

Differential effects of orthographic and phonological consistency in cortex for children with and without reading impairment

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ABSTRACT

One of the central challenges in mastering English is becoming sensitive to consistency from spelling to sound (i.e. phonological consistency) and from sound to spelling (i.e. orthographic consistency). Using functional magnetic resonance imaging (fMRI), we examined the neural correlates of consistency in 9–15-year-old Normal and Impaired Readers during a rhyming task in the visual modality. In line with our previous study [Bolger, D. J., Hornickel, J., Cone, N. E., Burman, D. D., & Booth, J. R. (in press). Neural correlates of orthographic and phonological consistency effects in children. *Human Brain Mapping*], for Normal Readers, lower phonological and orthographic consistency were associated with greater activation in several regions including bilateral inferior/middle frontal gyri, bilateral anterior cingulate cortex as well as left fusiform gyrus. Impaired Readers activated only bilateral anterior cingulate cortex in response to decreasing consistency. Group comparisons revealed that, relative to Impaired Readers, Normal Readers exhibited a larger response in this network for lower phonological consistency whereas orthographic consistency differences were limited. Lastly, brain–behavior correlations revealed a significant relationship between skill (i.e. Phonological Awareness and non-word decoding) and cortical consistency effects for Impaired Readers in left inferior/middle frontal gyri and left fusiform gyrus. Impaired Readers with higher skill showed greater activation for higher consistency. This relationship was reliably different from that of Normal Readers in which higher skill was associated with greater activation for lower consistency. According to single-route or connectionist models, these results suggest that Impaired Readers with higher skill devote neural resources to representing the mapping between orthography and phonology for higher consistency words, and therefore do not robustly activate this network for lower consistency words.

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1. Introduction

Some alphabetic writing systems, such as English, are fairly inconsistent in the mapping between orthography and phonology. Numerous studies have shown that lower phonological consistency, which occurs when the same spelling has different pronunciations (e.g. *seat* versus *sweat*), slows reaction time of adults during lexical decision, naming, and reading tasks in the visual modality (Fiez, Balota, Raichle, & Petersen, 1999; Jared, McRae, & Seidenberg, 1990; Lacruz & Folk, 2004; Stone, Vanhoy, & VanOrden, 1997; Ziegler, Montant, & Jacobs, 1997). Recent work has also shown that

lower orthographic consistency, which occurs when a sound can be spelled in multiple ways (e.g. *grade* and *laid*), slows reaction time in adults during lexical decision and naming tasks in the visual modality (Kessler, Treiman, & Mullennix, 2007; Lacruz & Folk, 2004; Massaro & Jesse, 2005; Stone et al., 1997; Ziegler et al., 1997).

A decade-old meta-analysis by Metsala, Stanovich, and Brown, (1998) concluded that the phonological consistency effect was not statistically different in Normal Readers versus Impaired Readers. The mean effect size for the Normal Readers was $d=0.68$ (95% confidence interval=0.56–0.80) and the mean effect size for Impaired Readers was $d=0.58$ (95% confidence interval=0.46–0.70). They reported that many studies found significant consistency effects of equal magnitude in Normal Readers and Impaired Readers (Baddeley, Logie, & Ellis, 1988; Ben-Dror, Pollatsek, & Scarpati, 1991; Bruck, 1988; Bruck & Treiman, 1990; Holligan & Johnston, 1988; Manis, Szeszulski, Holt, & Graves, 1990; Olson, Kliegl, Davidson, & Foltz, 1985; Stanovich, Nathan, & Zolman, 1988; Szeszulski & Manis, 1987). However, they also reported that

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some studies found significant consistency effects for both Normal Readers and Impaired Readers that was greater for Normal Readers (Beech & Awaida, 1992; Murphy & Pollatsek, 1994; Siegel & Ryan, 1988; Szeszowski & Manis, 1987), significant consistency effects for Normal Readers but not for Impaired Readers (DiBenedetto, Richardson, & Kochnowar, 1983; Frith & Snowling, 1983; Johnston, Anderson, Perrett, & Holligan, 1990; Siegel & Ryan, 1988), and no significant consistency effects for either Normal Readers or Impaired Readers (Beech & Harding, 1984; Treiman & Hirsh-Pasek, 1985). Interestingly, they reported no studies that showed a larger phonological consistency effect for Impaired Readers.

More recent studies have also been inconclusive regarding the consistency effect. Two studies reported differences between Normal Readers and Impaired Readers in learning lower versus higher consistency words. In one study, Chinese dyslexics performed less well than reading-match controls in learning lower phonologically consistent compared to higher phonologically consistent words (Ho, Chan, Tsang, Lee, & Chung, 2006). However, another study with English phonological dyslexics did not show an advantage for learning higher phonological consistency compared to lower phonological consistency words as compared to age- and reading-match controls (Bailey, Manis, Pedersen, & Seidenberg, 2004). To our knowledge, only one study has examined orthographic consistency effects in Normal Readers compared to Impaired Readers. This study found that both dyslexic and control children showed phonological consistency effects in reading and spelling, but only dyslexic children showed orthographic consistency effects in reading, and it was significantly larger than for Normal Readers (Davies & Weekes, 2005). Although the results of previous studies are likely to be contradictory because of differences in languages studied, tasks used and characteristics of the populations, altogether the research suggests that there is a larger phonological consistency effect in Normal Readers compared to Impaired Readers. The limited behavioral research on orthographic consistency prohibits any conclusion regarding group differences.

Neuroimaging studies have shown that phonological consistency is associated with specific brain activity. Studies have found that adults show greater activation for lower phonological consistency words in left inferior frontal gyrus (Binder, Medler, Desai, Conant, & Liebenthal, 2005; Fiez et al., 1999; Herbster, Mintun, Nebes, & Becker, 1997; Katz et al., 2005; Peng et al., 2004; Tan, Feng, Fox, & Gao, 2001), left superior temporal cortex (Peng et al., 2004; Tan et al., 2001) and left inferior parietal cortex (Binder et al., 2005; Peng et al., 2004). Other studies not examining the phonological consistency effect have implicated posterior dorsal inferior frontal gyrus and superior temporal gyrus in phonological processing (Poldrack et al., 1999; Vigneau et al., 2006) and inferior parietal cortex in integrating orthographic and phonological representations (Booth et al., 2002, 2003). Neuroimaging studies also show that lower phonological consistency words produce greater activation in medial frontal gyrus/anterior cingulate cortex (Binder et al., 2005; Tan et al., 2001). Various studies have implicated medial frontal gyrus/anterior cingulate cortex in conflict resolution (Barber & Carter, 2005; Kerns et al., 2004). Finally, only one study has shown a phonological inconsistency effect in fusiform gyrus, but this was limited to low frequency words (Peng et al., 2004). Fusiform gyrus has been implicated in orthographic processing (Cohen, Jobert, Le Bihan, & Dehaene, 2004; Dehaene et al., 2004). However, patient studies suggest that the fusiform gyrus may play a critical role in the phonological consistency effect. Adult patients with damage to posterior inferior temporal cortex (BA 20, 37) have a more severe deficit with spelling lower consistency compared to higher consistency words, and most errors are phonologically plausible (Rapcsak & Beeson, 2004). In addition, a case study in 14-year-old girl with left occipital lesion showed that she was more successful at reading

higher consistency than lower consistency words, with most errors involving regularization (Samuelsson, 2000).

Only one imaging study has examined the neural correlates of orthographic and phonological consistency effects in children (Bolger, Hornickel, Cone, Burman, Booth, *in press*). In the same rhyming task used in the current study, we found both lower orthographic and phonological consistency was correlated with greater activation in left inferior frontal gyrus and bilateral medial frontal gyrus/anterior cingulate cortex. The consistency effects for the rhyming task were greater than the consistency effects for a spelling task, presumably because the former required mapping between orthographic and phonological representations for correct performance but the latter did not. In addition, accuracy was correlated with consistency effects for the rhyming task in left fusiform gyrus. Lower skill children were not sensitive to phonological or orthographic consistency, moderate skill children were only sensitive to lower phonological and orthographic consistency, and high skill children were sensitive to both higher and lower phonological and orthographic consistency. The brain-behavior correlations in fusiform gyrus suggest that children are initially sensitive lower consistency words and only with greater expertise do they become tuned to higher consistency words. More generally, these results are consistent with behavioral studies suggesting that consistency effects are larger in more skilled readers.

Two prominent models of reading have been used to account for consistency effects. Dual-route models (Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001) postulate a fast lexical route (also referred to as addressed or direct) that associates whole words in an orthographic system to whole words in a phonological system plus a slower, independent sub-lexical route (also referred to as assembled or indirect) that contains grapheme (letter)–phoneme (sound) correspondence rules. Dual-route models argue these rules are used for processing unfamiliar words (i.e. low frequency words) and pseudowords that do not have an orthographic or phonological representation. Although the sub-lexical route can also process high frequency words, the faster lexical route typically processes high frequency words, as well as words with lower phonological consistency (i.e. irregular or exception words) because the grapheme–phoneme correspondence rules would generate incorrect pronunciations for these words. In contrast, single-route or connectionist models (Plaut, McClelland, Seidenberg, & Patterson, 1996) argue that there is one mechanism for mapping between orthographic and phonological representations and these models have been used to account for frequency, consistency and pseudoword effects without postulating separate grapheme–phoneme correspondence rules. Some neuroimaging studies have adopted the dual-route approach and have argued that the dorsal system involving inferior parietal and posterior superior temporal cortex is involved in rule-based mapping between orthography and phonology (Pugh et al., 2000). These models predict that this ruled-based system should show greater activation for higher consistency words because these words can be processed with grapheme–phoneme correspondence rules. However, as reviewed above, the literature suggests that temporo-parietal cortex actually shows greater activation for lower consistency words. In contrast, single-route models argue that lower consistency words should produce higher cross entropy values meaning that larger numbers of units of information (i.e. more wide spread activation) are necessary to represent this information. The single-route model is, therefore, more in line with the neuroimaging literature that shows lower consistency words produce greater activation in temporo-parietal cortex.

Our previous study examined orthographic and phonological consistency effects in a large sample of Normal Readers, and whether these effects were correlated with skill. The goal of the current study was to examine differences between Normal Readers

(9–15 year olds) and age-matched Impaired Readers in the neural correlates of both the phonological and orthographic consistency effect. We examined the hemodynamic response function (HRF) to the first word in a rhyming task in which an initial word is presented followed by a probe word, both presented visually upon which a rhyming decision is made. Given the highly interactive nature of the language network as revealed by effective connectivity (Bitan et al., 2005, 2006), we expected both lower phonological and orthographic consistency to result in greater brain activation in left hemisphere regions implicated in prior research on the phonological consistency effect—particularly left inferior frontal gyrus and medial frontal gyrus/anterior cingulate cortex. Although no previous neuroimaging study has examined the neural correlates of consistency effects in Impaired Readers, based on previous behavioral research, we expected consistency effects in these brain regions to be larger in Normal Readers compared to Impaired Readers, and this group difference may be especially pronounced for phonological consistency because the rhyming task required mapping from orthographic to phonological representations for correct performance. In addition, based on our neuroimaging study within Normal Readers that found higher skill was correlated with a larger consistency effect in left fusiform gyrus (Bolger et al., *in press*), we also expected to find group differences between normal and Impaired Readers in this region.

2. Methods

2.1. Participants

A total of 24¹ (12 Impaired Readers and 12 Normal Readers) 9–15-year-old children, 6 females and 18 males, participated in the study. Children were all right handed, (mean = 78, range 50–90) according to a 9-item Likert scale questionnaire (–90 to 90, positive scores indicate right hand dominance) (Olfield, 1971), and native English speakers, with normal hearing and normal or corrected-to-normal vision. Parents of children were given an interview to assess developmental history of their child including of reading, attention and oral-language deficits. Parents reported their children to be free of neurological diseases or psychiatric disorders and to not be taking medication affecting the central nervous system. Parents also reported their children did not have poor educational opportunities.

Parents of Impaired Readers (3 female and 9 male) reported previous diagnosis of reading or learning disability in their children. In addition to prior diagnosis, inclusion criteria required that participants score in the bottom 25th percentile (<90, range = 73–89) on the average of 4 standardized reading tests: the Woodcock-Johnson (WJ-III) Word Attack and Word Identification sub-tests (Woodcock, McGrew, & Mather, 2001), and the Test of Word Reading Efficiency (TOWRE) Sight Word Efficiency and Phonetic Decoding Efficiency sub-tests (Torgeson, Wagner, & Rashotte, 1999). All Impaired Readers also had to score above the 25th percentile for full-scale intelligence (>90, range = 90–112) on the Wechsler Abbreviated Scale of Intelligence (WASI) (Wechsler, 1999). The overall discrepancy between performance IQ and the average reading score was greater than 10 points for 11 of 12 Impaired Readers (mean = 16.5, range = 9–20) with one participant having a 9-point difference. Parents of Impaired Readers reported their children having no other oral-language or attention deficits. Criteria for inclusion for Normal Readers required that they scored above the 25th percentile on the average of 4 standardized reading tests (>90, range = 98–124) and on full-scale intelligence (>90, range = 99–130). Normal Readers were matched on age (within 4 months) and gender with Impaired Readers. Parents of Normal Readers reported their children having no history of reading, attention or oral-language deficits. We chose to use age-matched Normal Readers because several studies of 9–15-year-old children have shown developmental changes in brain activation that are independent of behavioral performance on the task (Bitan et al., 2007; Booth, Cho, Burman, & Bitan, 2007; Booth, Mehdiratta,

Burman, & Bitan, 2008; Chou, Booth, Bitan, et al. 2006; Chou, Booth, Burman, et al., 2006). Table 1 presents the means and standard deviations as well as indicates tests in which group differences were statistically reliable (based on two-sample *t*-tests).

Children were recruited from the Chicago metropolitan area through brochures sent to schools, hospitals and learning centers. Advertisements were also placed in local newspapers and magazines. The Institutional Review Board at Northwestern University and Evanston Northwestern Healthcare Research Institute approved the informed consent procedures.

2.2. Task parameters

2.2.1. Lexical conditions

Words were presented visually in a sequential order in which each word was presented for 800 ms with a 200 ms blank inter-stimulus interval (see Fig. 1). A red fixation-cross appeared on the screen after the second word, indicating the need to make a response by pressing one of two buttons during the subsequent 2700 ms interval. Participants determined if two words rhymed. For a 'yes' response, participants used their right index finger to press a button and for a 'no' response participants used their right middle finger to press a second button. Twenty-four word pairs were presented in each one of four lexical conditions that independently manipulated the orthographic and phonological similarity between words. In the two non-conflicting conditions, the two words were either similar in both orthography and phonology (O+P+, e.g. *dime-lime*), or different in both orthography and phonology (O–P–, e.g. *staff-gain*). In the two conflicting conditions, the two words had either similar orthography but different phonology (O+P–, e.g. *pint-mint*), or different orthography but similar phonology (O–P+, e.g. *jazz-has*). However, the current study did not examine this manipulation because we were interested in the effect of phonological and orthographic consistency on brain activation when processing the first word.

2.2.2. Control conditions

Two perceptual control conditions were used in which two symbol strings (i.e. rearranged parts of lower case Courier letters) were presented visually in sequential order and the participant had to determine whether the strings matched. In the 'Simple' condition, the symbol string consisted of a single symbol, while in the 'Complex' condition the symbol string consisted of three different symbols. In the 'Simple' condition a match constituted two sequentially presented single symbols that were exactly the same. In the 'Complex' condition, a match constituted two sequentially presented symbol triplets that were exactly the same (non-matches consisted of symbol triplets that differed by one symbol). Timing and response parameters were the same as for the lexical conditions. Twenty-four items were presented in each perceptual condition, with half of them matching. In addition to the perceptual control conditions, 72 fixation trials were included as a baseline. In the fixation condition, a black fixation-cross was presented for the same duration as the stimuli in the lexical and perceptual conditions and participants were instructed to press a button when the black fixation-cross turned red. However, the current study did not examine the control conditions because we were interested in the effect of phonological and orthographic consistency on lexical processing. The order of lexical, perceptual and fixation trials was optimized for event-related design (Burock, Buckner, Woldorff, Rosen, & Dale, 1998) and fixed for all subjects.

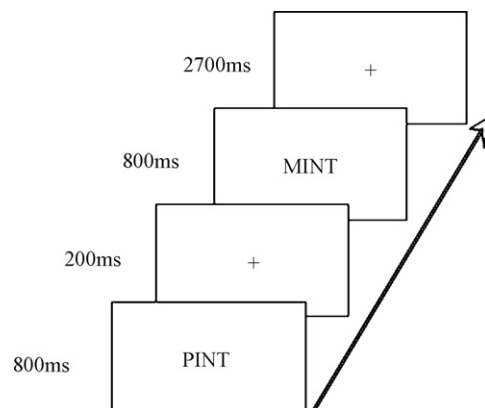


Fig. 1. Two words were presented visually with the first followed by the second at a 1 s stimulus onset asynchrony (SOA). The hemodynamic response functions (HRFs) of first and second words were modeled separately with the conditions of interest being applied to the modeled first word so as to minimize neural activity due to task specific (i.e. rhyming) processing. The repetition time (2 s) differed from trial time (4.5 s) enabling the deconvolution of the HRF response to each stimulus.

¹ We collected behavioral and neuroimaging data from 27 children that were given formal diagnoses of a reading disability of which 11 participants did not meet our inclusion criteria. An additional 4 participants in this group were not included due to excessive movement in the scanner or exceedingly poor performance (below 60% accuracy) on the behavioral task during scanning. Data were collected from 58 children in the typically achieving group of which 11 were excluded due to excessive movement in the scanner and 1 was excluded due to poor performance on the behavioral task. As stated previously, 12 of these typically achieving participants were selected for inclusion into the study based on matching age and gender relative to peers in the Impaired Readers.

Table 1
Mean, standard deviation and ranges for standardized tests for Normal and Impaired Readers

	Normal (N = 12)	Impaired (N = 12)
Age (range)	11.06 (8.09–14.11)	11.9 (8.11–14.10)
Verbal IQ (WASI)	110 (7.92)**	96.8 (11.5)
Performance IQ (WASI)	109 (6.82)**	97.8 (6.69)
Full-scale IQ (WASI)	111 (7.14)**	96.9 (8.82)
Phonological Awareness (CTOPP)	102 (14.26)**	85 (7.89)
Word Identification (WJ-III)	110 (7.12)**	84 (7.66)
Word Attack (WJ-III)	106 (8.84)**	83 (8.14)
Sight Word Efficiency (TOWRE)	105 (8.62)**	83 (8.37)
Phonetic Decoding Efficiency (TOWRE)	102 (12.1)**	75.7 (8.65)

WASI: Wechsler Abbreviated Scale of Intelligence; CTOPP: Comprehensive Test of Phonological Processing; WJ-III: Woodcock-Johnson Test of Achievement (3rd edition); TOWRE: Test of Word Reading Efficiency.

** Group difference is significant at the $p < 0.001$ level.

2.2.3. Stimulus characteristics

All words were monosyllabic and 4–7 letters long. Phonological enemies were defined as the number of words with similar spelling but different pronunciation of the rhyme and orthographic enemies were defined as the number of words with similar pronunciation but different spelling of the rime. Friends were defined as words with the same rime spelling and same rhyme pronunciation as the stimulus. Consistency was computed as the ratio of friends to the sum of friends and enemies (i.e. friends/(friends + enemies)) based on the 2998 mono-syllable words (Plaut et al., 1996). Words that have a ratio approaching 1.0 have very few or no enemies (higher consistency), while words with a ratio approaching 0.0 have few or no friends (lower consistency). Word frequency (1996) was not correlated with phonological or orthographic inconsistency, $r(95) = -0.02$, $p = 0.848$ and $r(95) = 0.04$, $p = 0.618$, respectively. Phonological consistency was not correlated with orthographic consistency, $r(95) = 0.11$, $p = 0.338$. We also conducted analyses comparing grapheme and phoneme length (the number of graphemes and phonemes in each word) with both consistency types. While significantly correlated with each other, $r(95) = 0.63$, $p < 0.005$, the only significant relationship found was between phoneme length and orthographic consistency, $r(95) = 0.24$, $p < 0.05$. This is predictable considering that words with longer pronunciations are more likely to have more ways of spelling each phonetic component. The full set of values for both types of consistency and grapheme and phoneme length are provided in Appendix A.

2.3. Experimental procedure

After informed consent was obtained and standardized measures were administered, participants were invited for a practice session, in which they were trained to minimize head movement using an infrared tracking device in front of a computer screen. In addition, they performed one run of the experimental task in a simulator scanner, in order to make sure they understood the task 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 from the practice session.

2.4. MRI data acquisition

Images were acquired using a 1.5T General Electric (GE) scanner, using a standard head coil. Head movement was minimized using vacuum pillow (Bionix, Toledo, OH). The stimuli were projected onto a screen, and viewed through a mirror attached to the inside of the head coil. Participants' responses were recorded using an optical response box (Current Designs, Philadelphia, PA). The blood-oxygen level dependent (BOLD) functional images were acquired using the echo planar imaging (EPI) method. The following parameters were used for scanning: time of echo (TE) = 35 ms, flip angle = 90°, matrix size = 64 × 64, field of view = 24 cm, slice thickness = 5 mm, number of slices = 24; time of repetition (TR) = 2000 ms. Two runs, with 240 repetitions each, were administered for the functional images. In addition, structural

T1 weighted 3D image were 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.

2.5. Image analysis

Data analysis was performed using Statistical Parametric Mapping (SPM2, <http://www.fil.ion.ucl.ac.uk/spm>). The images were spatially realigned to the first volume to correct for head movements. No individual runs had more than 4 mm maximum displacement in the x, y or z dimension. Since interpolation was used to minimize timing-errors between slices. The functional images were co-registered with the anatomical image, and normalized to the standard T1 Montreal Neurological Institute (MNI) template volume. The data was then smoothed with a 10 mm isotropic Gaussian kernel. Initial statistical analyses included 'first words', 'second words', 'perceptual conditions', and 'fixation' events as the four conditions of interest. A high pass filter with a cutoff period of 128 s was applied. First and second words of each pair were treated as individual events for analysis and modeled using a canonical HRF with intrinsic autocorrelations. The analysis of consistency effects was conducted only on the first words. Group results were obtained using random-effects analyses by combining subject-specific summary statistics across the group as implemented in SPM2.

In the analyses, we entered phonological and orthographic consistency as continuous variables to determine if brain activation systematically correlated with these variables. Because phonological consistency was skewed (many of the words had a consistency value at or near 1.0), we used a log 10 transformation to normalize the distribution. Table 2 displays the strategy for conducting analyses and the series of tests that are reported in this work. Serving as the fundamental unit of analysis, values of phonological and orthographic consistency were implemented for first word stimuli as item-level parametric modulators in separate first-level (within-subject) statistical models. The resulting model coefficients for individual subjects were entered into subsequent second-order random effects analyses for effects. In order to determine the main effect of overall consistency for the two groups independently, we conducted one-sample *t*-tests collapsing across consistency type within-subject for Normal (Analysis 1) and Impaired Readers (Analysis 4). The next set of analyses used one-sample *t*-tests to isolate the effect of consistency type separately for Normal (Analyses 2 and 3) and Impaired Readers (Analyses 5 and 6). For analyses comparing the Normal to Impaired Readers (Analyses 7–9), a functional mask was created from the union of the resulting F-maps for the Normal and Impaired Readers (each at uncorrected *p*-value of 0.001) collapsing across consistency type. We then compared differences in cortical response between groups by directly comparing Normal to Impaired Readers using independent-samples *t*-tests first for overall effects (Analysis 7), and then for phonological and orthographic consistency separately (Analyses 8 and 9). Because numerous studies have shown that Phonological Awareness and decoding ability are substantial predictors

Table 2
Strategy for analyzing the fMRI results comparing consistency effects, orthographic consistency (OrthCon) and phonological consistency (PhonCon), for Normal and Impaired Readers

	Contrast	Figures/tables
Analysis 1: Effect of overall consistency for Normal Readers	Average of 2 model coefficients > 0	Table 3; Fig. 2
Analyses 2 and 3: Effect of each consistency type for Normal Readers	OrthCon > 0, PhonCon > 0	Table 3
Analysis 4: Effect of overall consistency for Impaired Readers	Average of 2 model coefficients > 0	Table 3
Analyses 5 and 6: Effect of each consistency type for Impaired Readers	OrthCon > 0, PhonCon > 0	Table 3
Analysis 7: Group differences in overall consistency	Normal > Impaired for average of 2 model coefficients,	Table 4; Fig. 2
	Normal > Impaired for OrthCon	
	Normal > Impaired for PhonCon	Table 4; Fig. 2
Analyses 8 and 9: Group differences for each consistency type		
Analysis 10: Brain-behavior correlations within each group	2nd level regression: $PA_{(Normal)} + PA_{(Impaired)}$ for OrthCon and PhonCon separately	Figs. 3 and 4

of reading skill (Torgesen, Morgan, & Davis, 1992; Torgesen, Wagner, & Rashotte, 1994; Wagner, Torgesen, Laughon, Simmons, & Rashotte, 1993; Wagner, Torgesen, & Rashotte, 1994), we additionally tested brain–behavior correlations with our model coefficients for phonological and orthographic consistency and the Phonological Awareness composite scores on the Comprehensive Test of Phonological Processes (Wagner, Torgesen, & Rashotte, 1999) as well as the Word Attack subtest (non-word decoding) on the Woodcock-Johnson (Woodcock et al., 2001). The correlations within Normal and Impaired Readers, and the difference in slope values between groups, were analyzed using multiple regression analyses with separate behavioral predictors (Phonological Awareness and Word Attack) for each group entered as separate variables. Group differences in correlation slope values were assessed by contrasting the resulting effects for the model predictors of the behavioral measure with consistency for each group. All reported effects are significant at $p < 0.05$ false discovery rate (FDR) corrected and contain 10 or greater voxels.

3. Results

3.1. Behavioral results

The analysis of accuracy on the two groups showed that mean accuracy for Normal Readers ($M = 86\%$, $S.D. = 7.0\%$) was significantly greater than mean accuracy for Impaired Readers in a two-sample t -test ($M = 63\%$, $S.D. = 7.0\%$; $t(22) = 7.71$, $p < 0.001$). In order to test the relationship between item consistency (for the first words which we are analyzing in this study) and trial accuracy, we ran linear regressions for each group separately on both orthographic and phonological consistency. These results should be taken with caution considering that trial accuracy was based on rhyming judgment to both the first and second word. However, we conducted this analysis to approximate any possible relationships between our measure of consistency and task performance. The analyses of the Normal Readers revealed no relationship between trial accuracy and phonological consistency ($r = 0.27$, $t(94) = 1.44$, $p > 0.05$), but a significant relationship for orthographic consistency ($r = 0.49$, $t(94) = 3.31$, $p < 0.005$). The analyses of the Impaired Readers revealed a significant relationship between accuracy and phonological consistency ($r = 0.47$, $t(94) = 2.65$, $p < 0.01$) and a similarly significant relationship for orthographic consistency ($r = 0.49$, $t(94) = 3.31$, $p < 0.01$). Interaction tests of slope differences between groups were conducted with analysis of variance (ANOVA) and revealed no differences between groups for the relationship of consistency with behavioral accuracy.

3.2. fMRI results

3.2.1. Normal Readers

To assess the overall effects of consistency in Normal Readers, we collapsed across the model predictors for orthographic and phonological consistency type for each subject and then calculated a random-effects one-sample t -test. Replicating our previous findings with normal children (Bolger et al., *in press*), greater activation was correlated with greater inconsistency including bilateral anterior cingulate, bilateral inferior frontal gyrus and left fusiform gyrus (see Table 3 and Fig. 2 left column). We failed to replicate greater activation for higher consistency in bilateral posterior cingulate and left middle temporal gyrus shown in our previous study. This is likely due to variability with fewer subjects in this study compared to the previous ($N = 12$ versus 46). We examined the effect of each consistency type separately using 2 one-sample t -tests with a Bonferroni correction for multiple tests of the data. As shown in Table 3, these tests revealed the same general set of clusters for lower consistency as revealed by the collapsed analysis for both orthographic and phonological consistency types.

3.2.2. Impaired Readers

We assessed the overall effect of consistency in Impaired Readers, again collapsing across model predictors for orthographic and

phonological consistency types in a one-sample t -test. This test revealed only a single cluster of voxels in bilateral anterior cingulate reliably activated as a function of lower consistency and no activations associated with higher consistency (see Table 3). We examined the unique effects of each consistency type for Impaired Readers in separate one-sample t -tests with a Bonferroni correction for multiple tests of the data. The results of these analyses revealed no significant clusters of activation for either consistency type alone.

3.2.3. Group comparison

In order to compare the differences between groups, we used random-effects 2-sample t -tests to compare the overall effect of consistency collapsed across type as well as individual tests of both orthographic and phonological consistency. A cortical mask was applied by merging the F-maps of overall consistency effects for both Normal and Impaired Readers using an uncorrected p -value of 0.001. The first analyses of group differences comparing overall consistency effects revealed clusters with greater model coefficients for the Normal compared to Impaired Readers in bilateral anterior cingulate, bilateral inferior/middle frontal gyri, bilateral middle temporal gyri, left superior temporal gyrus and left inferior temporal gyrus extending into fusiform gyrus (see Table 4; Fig. 2 right column of brain images). To examine the contribution of each consistency type to the overall effect, the intensity of activation (parameter estimates) were extracted for each consistency type as shown in the graphs on the far right in Fig. 2. These analyses reveal that group differences are largely due to greater activation as a function of lower consistency for Normal Readers (lower consistency is plotted as positive beta values for ease of interpretation because the majority of our effects were in this direction). Individual group comparisons of orthographic and phonological consistency were conducted with the same cortical mask (above) and Bonferroni correction for multiple comparisons. These analyses revealed that, for lower phonological consistency, Normal Readers exhibited greater activation in generally the same set of clusters (excluding bilateral middle temporal gyri) identified in the overall analysis, however, for lower orthographic consistency, only clusters in inferior/middle frontal gyri were reliably different between groups. These results are displayed in Table 4 and in the right column of images in Fig. 2 with orthographic consistency in green, phonological consistency in red, and overlap in blue.

We also analyzed differences between Normal and Impaired Readers after regressing out full-scale IQ standard scores and found little change in our main effects. Reductions in group differences after partialing IQ were evident only in right hemisphere frontal regions and anterior cingulate.

3.2.4. Brain–behavior correlations

To assess brain–behavior relationships, we conducted second-level multiple regression analyses separately for phonological and orthographic consistency with three predictors: a group variable (Normal versus Impaired Readers) and separate predictors of Normal and Impaired Readers' Phonological Awareness (PA) scores on the Comprehensive Test of Phonological Processes (Wagner et al., 1999) or Word Attack scores on the Woodcock-Johnson (Woodcock et al., 2001). Again, we applied the cortical mask discussed in the previous analyses and subsequent Bonferroni corrections. We conducted three sets of tests: one-sample t -tests of Phonological Awareness or Word Attack predictors separately for Normal Readers and Impaired Readers, and two-sample t -tests directly comparing Normal and Impaired Readers. For our purposes here, we will report regions in which reliable group differences were found and report the unique effect of each group.

Table 3
Greater activation as a function of lower consistency overall (Both) and separately for orthographic and phonological consistency for Normal and Impaired Readers

Region	BA	Normal > Impaired																			
		Both					Orthographic					Phonological					Both				
		x	y	z	Vol	t	x	y	z	Vol	t	x	y	z	Vol	t	x	y	z	Vol	t
Cingulate/medial frontal																					
R. Anterior cingulate gyrus	32/6	9	17	43	841	8.93	9	14	44	763	6.56	9	17	43	765	6.09	3	11	55	103	5.29
L. Anterior cingulate gyrus	32/6	-3	22	40	^a	7.74	-6	22	38	^a	6.08	-6	11	41	^a	5.51	-6	6	55	^a	5.33
L. Medial frontal gyrus	8	-6	14	44	^a	7.33															
R. Medial frontal gyrus	6																12	3	61	^a	3.58
L. Superior frontal gyrus	6						-3	11	49	^a	4.99	-3	11	49	^a	5.07					
Lateral frontal																					
L. Inferior frontal gyrus	46	-50	35	9	1848	7.82	-45	38	9	1822	7.03	-50	35	9	1659	6.77					
^a	47	-33	24	-3	^a	7.74	-36	17	-6	^a	8.56	-36	29	-4	^a	5.34					
^a	44	-48	9	15	^a	6.79	-54	9	15	^a	5.69	-45	9	11	^a	5.93					
L. Precentral gyrus	6	-45	0	36	^a	5.64	-42	3	30	^a	6.40										
L. Middle frontal gyrus	46/44	-50	30	21	^a	6.91	-48	33	18	^a	6.68										
R. Inferior frontal gyrus	47	39	23	-4	863	7.03						36	26	-4	825	5.56					
R. Insula	13	33	18	2	^a	7.30															
R. Middle frontal gyrus	46/10	39	45	23	^a	3.59	50	30	21	826	6.57	50	27	15	^a	4.80					
^a	45/47	53	27	18	^a	6.78	30	23	-9	^a	6.25										
^a	10						42	48	20	14	2.71										
^a	9	36	45	31	18	3.37						36	45	31	18	3.17					
Temporal/occipital																					
L. Fusiform gyrus	37	-42	-64	-4	82	4.79	-42	-64	-4	41	2.59	-48	-61	-7	75	4.90					
L. Inferior occipital gyrus	19	-45	-73	-1	^a	4.27	-45	-73	-1	^a	2.79	-42	-73	-4	^a	4.05					
L. Inferior temporal gyrus	37	-53	-55	-10	^a	3.33						-53	-55	-10	^a	4.52					
L. Middle temporal gyrus	22	-65	-37	10	27	3.93	-65	-40	16	27	3.03	-65	-38	7	27	3.19					
L. Superior temporal gyrus	22	-65	-26	4	^a	3.87	-65	-26	4	^a	2.69	-65	-26	4	^a	3.14					
R. Middle temporal gyrus	19	42	-81	21	10	3.53						42	-81	21	10	3.88					
R. Middle occipital gyrus	19	48	-78	15	^a	3.21															
Occipital/parietal																					
L. Postcentral gyrus	2	-48	-27	43	15	3.58	-48	-27	43	14	3.77	-50	-21	43	13	2.91					
L. Cuneus	18	-6	-78	20	^a	3.96	-6	-75	18	^a	3.28	-6	-78	20	^a	3.27					
^a							-6	-77	26	^a	2.68	-9	-83	26	^a	3.89					
R. Cuneus	18	6	-83	21	28	4.49	6	-84	18	20	3.9	3	-83	24	^a	2.98					
Sub-cortical																					
L. Thalamus							0	-3	6	15	3	0	-9	3	22	4.29					
R. Thalamus	^a	3	-9	3	22	4.23															

No reliable regions were found for individual consistency type in Impaired Readers. *Note:* Clusters presented are more than 10 contiguous voxels surviving an alpha of 0.001 (uncorrected). All areas survive FDR corrected $p < 0.05$. Volume (Vol) of clusters is indicated in voxels of 3 mm^3 for the maximal peak. BA: Brodmann's Areas, x, y, z: Montreal Neurological Institute (MNI) coordinates, t: statistical t-value, R: right, L: left.

^a Subpeaks of larger clusters immediately above.

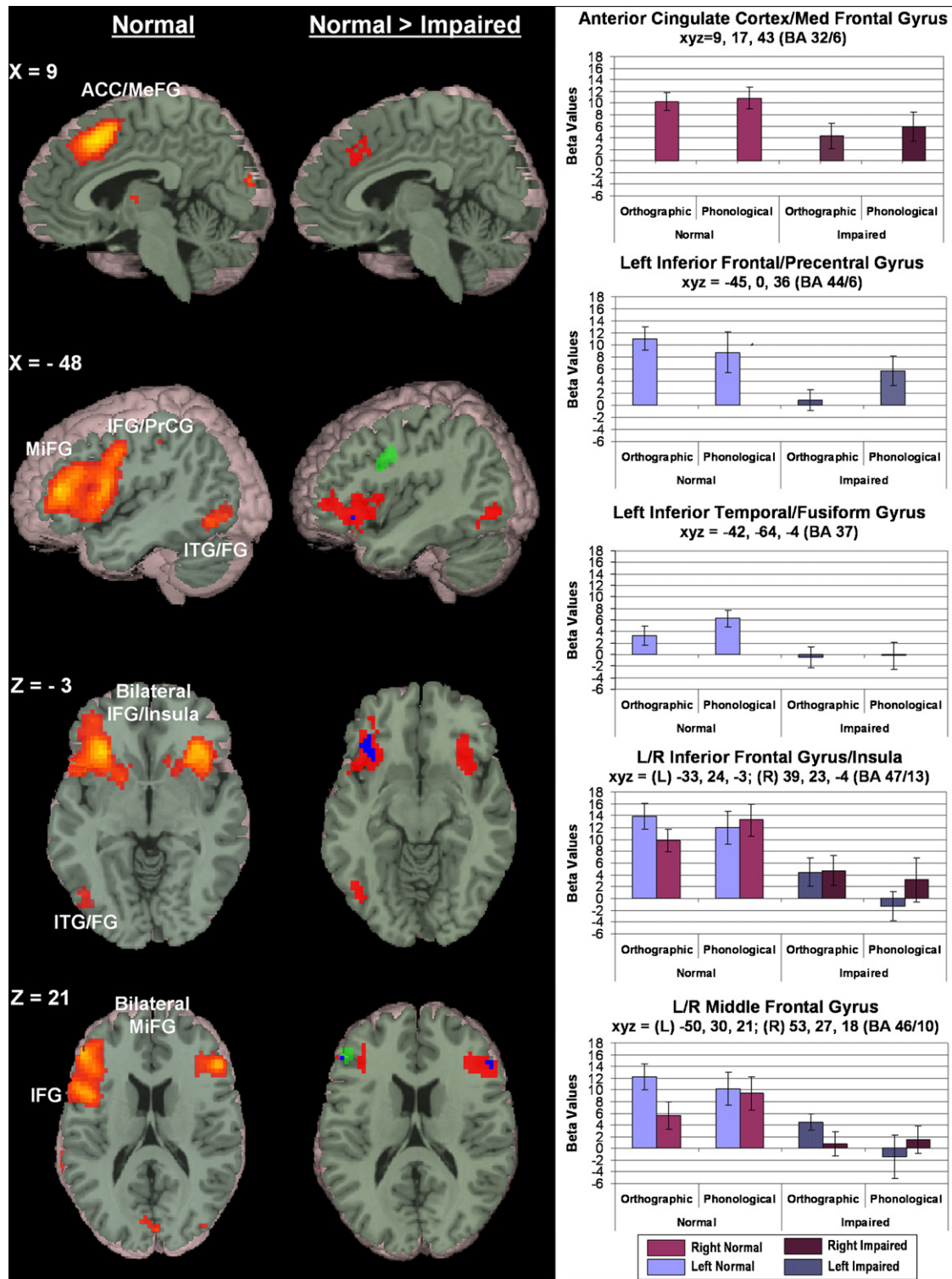


Fig. 2. Main effects of consistency. (Images, left column) Cortical regions in Normal Readers for which activation reliably increased with overall lower consistency (both phonological and orthographic). The regions include anterior cingulate cortex (ACC), medial frontal gyrus (MeFG), middle frontal gyrus (MiFG), inferior frontal gyrus (IFG), precentral gyrus (PrCG), inferior temporal gyrus (ITG), fusiform gyrus (FG), and Insula. (Images, right column) Regions in which the consistency effect is greater for Normal compared to Impaired Readers. Colors indicate whether task differences were due to phonological consistency (red), orthographic consistency (green) or both (overlap in blue). (Graphs, far right) Graphs show the resulting average parameter estimates and standard error bars of the correlations for each consistency type for individual peaks within the resulting ROIs. Conditions defined on the x-axis for orthographic and phonological consistency for Normal Readers (solid bars) and for Impaired Readers (hashed bars). Blue bars indicate ROIs in the left hemisphere and red bars indicated ROIs in the right hemisphere. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

Table 4

Group differences in consistency effects for regions where the correlations with lower consistency are larger for Normal compared to Impaired Readers

Region	BA	Normal > Impaired														
		Both					Orthographic					Phonological				
		x	y	z	Vol	t	x	y	z	Vol	t	x	y	z	Vol	t
Cingulate/medial frontal																
L. Medial frontal gyrus	8	–3	20	43	414	3.93						0	22	40	118	2.87
L. Anterior cingulate	32	–3	33	23	^a	2.16										
R. Anterior cingulate	32	12	33	26	^a	3.15						3	25	32	^a	3.00
	^a 32											12	33	26	^a	2.62
Lateral frontal																
L. Inferior frontal gyrus	47	–33	23	–9	1487	5.78	–39	26	–9	27	4.22	–33	23	–9	492	4.87
	^a 46/47											–27	20	–14	^a	4.54
	^a 47											–42	12	–8	^a	3.52
L. Middle frontal gyrus	46/44	–48	36	12	^a	4.09	–48	33	18	37	5.35					
L. Inferior frontal gyrus	9						–42	4	30	46	4.42					
L. Middle frontal Gyrus	10	–42	41	–2	^a	4.52										
R. Inferior frontal gyrus	45/47	53	27	18	702	5.43	53	27	18	23	4.05	50	27	15	470	3.96
R. Middle frontal gyrus	9						53	22	29	^a	4.42					
R. Inferior frontal gyrus	47	36	20	–4	^a	4.19						36	26	–1	^a	4.84
R. Insula	13	33	21	4	^a	4.17						33	21	4	^a	4.10
Temporal																
L. Middle temporal gyrus	21	–50	6	–18	17	2.77										
R. Middle temporal gyrus	21	59	3	–10	13	2.95										
L. Superior temporal gyrus	22	–65	–40	10	24	3.55						–65	–37	10	12	3.06
	^a 22	–65	–26	4	^a	2.28										
Occipital/temporal																
L. Inferior occipital gyrus	18/19	–45	–73	–1	108	5.02						–45	–76	1	51	4.25
L. Inferior temporal gyrus	37/19											–45	–67	–2	^a	3.83
L. Middle occipital gyrus	18	–24	–87	13	^a	3.00						–24	–87	13	12	3.18
	^a 18	–24	–81	2	^a	2.48										
Sub-cortical																
R. Caudate		12	9	2	49	3.44										

No regions were shown to exhibit a larger consistency effect for Impaired over Normal Readers. Note: See Table 2 note.

^a Subpeaks of larger clusters immediately above.

For Phonological Awareness, there were no group differences for orthographic consistency, nor were there correlations within each group. Significant differences in slope values between Normal and Impaired Readers were observed for phonological consistency in anterior cingulate ($x, y, z = 6, 30, 45$, BA 32/8; Normal: $r = 0.08$, $p > 0.1$; Impaired: $r = -0.80$, $p < 0.001$; Difference: $t(1,20) = 5.60$, $p < 0.001$ uncorrected), and a cluster extending from left middle frontal ($x, y, z = -41, 40, 18$, BA 46; Normal: $r = 0.08$, $p > 0.1$; Impaired: $r = -0.45$, $p < 0.01$; Difference: $t(1,20) = 3.82$, $p < 0.05$ FDR) to ventral inferior frontal gyrus ($x, y, z = -42, 51, -3$, BA 10; Normal: $r = 0.07$, $p > 0.1$; Impaired: $r = -0.56$, $p < 0.005$; Difference: $t(1,20) = 4.48$, $p < 0.05$ FDR). Cortical clusters for inferior and middle frontal gyri showing group differences in slope are shown in the top left of Fig. 3 and scatter-plots are displayed in the bottom left of this figure.

For Word Attack, there were no group differences for phonological consistency, and only a negative correlation for Impaired Readers in left inferior frontal gyrus ($x, y, z = -48, 18, -9$; BA 47; $r = -0.41$, $p < 0.001$ uncorrected). For orthographic consistency, we found significant differences in slope values between Normal and Impaired Readers in left fusiform/middle occipital gyrus ($x, y, z = -48, -60, -9$; BA 37/19; Normal: $r = 0.56$, $p < 0.005$; Impaired: $r = 0.62$, $p < 0.001$; Difference: $t(20) = 4.76$, $p < 0.05$ FDR). The cluster showing this effect for fusiform gyrus is shown in the top right of Fig. 3 and the scatter-plot is displayed in the bottom right of this figure.

To display the effect of Phonological Awareness on the relationship between consistency and cortical activation for the Normal and Impaired Readers, we interpolated the model estimates (beta values) of individual subjects to the set of orthographic and phonological consistency values (roughly 46 unique values) and then

plotted those lines as a function of Phonological Awareness and Word Attack in each group separately. We used linear interpolation across the behavioral measures for each consistency value to smooth the data that is shown in Fig. 4. For the effect of Phonological Awareness, the data show a slight (non-significant) increase in slope as a function of Phonological Awareness for Normal Readers, indicating that higher skill was associated with greater activation for lower inconsistency words. In contrast, Impaired Readers showed a significant change from a positive to a sharply negative slope as a function of consistency, indicating that higher skill was associated with greater activation for higher consistency words and less activation for lower consistency words (see Fig. 4, top graphs). The coefficients in these regression analyses do not significantly change when the presumed outlier in Impaired Readers is removed (see Fig. 3 scatter-plots).

We performed the same analysis with standardized scores from the Word Attack task to show the relationship between consistency and cortical activation as a function of this measure of non-word decoding ability. As with Phonological Awareness, we interpolated the model estimates of the consistency effect in fusiform gyrus (based on the group analysis) for individual subjects to the set of orthographic and phonological consistency values. Shown in Fig. 4 (bottom graphs), modulation of the consistency effect in fusiform gyrus as a function of Word Attack scores shows a similar pattern for the Impaired Readers as seen for Phonological Awareness in frontal regions. Normal Readers, on the other hand, exhibit a pronounced change of slope between lower skill showing a negative slope (greater activation for higher consistency words) to higher skill showing a positive slope (greater activation for lower consistency words).

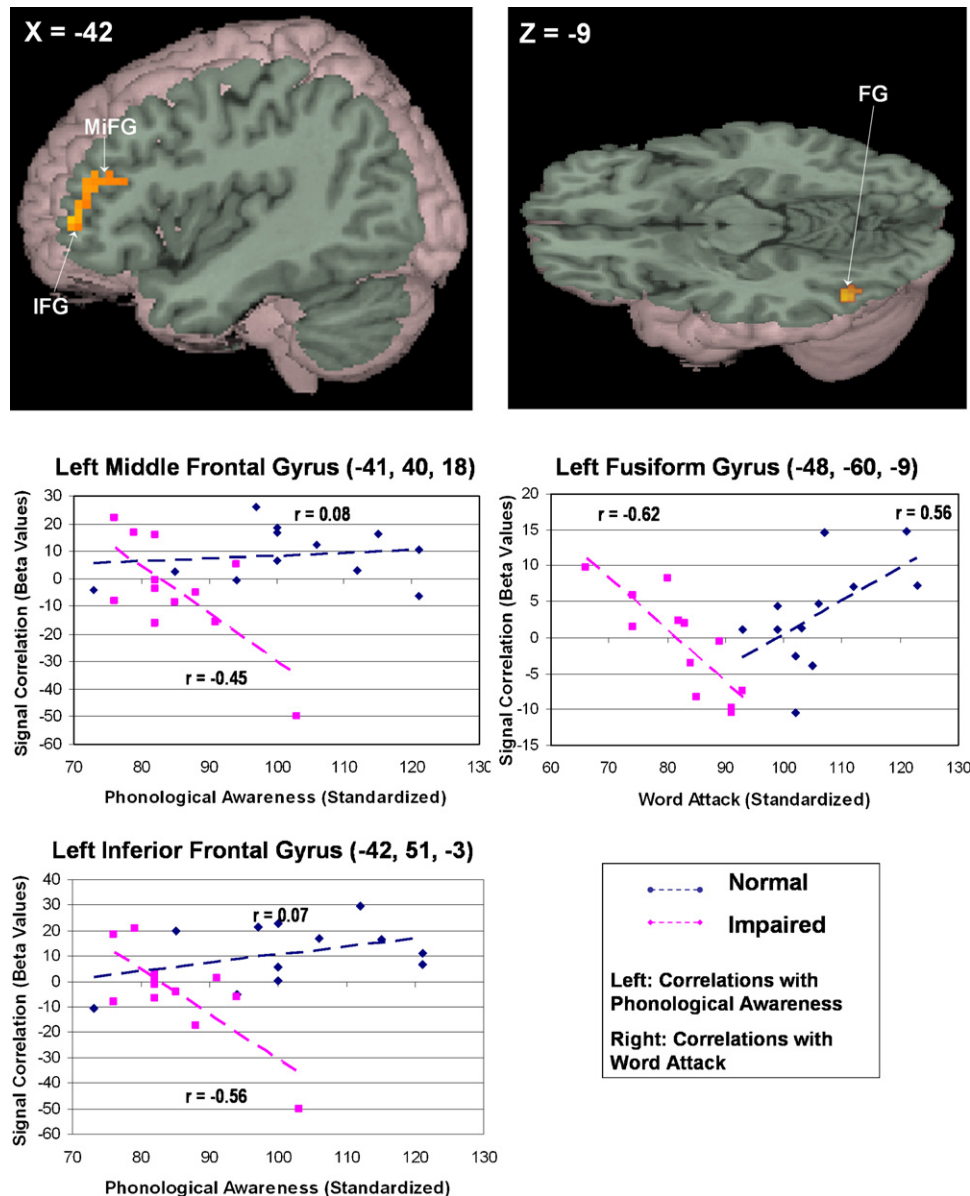


Fig. 3. Brain–behavior correlations. (Top row) Cortical regions in which linear estimates of brain–behavior correlations between skill and cortical effects of consistency significantly differ for Impaired versus Normal Readers. (Left column) Regions include middle frontal gyrus (MiFG) and inferior frontal gyrus (IFG) for Phonological Awareness (CTOPP) and phonological consistency. The graphs show that these correlations had a significantly negative slope for Impaired Readers (pink), compared to a slight, but insignificant, positive slope for Normal Readers (blue). (Right column) Regions include fusiform gyrus for Word Attack (WJ-III, a measure of non-word decoding) and orthographic consistency. The graphs show that these correlations had a significantly negative slope for Impaired Readers (pink), compared to a significantly positive slope for Normal Readers (blue). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

4. Discussion

While previous studies have examined differences in neural activation in normal and Impaired Reading in children using fMRI (Hoeft et al., 2007; Shaywitz et al., 2007), there have been no neuroimaging studies investigating how the consistency between spelling and sound patterns in words impacts impaired as compared to Normal Readers. Our previous study (Bolger et al., *in press*) was the first to examine the neural correlates of consistency effects in normal children and their relationship to performance on the task. In the current study, we extended our investigation to look at the relationship of Phonological Awareness and decoding, well-studied predictors of reading disability (Torgesen et al., 1992, 1994; Wagner et al., 1993, 1994), with cortical consistency effects in both normal and Impaired Readers. Our previous work was also the

first to investigate the cortical effects of orthographic consistency (sound to spelling). The current study extended this work by investigating whether Impaired Readers are sensitive to this property of words relative to phonological consistency (spelling to sound). In order to do this, we examined consistency effects for a rhyming task that required mapping between orthographic and phonological representations for correct performance. In this task, two words were presented sequentially in the visual modality and the HRF to the first word in the pair was modeled.

Consistent with previous studies including our own (Bolger et al., *in press*), we found greater activation for lower consistency words for Normal Readers in left inferior frontal gyrus (Binder et al., 2005; Fiez et al., 1999; Herbster et al., 1997; Katz et al., 2005; Peng et al., 2004; Tan et al., 2001), left superior temporal cortex (Peng et al., 2004; Tan et al., 2001), left inferior temporal/fusiform

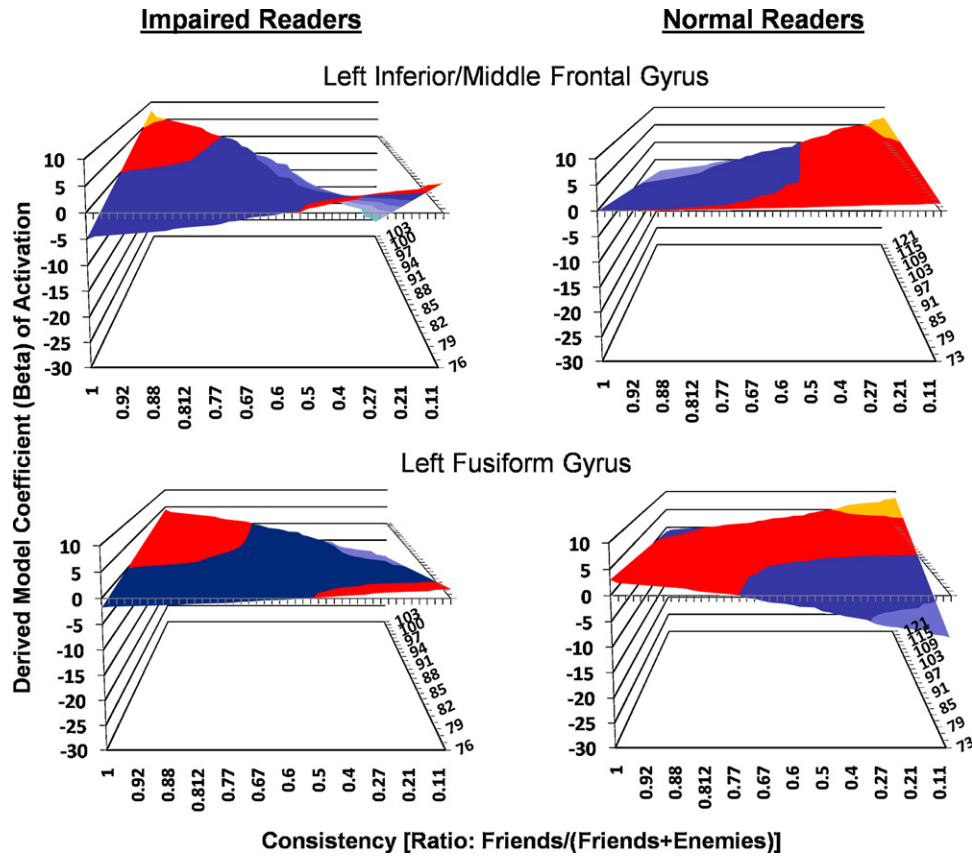


Fig. 4. Three-dimensional representation of the relationship between activation (y-axis), consistency (x-axis) and skill (z-axis) in left inferior/middle frontal gyrus (top) for phonological consistency and left fusiform gyrus (bottom) for orthographic consistency in Impaired (left column) versus Normal (right column) Readers. (Top row) Normal Readers show a weak non-significant relationship between activation and Phonological Awareness (CTOPP), with higher skill showing greater activation for lower consistency words. In Impaired Readers, higher skill is correlated with less activation for lower consistency words, whereas higher skill is correlated with greater activation for higher consistency words. (Bottom row) Impaired Readers show similar skill effects for fusiform gyrus with Word Attack (WJ-III, a measure of non-word decoding). The correlation for Normal Readers is now significantly positive, indicating that higher skill is correlated with greater activation for lower consistency words.

gyrus (Peng et al., 2004), and medial frontal gyrus/anterior cingulate cortex (Binder et al., 2005; Tan et al., 2001). Generally, these results suggest that this network of regions (excluding medial frontal gyrus/anterior cingulate), which has been discussed as uniquely involved in orthographic and phonological processing (Fiez & Petersen, 1998; Jobard, Crivello, & Tzourio-Mazoyer, 2003), is more generally involved in the integration of phonological and orthographic information. These results do not support dual-route models (Coltheart et al., 2001) that argue lower consistency words (i.e. irregular or exception words) are processed by a separate mechanism as compared to higher consistency words (i.e. regular). In contrast, these results are consistent with single-route models (Plaut et al., 1996) that argue lower consistency words should produce greater activation in regions involved in processing orthographic and phonological representations.

Our results showed that for Impaired Readers, only medial frontal gyrus/anterior cingulate exhibited any response to lower consistency but that this response was weaker than for Normal Readers. Activation in medial frontal gyrus/anterior cingulate has been most commonly linked to cognitive control in executive processing often implicated when conflict between alternative responses are considered (Barber & Carter, 2005; Kerns et al., 2004; MacDonald, Cohen, Stenger, & Carter, 2000). Our findings suggest that activation in this region in our task is due to the competition between alternative pronunciations (for phonological consistency) and spellings (for orthographic consistency) when a lower consistency word such as “pint” is presented. Our previous study,

with the same groups of participants on the same task, but that did not examine consistency effects, found that both normal and Impaired Readers activated medial frontal gyrus/anterior cingulate and that there was no difference between groups in activation in this region (Cao et al., *in press*). This suggests that Impaired Readers can robustly activate medial frontal gyrus/anterior cingulate, but that it is not as responsive to the conflict between orthographic and phonological representations as compared to Normal Readers. This lack of responsiveness is likely due to deficits in other brain regions that are responsible integrating orthographic and phonological representations.

The results also showed that Normal Readers showed a stronger overall response to consistency than Impaired Readers in left inferior frontal gyrus and left fusiform gyrus. These results are in line with behavioral studies showing a stronger consistency effect in normal compared to Impaired Readers (Beech & Awaida, 1992; Murphy & Pollatsek, 1994; Siegel & Ryan, 1988; Szeszulski & Manis, 1987). The current results are also in line with previous studies that have found reduced activation for reading tasks in impaired compared to Normal Readers in left inferior frontal gyrus (Georgiewa et al., 1999) and left fusiform gyrus (Shaywitz et al., 2002). Left inferior frontal gyrus has been implicated in phonological processing (Poldrack et al., 1999; Vigneau et al., 2006) and left fusiform gyrus has been implicated in orthographic processing (Cohen et al., 2004; Dehaene et al., 2004). Together with evidence that suggests that Impaired Readers have weaker white matter connectivity in temporo-parietal cortex (Deutsch et al., 2005; Klingberg

et al., 2000), our results suggests that a central deficit in reading disability is the lack of integration of orthographic and phonological information (Compton, 2000; Stanovich, Cunningham, & Feeman, 1984). These effects may likely be due to the quality of the sub-lexical spelling and sound representations of lexical items. That is, Impaired Readers may have an established lexical representation for the words 'pint' and 'mint', however, these readers may fail to decompose these items into sub-lexical orthographic constituents (e.g. p/m+int) and associate them with varying phonological constituents (e.g. /AYnt/ versus /int/). This ability to associate letters and letter patterns with their corresponding speech sounds is believed to be a fundamental factor in determining reading skill (Ehri, 1992; Perfetti, 1992).

Our results show more robust differences between normal and Impaired Readers in phonological relative to orthographic consistency. Normal Readers showed a stronger effect for phonological consistency in left superior temporal gyrus and left fusiform gyrus that have been implicated in phonological and orthographic processing (Cohen et al., 2004; Vigneau et al., 2006). Although there is behavioral evidence showing stronger phonological consistency effects in Normal Readers, only one study has examined orthographic consistency effects in Impaired Readers (Davies & Weekes, 2005), so the relation of different forms of consistency to reading impairment is not clear. However, given that our rhyming task in the visual modality required mapping from orthography to phonology it makes sense that we established larger group differences in phonological consistency that indexes spelling to sound correspondences. Normal Readers also demonstrated a stronger effect in left ventral inferior frontal gyrus (BA 46/47) for both orthographic and phonological consistency, though the group difference was larger for phonological consistency. A recent meta-analysis (Vigneau et al., 2006) showed clusters for both phonological and semantic tasks near the peak reported in our study, so the involvement of this region in consistency effects is not clear. In terms of orthographic consistency, Normal Readers demonstrated a stronger effect than Impaired Readers in two peaks of left dorsal inferior frontal gyrus (BA 44/9). The peaks reported in our study are quite close (less than 1 cm) to two clusters identified in the aforementioned meta-analysis and they interpreted these regions as being involved in activation of articulatory gestures and phonological working memory. The reading task in our study required participants to map from spelling to sound for the first word and then to maintain that phonological representation in order to make a rhyming judgment to the second word. Orthographically inconsistent words (multiple spellings for the rhyme, e.g. /aye/ as in sigh, tie, rye, eye, guy) may require more orthographic–phonological integration resources in order to maintain the representation of the first word in the face of conflicting orthographic information.

In several cortical regions, individual differences in key sub-skills of reading are correlated with the effects of orthographic and phonological consistency. Phonological Awareness is the conscious sensitivity to the sound structure of language and includes the ability to distinguish and manipulate speech. Phonological Awareness has been shown to be a strong predictor of reading skill (Torgesen et al., 1992, 1994; Wagner et al., 1993, 1994). In our study, there was a (non-significant) trend for Normal Readers with higher Phonological Awareness to show greater activation for *lower* phonological consistency in left inferior and middle frontal gyri. In contrast, higher Phonological Awareness in Impaired Readers was reliably associated with greater activation for *higher* phonological consistency in these same regions. The strong relationship between skill and phonological consistency effects may account for the lack of overall consistency effects in the Impaired Readers in our study and for null effects found in previous behavioral studies of Impaired Readers (DiBenedetto et al., 1983; Frith & Snowling, 1983; Johnston

et al., 1990; Siegel & Ryan, 1988). Decoding, the ability to manipulate letter-sound relationships, has been shown to be a stronger predictor of reading skill than Phonological Awareness using hierarchical linear modeling (Compton, 2000; Stanovich et al., 1984). In addition, remediation strategies focusing on decoding skills have been shown to be more effective than those focusing on Phonological Awareness (Ehri et al., 2001; National Reading Panel, 2000). In our study, there was a significant decrease in slope values for Impaired Readers as a function of decoding skill in left fusiform gyrus, indicating greater activation for *higher* orthographic consistency. In contrast, Normal Readers showed a reliably increase in slope values as decoding scores increased as illustrated in Fig. 4, indicating greater activation for *lower* orthographic consistency in this same region.

Our Phonological Awareness measure required children to say a word after they had deleted a sound from the word and to combine sounds to form whole words, and therefore, this measure taps into the ability to segment and manipulate individual sounds. Impaired Readers with higher phonological skill may be able to take advantage of the consistent mappings between orthography and phonology (e.g. ball, call, fall, hall, mall, tall, wall) in order to establish robust grapheme–phoneme correspondences for these words. This interpretation is in line with a study reporting that Impaired Readers, with a deficit in phonological processing, did not show an advantage for learning consistent compared to inconsistent words as compared to age- and reading-match controls (Bailey et al., 2004). Our measure of decoding required that readers accurately pronounce non-word letter strings that follow known patterns in the English language. This task taps the reader's knowledge of orthographic patterns and their mappings with phonological forms. Whereas Phonological Awareness modulates phonological consistency effects in frontal regions, decoding ability modulates orthographic consistency effects in left fusiform gyrus that has been associated with orthographic processing in both normal and Impaired Readers (Shaywitz et al., 2002). The left fusiform region is argued to reflect pre-lexical, orthographic processing (Cohen et al., 2002; McCandliss, Cohen, & Dehaene, 2003) or an orthographic lexicon in which letter string stimuli are processed to enable visual recognition of word forms (Kronbichler et al., 2007). As our previous study showed (Bolger et al., *in press*), Normal Readers show greater activation for lower consistency words (both phonological and orthographic) suggesting that orthographic processing in this region relies on the acquisition of spelling-sound patterns based on increasing word form knowledge. Impaired Readers may lack word knowledge of the alternative mappings between spelling and sounds, and therefore more skilled decoders in this population may over-rely on consistent patterns and fail to process inconsistent patterns.

Single-route or connectionist models of reading (Harm & Seidenberg, 1999) potentially provide a computational account of the different correlation of skill for the normal and Impaired Readers with the cortical response to consistency. In Normal Readers, lower consistency words produce unique and wide-spread patterns of activation in the lexical network, whereas higher consistency words produce overlapping (with other words that are pronounced similarly) and less extensive patterns of activation. As shown by our previous work (Bolger et al., *in press*), increasing skill in Normal Readers is associated with cortical sensitivity (increasing activation) to lower than to higher consistency words. This suggests that the acquisition of overlapping and less extensive patterns of activation for higher consistency words is a prolonged process reflecting experience with a variety of wordforms. Therefore, higher skill in Normal Readers should be associated with less activation for higher consistency compared to lower consistency words. The Impaired Readers in our study had deficits in non-word decoding and this has

been assumed to reflect a phonological deficit (Manis, Seidenberg, Doi, McBride-Chang, & Petersen, 1996). Single-route models have simulated these deficits by damaging the phonological network (Harm & Seidenberg, 1999). These models show that phonological damage results in the need for more accurate mapping from orthography to phonology for higher consistency words and this results in more word specific mapping (i.e. unique and wide-spread) for these words. Impaired Readers with higher skill have presumably created even more word specific mapping between orthography and phonology, which results in even greater activation for higher consistency words. The greater computational resources required for higher consistency words effectively means that there are less resources for lower consistency words, so higher skill in Impaired Readers is associated with greater activation for higher compared to lower consistency words.

In conclusion, our study showed that Normal Readers have stronger consistency effects than Impaired Readers in left inferior frontal gyrus, left fusiform gyrus and medial frontal gyrus/anterior cingulate. These group differences are likely to result from deficits in effectively integrating orthographic and phonological patterns in the Impaired Readers. The stronger consistency effects for Normal Readers, and lack of consistency effects within the Impaired Readers, however, may be due to individual differences in Phonological Awareness and decoding skills within the Impaired Readers.

Impaired Readers with higher Phonological Awareness and decoding skills showed greater activation in left inferior/middle frontal gyri and left fusiform gyrus for higher consistency words, suggesting that they more effectively engage the reading network for processing words with consistent spelling-to-sound correspondences. Particular sub-skills predictive of disability appear play a strong mediating role in consistency effects for Impaired Readers; namely, Phonological Awareness which mediated phonological consistency effects in left frontal regions, and decoding ability, which mediated orthographic consistency effects in left occipito-temporal cortex.

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Appendix A

List of words used in the study with values for frequency^a and consistency, and the grapheme and phoneme length

Word	Freq ^a	Ortho. Consist.	Phono. Consist.	Graph. Length	Phon. Length	#Friends	#Ortho. Enemy	#Phono. Enemy
Boom	1.71	0.62	1	4	3	8	0	5
Boss	3.5	0.89	0.89	4	3	8	1	1
Brain	11.96	0.57	1	5	4	17	0	13
Brass	3.35	0.91	0.91	5	4	10	1	1
Breast	2.04	0.06	0.17	6	5	1	5	16
Cage	5.7	0.9	1	4	3	9	0	1
Calm	8.17	0.6	1	4	3	3	0	2
Cap	9.34	0.94	0.94	3	3	17	1	1
Car	62.52	0.86	0.92	3	3	12	1	2
Card	7.53	1	0.88	4	4	7	1	0
Care	50.01	0.5	0.94	3	3	17	1	17
Cart	3.23	0.91	0.77	4	4	10	3	1
Caught	34.91	0.27	0.75	6	3	3	1	8
Chance	29	0.86	1	6	4	6	0	1
Charm	1.68	1	0.67	5	4	4	2	0
Chase	2.46	0.25	0.67	5	3	4	2	12
Cheat	0.49	0.54	0.82	5	3	14	3	12
Cheer	3.16	0.35	1	5	3	11	0	20
Christ	1.18	1	0.13	6	5	1	7	0
Class	37.21	0.91	0.91	5	4	10	1	1
Clean	28.81	0.42	1	5	4	8	0	11
Clear	37.7	0.48	0.75	5	4	15	5	16
Climb	12.03	0.08	0.5	5	4	1	1	12
Cone	2.6	0.56	0.79	4	3	15	4	12
Cork	0.93	0.86	0.86	4	4	6	1	1
Cove	1.1	0.82	0.6	4	3	9	6	2
Crease	0	0.5	0.57	6	4	4	3	4
Dare	5.37	0.5	0.94	4	3	17	1	17
Deaf	3.42	0.33	0.33	4	3	1	2	2
Doll	2.89	1	0.22	4	3	2	7	0
Dose	0.37	0.67	0.18	4	3	2	9	1
Drown	1.19	0.89	0.5	5	4	8	8	1
Fall	34.4	0.6	0.92	4	3	12	1	8
Fan	2.11	1	0.88	3	3	15	2	0
Fist	2.81	0.78	0.88	4	4	7	1	2
Five	59.51	1	0.82	4	3	9	2	0
Flash	6.13	0.95	0.95	5	4	19	1	1
Flood	3.33	0.25	0.22	5	4	2	7	6
Fluff	0.31	0.79	1	5	4	11	0	3
Foe	0.14	0.24	0.89	3	3	8	1	25
Food	151.27	0.33	0.33	4	3	3	6	6
Frost	4.46	1	0.38	5	5	3	5	0
Froze	1.97	0.09	1	5	4	1	0	10
Fruit	12.48	0.1	1	5	4	2	0	18
Gone	59.9	0.11	0.05	4	3	1	18	8

Appendix (Continued)

Word	Freq ^a	Ortho. Consist.	Phono. Consist.	Graph. Length	Phon. Length	#Friends	#Ortho. Enemy	#Phono. Enemy
Grade	9.8	0.57	1	5	4	12	0	9
Grand	6.65	1	0.92	5	5	11	1	0
Grow	73.01	0.52	0.57	4	4	17	13	16
Half	61.44	0.4	1	4	3	2	0	3
Hatch	2.67	1	0.8	5	3	8	2	0
Hood	2.43	0.57	0.44	4	3	4	5	3
Hut	5.31	0.75	0.9	3	3	9	1	3
Jet	2.77	0.75	1	3	3	12	0	4
Mark	23.04	0.9	1	4	4	9	0	1
Mom	16.08	0.2	0.33	3	3	1	2	4
Moose	1.8	0.36	0.8	5	3	4	1	7
Nail	2.98	0.56	1	4	3	19	0	15
Name	88.96	0.8	1	4	3	12	0	3
Nod	1.43	0.77	1	3	3	10	0	3
Norm	0	0.67	0.8	4	4	4	1	2
Note	14.19	0.33	1	4	3	5	0	10
Page	49.64	0.9	1	4	3	9	0	1
Palm	5.57	0.6	1	4	3	3	0	2
Paste	1.33	0.86	0.86	5	4	6	1	1
Phase	0.64	0.09	0.33	5	3	2	4	21
Pint	0.43	1	0.08	4	4	1	11	0
Plea	0.07	0.2	0.83	4	3	5	1	20
Pose	0.14	0.64	0.64	4	3	7	4	4
Putt	0	0.17	1	4	3	2	0	10
Quo	0	0.12	0.57	3	3	4	3	29
Run	66.07	0.63	1	3	3	10	0	6
Scarce	2.12	1	0.5	6	5	1	1	0
Scheme	0.51	0.14	1	6	4	2	0	12
Seat	17.88	0.54	0.82	4	3	14	3	12
Seek	3.52	0.38	1	4	3	10	0	16
Shall	29.27	0.33	0.08	5	3	1	12	2
Shed	4.98	0.5	1	4	3	11	0	11
Shell	8.09	0.89	1	5	3	16	0	2
Sir	21.99	0.25	1	3	3	4	0	12
Slap	1	0.94	0.94	4	4	17	1	1
Soup	3.92	0.18	0.75	4	3	3	1	14
Splash	1.77	0.95	0.95	6	5	19	1	1
Spruce	1.9	0.18	1	6	5	2	0	9
Stroll	0.45	0.3	0.78	6	5	7	2	16
Stuff	10.13	0.79	1	5	4	11	0	3
Tax	3.51	0.86	1	3	3	6	0	1
Theme	0.5	0.14	1	5	3	2	0	12
Thigh	0.28	0.14	1	5	2	4	0	24
Thus	10.34	0.57	1	4	3	4	0	3
Took	134.4	1	0.92	4	3	11	1	0
Trap	5.97	0.94	0.94	4	4	17	1	1
View	11.17	0.02	1	4	3	1	0	44
Walk	44.23	0.71	1	4	3	5	0	2
Weird	1.44	0.5	1	5	4	1	0	1
Woe	0	0.24	0.89	3	2	8	1	25

^a *The Educator's Word Frequency Guide* (1996). Touchstone Applied Science Associates, Inc.: Brewster, NY.

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