared to children with reading difficulties. This is demonstrated by greater fusiform activation in the typically achieving children in the auditorily-presented rhyme decision task. Furthermore, greater activation in this region is associated task difficulty in typically achieving children, and with higher nonword decoding skill in children with reading difficulties. Taken together, the findings suggest that although some aspects of the neural bases of spoken word processing appear to be intact in children with reading difficulties, other aspects of processing, including the integration of phonological and orthographic representations are impaired.

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## 5. Experimental procedures

### 5.1. Participants

Twelve TA children (mean age=11.5, SD=2.2, range=8.8 to 14.9 years; 8 boys) and twelve children with RD (mean age=11.4 years, SD=2.3; range=8.7 to 14.8 years; 10 boys)

participated in the fMRI study. Children were recruited from the Chicago metropolitan area.

Parents of children were given an informal interview to insure that all children met the following inclusionary criteria: (1) native English speakers, (2) right-handedness, (3) normal hearing and normal or corrected-to-normal vision, (4) free of neurological disease or psychiatric disorders, (5) not taking medication affecting the central nervous system, (6) no history of intelligence or oral-language deficits, and (7) no Attention Deficit Hyperactivity Disorder (ADHD). After the interview, informed consent was obtained in accordance with procedures approved by the Institutional Review Board at Northwestern University and Evanston Northwestern Healthcare Research Institute.

Standardized testing was then administered to assess children's IQ, reading, and language abilities. This included the Wechsler Abbreviated Scale of Intelligence (WASI, [Wechsler, 1999](#)) with two verbal subtests (vocabulary and similarity) and two performance subtests (block design and matrix reasoning); measures of word and nonword reading accuracy (Word Identification and Word Attack subtests of the Woodcock Johnson III Tests of Achievement, WJ-III; [Woodcock, McGrew & Mather, 2001](#)) and speed (Sight Word Efficiency and Phonetic Decoding Efficiency subtests of the Test of Word Reading Efficiency, TOWRE; [Wagner et al., 1999a](#)); as well as phonological awareness measures from the Comprehensive Test of Phonological Processing (CTOPP, Elision and Blending Words subtests; [Wagner et al., 1999b](#)).

Children with RD had standard scores of 85 or below on at least one of the four reading measures. Each child in this group also met the following group inclusionary criteria: (1) verbal IQ above 80, and (2) average of the four reading measures (word and nonword accuracy and speed) below 95. For all but two of these children, the average reading score fell below 90, with a group range of 57 to 93. The age-matched TA children, none of whom had a history of reading difficulties, met the following group criteria: (1) difference of age with matched RD children equal to or less than four months, (2) verbal IQ above 80, and (3) average of the four reading measures above 95 (ranging from 96 to 124). See [Table 1](#) for each group's mean standard score (and standard deviation) on each of the standardized tests.<sup>3</sup>

We compared the two groups on their standardized reading and language performance using a 2 group (RD and TA children) × 2 test (verbal IQ and reading test average) analysis of variance (ANOVA). As expected, we found a significant interaction between group and test ( $F(1,22)=9.90$ ,  $p=.005$ ). Follow-up *t*-tests showed that although children with RD scored lower than TA children on both verbal IQ and the average of reading tests, the difference between the two groups was greater on the average of reading tests ( $t(22)=2.79$ ,  $p=.011$ , and  $t(22)=6.31$ ,  $p<.001$ , respectively).

## 5.2. Rhyme judgement task and procedures

On each trial, children heard two sequentially presented auditory words, presented binaurally through earphones.

The pairs of words either rhymed, or did not rhyme, and children were required to make a rhyme judgment response by pressing one of two keys on a handheld keypad. Participants were instructed to quickly and accurately as possible to respond to all trials, using the right index finger for a yes (rhyme) response and the right middle finger for a no (non-rhyme) response. Throughout the trial, a black fixation-cross remained on the screen to help minimize eye movements. The duration of each word was between 500 and 800 milliseconds (ms) followed by a brief period of silence, with the second word beginning 1000 ms after the onset of the first. A red fixation-cross appeared on the screen 1000 ms after the onset of the second word, indicating the need to make response during. This response interval had a duration of 2400 ms. Word pairs, varying in terms of their orthographic and/or phonological similarity ([Table 2](#)), were presented in one of four lexical conditions (24 pairs per condition). Two conditions were non-conflicting, such that the words in each pair had similar orthographic and phonological endings (O+P+: e.g., *gate-hate*), or had different orthographic and phonological endings (O-P-: e.g., *press-list*). Two additional conditions were conflicting, such that both words had similar orthographic but different phonological endings (O+P-, e.g., *pint-mint*), or had different orthographic but similar phonological endings (O-P+, e.g., *jazz-has*).

All words were monosyllabic, and were matched across conditions for written word frequency in adults and children ([Zeno et al., 1996](#)) and for adult word frequency for written and spoken language ([Baayen et al., 1995](#)). One-way ANOVAs did not reveal significant differences in word frequency across conditions. Although we attempted to match the lexical conditions for word consistency, the limited number of available words and the specific structure of the conditions precluded this possibility. Two measures of word consistency were calculated: phonological and orthographic ([Bolger et al., 2008](#)). ANOVA analyses of phonological or orthographic consistency as dependent variables and lexical condition as the independent variable showed a significant effect of condition ( $F(3,177)=35.4$ , and  $F(3,177)=10.9$ ,  $p<.001$ , respectively). The highest phonological inconsistency was in the O+P- condition and the highest orthographic inconsistency was in the O-P+ condition (see [Bolger et al., 2008](#), for more details related to consistency differences across conditions).

Control trials were included to control for visual processing, motor responses, and extraneous nonlinguistic auditory processing. These control trials were 72 null events for which participant was required to press a button when a black fixation-cross at the center of the visual field turned red. The null event had the same visual stimuli and motor response characteristics as both the lexical task and the perceptual controls, with sequential presentation of black fixation-cross followed by a red fixation-cross indicating the need to press the yes button on the response box. Two other control conditions were included as part of a larger study, but were not of interest in the current experiment. These included simple perceptual trials (single pure tone stimuli) and complex perceptual trials (three-tone stimuli) where the participant was asked to decide whether two sequentially presented items were the same (see [Cone et al., 2008](#)) for further details on the perceptual conditions).

<sup>3</sup> Standardized tests have a population mean of 100 and a standard deviation of 15.

Prior to taking part in the fMRI scanning session, participants were required to complete a practice scan session, in which they were trained in minimizing head movement in front of a computer screen using an infrared tracking device. At this time, they performed one run of the rhyming task in a simulator scanner, in order to make sure they understood the tasks and to acclimatize themselves to the scanner environment. Different stimuli were used in the practice and in the scanning sessions. Scanning took place within a week of the practice session.

## 6. MRI data acquisition

Participants lay in the scanner with their head position secured with a specially designed vacuum pillow (Bionix, Toledo, OH). An optical response box was placed in the participants' right hand (Current Designs, Philadelphia, PA). Visual stimuli were projected onto a screen, while participants viewed them via a mirror attached to the inside of the head coil. Participants wore sound attenuating headphones to hear auditory stimuli and minimize the effects of the ambient scanner noise (Resonance Technology, Northridge, CA). The rhyming task was administered in two 8 minute runs, with 108 trials per run. The order of lexical, perceptual and fixation trials was optimized for event-related design using OptSeq (Burock et al., 1998; <http://surfer.nmr.mgh.harvard.edu/optseq/>), with this order being fixed for all subjects.

Images were acquired using a 1.5 Tesla GE (General Electric) scanner. The BOLD (blood oxygen level dependent) signal was measured using a susceptibility weighted single-shot EPI (echo planar imaging) method. Functional images were interleaved from bottom to top in a whole brain acquisition. The following scan parameters were used: TE=35 ms, flip angle=90°, matrix size=64×64, field of view=24 cm, slice thickness=5 mm, number of slices=24; TR=2000 ms. Each functional run had 240 repetitions. A high resolution, T1 weighted 3D image was acquired (TR=21 ms, TE=8 ms, flip angle=20°, matrix size=256×256, field of view=22 cm, slice thickness=1 mm, number of slices=124), using an identical orientation as the functional images.

Data was analyzed using SPM2 (Statistical Parametric Mapping) (<http://www.fil.ion.ucl.ac.uk/spm>). Images were spatially realigned to the first volume to correct for head movements. No run had more than 4 mm displacement in any of the x, y or z dimensions. Sinc interpolation was used to minimize timing-errors between slices. Functional images were co-registered with the anatomical image, and normalized to the standard T1 Montreal Neurological Institute (MNI) template volume. The data was smoothed with a 10 mm isotropic Gaussian kernel. Statistical analyses at the first level were calculated using an event-related design with the four lexical conditions, two perceptual conditions, and the null condition included as conditions of interest. A high pass filter with a cutoff of 128 s was applied. Word pairs and perceptual pairs were treated as individual events for analysis and modeled using a canonical hemodynamic response function (HRF).

In order to examine activation associated with linguistic processing, we first created a mask to include cortical areas involved in the rhyme task. First, contrast maps were generated for each group, based on the subtraction of activation of the group's average lexical condition versus null at a lenient

threshold ( $p=.01$ , uncorrected). Next, the contrast map for the two groups was added together to create a map of the union of the activation for both groups. Finally, this mask was applied to all analyses to determine significant within-group activation and significant activation differences between groups. One-sample t-tests were used to examine main effects within each group, and two-sample t-tests to examine group differences for each of the following contrasts: (1) the average of the lexical conditions versus null, (2) the O+P- versus the O-P- conditions (conflicting versus non-conflicting for the non-rhyming pairs), and (3) the O-P+ versus the O+P+ conditions (conflicting versus non-conflicting for the rhyming pairs). We examined the effect of conflict between orthographic and phonological information by comparing the conflicting versus non-conflicting conditions for the rhyming and for the non-rhyming word pairs separately, such that this effect was evaluated by comparing conflict between conditions with similar response characteristics (i.e., "yes" or "no" rhyme decision). Areas of activation reported for all analyses were significant at  $p<.001$ , uncorrected, at the voxel level, with a minimum cluster size of 15 voxels.

Where between-group analyses were significant, we repeated the analyses using performance IQ and age as covariates (separately). These additional analyses were performed in order to ensure that observed group differences were not due to differences in age or nonverbal intelligence. We also further explored how the neural activation in regions associated with orthographic processing (i.e., left fusiform gyrus) might be related to performance and/or skill, such that where we observed significant within-group effects or between-group differences, we extracted individual contrast values of activation from this region in order to perform further analyses. We performed within-group correlations between these values and behavioral data, including nonword decoding (WJ-III Word Attack subtest) score and the conflict effect (reaction time to conflicting minus non-conflicting conditions, separately for "yes" and "no" responses). We then compared group differences in these correlation coefficients statistically, using z-tests.

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