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# Differentiating the neural response to intervention in children with developmental dyslexia

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**Abstract** Developmental dyslexia is associated with functional abnormalities within reading areas of the brain. For some children diagnosed with dyslexia, phonologically based remediation programs appear to rehabilitate brain function in key reading areas (Shaywitz et al., *Biological Psychiatry 55*: 101–110, 2004; Simos et al., *Neuroscience 58*: 1203–1213, 2002). However, a non-trivial number of children diagnosed with dyslexia fail to respond to these interventions (Torgesen, *Learning Disabilities Research & Practice 15*: 55–64, 2000). A cross-sectional fMRI study investigating post-treatment effects was conducted in an effort to better understand differences in brain function between treatment responders and non-responders. Educational testing and brain activation measured after treatment suggested that the reading intervention used in the present study rehabilitated several basic level reading processes in all participants diagnosed with dyslexia. However, activation in the left inferior parietal lobe differentiated treatment responders and non-responders in comparison to non-impaired readers. Children with persistent deficits in single word decoding (treatment non-responders) demonstrated significantly less activation in the left inferior parietal lobe when compared to non-impaired readers.

**Keywords** fMRI · Multisensory intervention · Phonological deficit · Treatment response

Developmental dyslexia is commonly recognized as a significant difficulty in learning to read that results from deficiencies within the language system. The deficiencies prevent the recognition and decoding of phonology—the underlying sound structure—of spoken words (Shaywitz et al., 2004). More specifically, children and adults with dyslexia have difficulty understanding that spoken words are made up of individual sounds (i.e., phonemes), and that those sounds map to letters in written language (Liberman, Shankweiler, & Liberman, 1989). Despite their difficulties with oral and written language, children and adults with

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dyslexia can learn to read if provided with appropriate instruction (e.g., Lovett et al., 2000). A number of intervention programs have been developed and the most successful interventions take into account the difficulty individuals with dyslexia face when processing phonemes. Children enrolled in such interventions are taught to recognize and decode the sound structure of words (e.g., Torgesen et al., 2001).

Although phonologically based interventions are often effective, 2% to 6% of children fail to respond to these interventions (Torgesen, 2000). Analyses of individual differences have identified some behavioral markers, such as relative levels of phonological awareness and decoding skill at the onset of treatment, that reliably predict treatment response (e.g., Torgesen et al., 2001; Wise et al., 2000). In addition, some researchers have speculated that resistance to treatment efforts may be associated with neurological differences in children diagnosed with dyslexia (McCandliss & Noble, 2003; Price et al., 2003; Shaywitz et al., 2004).

Recent advances in brain imaging technologies have provided a better understanding of the neurological substrate and functioning that support skilled reading. Brain imaging studies have identified a distributed network of brain regions in both the left and right hemispheres to be involved in skilled reading (Price et al., 2003). Imaging studies of word decoding in particular have consistently highlighted three primary regions of the left hemisphere to be of importance (e.g., Pugh et al., 2000). Briefly, the cortical area around the juncture of the posterior temporal and anterior occipital lobes is recruited for rapid word identification processes (e.g., McCandliss, Cohen, & Dehaene, 2003). There is evidence that activation in the occipitotemporal region increases with reading ability, suggesting that it is increasingly recruited as a function of an individual's reading skill development (Shaywitz et al., 2002). The juncture of the superior temporal and inferior parietal lobes, including the angular and supramarginal gyri, is associated with phonological analysis, the mapping of orthography to phonology, and retrieval of meaning (Hoeft et al., 2007; Horwitz, Rumsey, & Donohue, 1998). Finally, activation in phonological regions of the inferior frontal lobe is involved in phonological analysis and output (Shaywitz & Shaywitz, 2004).

While the reading circuit in the brain comprises more than the three areas in the left hemisphere highlighted above, we highlighted left hemisphere brain areas because of functional differences observed between children who struggle to read and non-impaired readers. For example, numerous functional imaging studies have demonstrated brain activity in the posterior primary reading areas of left hemisphere to be attenuated when adults and children with dyslexia are compared to non-impaired readers (see Demonet & Taylor, 2004; Pugh et al., 2000 for reviews). Moreover, adults and children with dyslexia show increased activity in prefrontal regions around the inferior frontal gyrus as a function of reading task demands, a result suggesting engagement of compensatory mechanisms in response to the difficulty of reading (Shaywitz et al., 1998). There are also reports of hyperactivation in individuals with dyslexia in right hemisphere analogues of the left hemisphere reading areas (Eden et al., 2004; Shaywitz et al., 1998; Simos et al., 2007).

Although there are significant differences in brain functioning of both adults and children with dyslexia compared to typically developing readers, there is also evidence that intensive, phonologically based treatment programs can ameliorate those differences. Several longitudinal studies using different imaging techniques demonstrate that children and adults who have completed treatment for dyslexia show increased activation in the primary reading areas of the posterior left hemisphere (e.g., Aylward et al., 2003; Eden et al., 2004; Shaywitz et al., 2004; Simos et al., 2002, 2007; Temple et al., 2003). However, even though the majority of children with dyslexia respond to phonologically based treatments, several fundamental questions still remain. Such as, what is the pattern of brain functioning observed in children who continue to struggle to read after receiving an intervention and how does it differ from those children who respond well to treatment?

Several studies provide insight into the brain function of struggling readers who continually struggled to read and how the brain function compared to that of struggling readers who eventually demonstrated remediated reading ability. For example, using fMRI, Shaywitz et al. (2003) compared brain activation evoked by both non-word and real word reading tasks in young adults who were either compensated readers, persistently poor readers, or non-impaired readers. Compensated and persistently poor readers demonstrated significantly less activation in posterior reading areas located in the left temporal parietal junction as well as the temporal occipital junction bilaterally when compared to non-impaired readers. Interestingly, persistently poor readers did not differ from the non-impaired readers in the left temporal parietal junction when performing the real word reading task, while the compensated readers demonstrated less activation in the posterior reading areas of the left hemisphere in comparison to non-impaired readers. Such findings demonstrate abnormalities in brain function persist into adulthood in individuals who struggled to learn how to read early in life and suggest that fundamental differences exist between how compensated and persistently poor readers read.

While an extremely informative study, it does not specifically address the brain function that accompanies persistently poor reading ability after children receive a targeted intervention for their reading difficulties. As such, the findings raise the question as to whether or not there would be persistent functional brain differences between compensated, persistently poor readers and non-impaired readers if the struggling readers had been provided with a targeted reading intervention during childhood. To address this question, some researchers have used magnetic source imaging to measure brain activation in children in an attempt to identify differences in brain function between treatment responders and struggling readers who do not respond as well to treatment (Simos et al., 2007). Prior to treatment, all struggling readers displayed an abnormal pattern of spatiotemporal activation that included bilateral occipitotemporal activation as well as inferior frontal, angular gyrus, and superior temporal activation that was either bilateral or right lateralized in nature. After treatment, responders demonstrated a more normalized reading network, but treatment non-responders continued to show abnormalities in the brain circuit engaged while they decoded non-words. Such data document differences in the brain circuitry activated when treatment responders and non-responders decode non-words.

In a continuation of these previous studies, we conducted a cross-sectional fMRI study to investigate the brain function of two groups of children with dyslexia: children who had average decoding and reading abilities after completing a 2-year phonologically based reading intervention program and an age- and gender-matched group of children who still exhibited below-average decoding and reading abilities after completing the same intervention. Specifically, the aim of the study was to identify any differences in brain function between the two groups of children with dyslexia and to compare their brain function to that of age- and gender-matched typically developing readers. A simple phoneme–grapheme mapping task was used during imaging to test functional differences. Performance of the fMRI task does not require participants to decode words or identify sight words like some tasks used in previous research, but performance of the task does require phonics skill.

Importantly, the children in the present study with dyslexia demonstrated deficits in phonological awareness prior to treatment but not after treatment. Despite the normalization of phonological processing skills, half of these children still were unable to decode words after receiving treatment and, as such, were classified as treatment non-responders. We were interested in whether or not the children who did not respond well to treatment would demonstrate comparable brain activation when performing a basic phonics task in comparison to those children who responded well to treatment. Our assumption was that, even though behaviorally both groups had average phonological processing ability after treatment and both performed the basic phonics task with equivalent levels of accuracy, performing the task would differentially activate brain regions in the two groups. Furthermore, we were interested in identifying how the brain areas recruited by treatment responders and non-responders would compare to non-impaired readers.

## Materials and methods

### Participants

Eighteen children, aged 10–14 years, participated in the study. Of these children, nine were female and 16 were determined to be right handed (Oldfield, 1971). Exclusion criteria included hearing loss, neurological disorders, psychiatric or emotional problems (e.g., conduct or anxiety disorders), attention-deficit hyperactivity disorder, and English as a second language.

Twelve of the 18 participants had been diagnosed with developmental dyslexia and were sampled from three cohorts of former patients (total sample of 50) who had completed an intervention program for dyslexia at a hospital-based learning disabilities clinic at either the end of the 2004, 2005, or 2006 academic years. The diagnostic procedure included a multidisciplinary evaluation consisting of an individually administered battery of tests including measures of intelligence, oral language, phonological processing, and academic achievement. The children's grapho-phonemic knowledge, decoding, word recognition, fluency, comprehension, and spelling were all assessed. Medical examinations, parent and child interviews, and questionnaires completed by teachers and parents were used to rule out extraneous factors as causes of the child's reading difficulties (e.g., uncorrected sensory deficits, emotional disorders, insufficient instruction, and inadequate home literacy environment). The diagnosis of dyslexia was made when the child's reading subskills were determined to be deficient as a result of poor phonological processing and were unexpected given the child's age/grade and other cognitive abilities.

Of the 12 children diagnosed with dyslexia, six were identified as having responded well to treatment and the remaining six children were identified as having not responded as well to treatment. Response to treatment was defined as significant growth in phonological awareness and decoding ability such that children were within the average range at the conclusion of treatment. As shown in Table 1, prior to treatment, treatment responders and non-responders both demonstrated below-average phonological abilities and did not reliably differ in either phonological awareness or phonological decoding abilities, $t(10)=.12$, $p=.90$; $t(10)=.39$, $p=.70$. However, the treatment groups did differ in baseline word recognition prior to treatment, $t(10)=4.8$, $p<.001$. Treatment non-responders presented with word reading abilities significantly below average, but as a group, the word recognition skills of treatment responders were at the lower boundary of the population average range. At the completion of treatment, participants classified as treatment responders demonstrated phonological awareness and word reading skills in the average range and adequate decoding of polysyllabic non-words, defined as greater than 70% correct (Richardson & DiBennedetto, 1985, p. 20). Conversely, treatment non-responders still showed inadequate decoding of polysyllabic non-words and below-average word reading ability after treatment, but they had average phonological awareness skills.

**Table 1** Group profiles at baseline, post-treatment, and before fMRI

| | Control | Treatment responders | | | Treatment non-responders | | |
|---|---|---|---|---|---|---|---|
| | Pre-fMRI | Baseline | Post-treatment | Pre-fMRI | Baseline | Post-treatment | Pre-fMRI |
| Full-scale IQ[a] | 110.2 (8.0) | 105.7 (6.8) | | | 101.2 (15.2) | | |
| Phonological awareness SS[b] | 109.0 (8.3) | 88.0 (12.7) | 103.00 (8.90) | 107.0 (7.3) | 87.0 (15.4) | 104.50 (16.73) | 101.5 (17.9) |
| Phonological decoding PC[c] | .86 (.17) | .23 (.20) | .80 (.15) | .83 (.12) | .28 (.30) | .55 (.17) | .56 (.16) |
| Word recognition SS[d] | 108.2 (6.1) | 90.0 (6.8) | 100.00 (8.51) | 103.3 (10.3) | 72.3 (5.6) | 81.83 (5.85) | 82.3 (4.4) |

Standard deviations are provided in parentheses

*SS* standard score, *PC* percent correct

[a] Wechsler Full-Scale IQ

[b] Comprehensive Test of Phonological Processing

[c] Decoding Skills Test

[d] Wechsler Individual Achievement Test

Importantly, treatment responders and non-responders did not significantly differ from one another in the amount of treatment they received, $t(10)=1.90$, $p=.09$. On average, children in the treatment responders group received 333 h of treatment and children in the non-responders group received 305 h of treatment. Moreover, the amount of time that had elapsed between completion of treatment and participation in this study did not differ between treatment responders and non-responders, $t(10)=1.00$, $p=.34$. On average, children in the responders group had completed therapy 13 months prior to taking part in this study and children in the treatment non-responders group had completed therapy 19 months before participating in this study.

In addition to the 12 children diagnosed with dyslexia, six age- and gender-matched children were recruited from the community to serve as control participants. Parent interviews confirmed that the control participants had no reported difficulties learning to read. Table 1 presents the reading and related skills for the control sample at the time of participation in this study.

## Intervention

All participants with dyslexia received treatment for their reading difficulties at a hospital-based learning disabilities clinic using a published curriculum (Avrit et al., 2006) that integrates the five components of effective reading instruction recommended by the National Reading Panel meta-analysis (National Institute of Child Health and Human Development, 2000). Briefly, *Phonemic Awareness* includes a systematic exploration of the articulation of phonemes and is fully integrated within decoding and spelling instruction. All phoneme–grapheme correspondence rules are introduced and time is allotted for practice toward automaticity in the application of *Phonics Skills* and for more guided reading practice with controlled and regular text. Articulation is stressed during reading instruction. Students are instructed to reference mouth position and movement through the use of mirrors, mouth pictures, and instructor modeling during phonological awareness, reading, and spelling instruction to emphasize articulation. Morphological knowledge is used to build *Vocabulary* and word relationships are taught in the context of reading text.

*Fluency* instruction incorporates guided and timed repeated reading of decodable words, phrases, and connected text. A combination of strategies and techniques is used for instruction in *Reading Comprehension*, including comprehension monitoring, question generation, story structure, summarizing, and inferencing. Students also learn how to utilize graphic and semantic organizers when reading narrative and expository texts.

The instruction was delivered in small groups of four to six students for approximately 90 min a day for 4 days each week over two academic years. Educators on staff at the hospital clinic who had advanced training to teach students with dyslexia taught all lessons. Approximately 35% of the contact time was devoted to direct instruction of phonological skills (25% phonics and 10% to phonological awareness). Reading comprehension and vocabulary lessons comprised an additional 30% of class time (20% and 10%, respectively). Fluency/reading rate exercises accounted for approximately 18% of instruction time. Finally, spelling instruction accounted for approximately 17% of instruction time.

## Procedure

*Behavioral assessment* All participants' reading and related skills were confirmed before participation in this study. Children in the control group were administered a test battery that assessed intellectual aptitude, phonological awareness, word reading, and phonological decoding the same day they were scanned. The intervention post-treatment scores were used for all participants with dyslexia who completed treatment in 2006. For students who completed treatment in 2004 or 2005, data from a separate study investigating longitudinal treatment effects were used to confirm current status. These measures had been administered to all participants in the dyslexia sample within 3 months of fMRI scanning. Those data are referred to as pre-fMRI scores in Table 1. Children in the treatment responder and non-responder groups did not differ in the amount of time that had passed since their basic reading abilities had last been assessed.

*Preparation of participants for MR environment* An MR scanner is a novel environment that can evoke anxiety. A common means of reducing anxiety and desensitizing children to the MR scanner is to provide participants with training in a simulator before actual scanning (Poldrack, Pare-Blagoev, & Grant, 2002). For this study, all participants were prepared for the scanning environment by first training in a full-scale mock-up MR scanner.

*Functional activation task* Brain activation was measured using a forced-choice phoneme–grapheme mapping task derived from the cross-modal letter identification task used by Shaywitz et al. (2004). The present task differed from the letter identification task in that the former task required participants to match letters with their *names*, whereas the phoneme–grapheme mapping task required participants to match letters with the way they *sound* (i.e., phoneme). The present task also differed from the former in that the present task is an event-related opposed to block design.

The functional activation task consisted of two different types of events: phoneme–grapheme events and tone–symbol events. For phoneme–grapheme events, participants heard a spoken phoneme (e.g. /b/) presented over a pair of headphones followed by a two-alternative, forced-choice (e.g., [B, D]) visual task (see Fig. 1). The participant pressed a button in his/her right or left hand depending on the side the matching letter was displayed. For tone–symbol trials, a 220-Hz tone was presented via headphones and was followed by two symbols displayed on a computer screen (.* or *.). Participants pressed a key to identify the position of the asterisk relative to the period (i.e., left or right; see Fig. 1). Participants

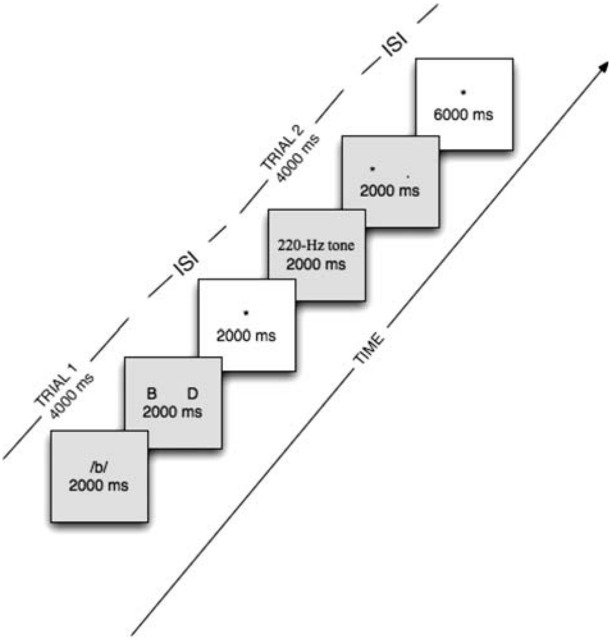


**Fig. 1** Cross-sectional view of the fMRI task. *TRIAL 1* is an example of a phoneme–grapheme mapping trial. *TRIAL 2* is an example of the tone–symbol control task. Between each trial is a variable inter-stimulus interval

completed 12 phoneme–grapheme events and 12 tone–symbol events in the scanning session. Each event lasted 4 s. Between events, a fixation point was presented in the center of the screen. The fixation point remained on the visual display between 4 and 12 s and was displayed on average 8 s. The phoneme–grapheme mapping task took 5 min to complete.

The first author acquired all MR scans and was not blind to which treatment group each child belonged at the time of scanning. Participants were placed head-first supine into the bore of the MR scanner. Visual stimuli were projected onto a screen placed at the foot of the MR scanner gurney using a front projection system connected to a computer running E-Prime (Psychology Software Tools, Inc.). Participants viewed the screen using a mirror mounted to the head coil. Auditory stimuli were presented to participants over a pair of headphones connected to the computer running E-Prime. Behavioral responses were recorded with two-button, fiber-optic response boxes (Resonance Technology, Inc.). Table 2 presents the behavioral performance on the activation tasks in the scanner for treatment responders, treatment non-responders, and controls. Accuracy and reaction time on the phoneme–grapheme matching task and the tone–symbols task were equivalent between the three groups, all *F*s<1.

**Table 2** Group performance on MR scan tasks

| | Control | Treatment responders | Treatment non-responders |
|---|---|---|---|
| Tone detection | | | |
| Accuracy | 1.00 (.00) | 1.00 (.00) | .99 (.03) |
| Latency | 794.47 (203.83) | 752.34 (134.16) | 816.60 (97.50) |
| Phoneme mapping | | | |
| Accuracy | .83 (.18) | .79 (.19) | .84 (.10) |
| Latency | 1,007.69 (90.92) | 952.97 (149.97) | 951.86 (129.55) |

Accuracy reported in percent correct. Latency reported in milliseconds. Standard deviations are provided in parentheses

### Functional imaging parameters

Whole brain images were acquired on a 3-T Siemens Trio Tims MR scanner using a 12-channel radio frequency head coil. An initial magnetic resonance angiography (MRA) time of flight sequence (flip angle=40°; TE=5.3 ms; TR=23 ms; inplane resolution =.82×.82 mm; slice thickness=3 mm; matrix size=256×256; slices=30) provided an image of each participant's vascular system and a geometric reference for the echo planar imaging (EPI) run. For the fMRI sequence, 46 3.0-mm axial slices were acquired using a T2*-weighted EPI sequence (flip angle=90°; echo time=20 ms; TR=2000 ms; voxel dimension=3.28×3.28×3 mm; acquisition matrix=64×64). A total of 147 volumes were collected during the EPI run. Structural images were acquired from 160 1-mm sagittal slices using a multiplanar rapidly acquired gradient echo sequence (flip angle=9°; TE=2.91 ms; TR=2250 ms; inplane resolution=1×1 mm; matrix size=256×240).

### Functional data analysis

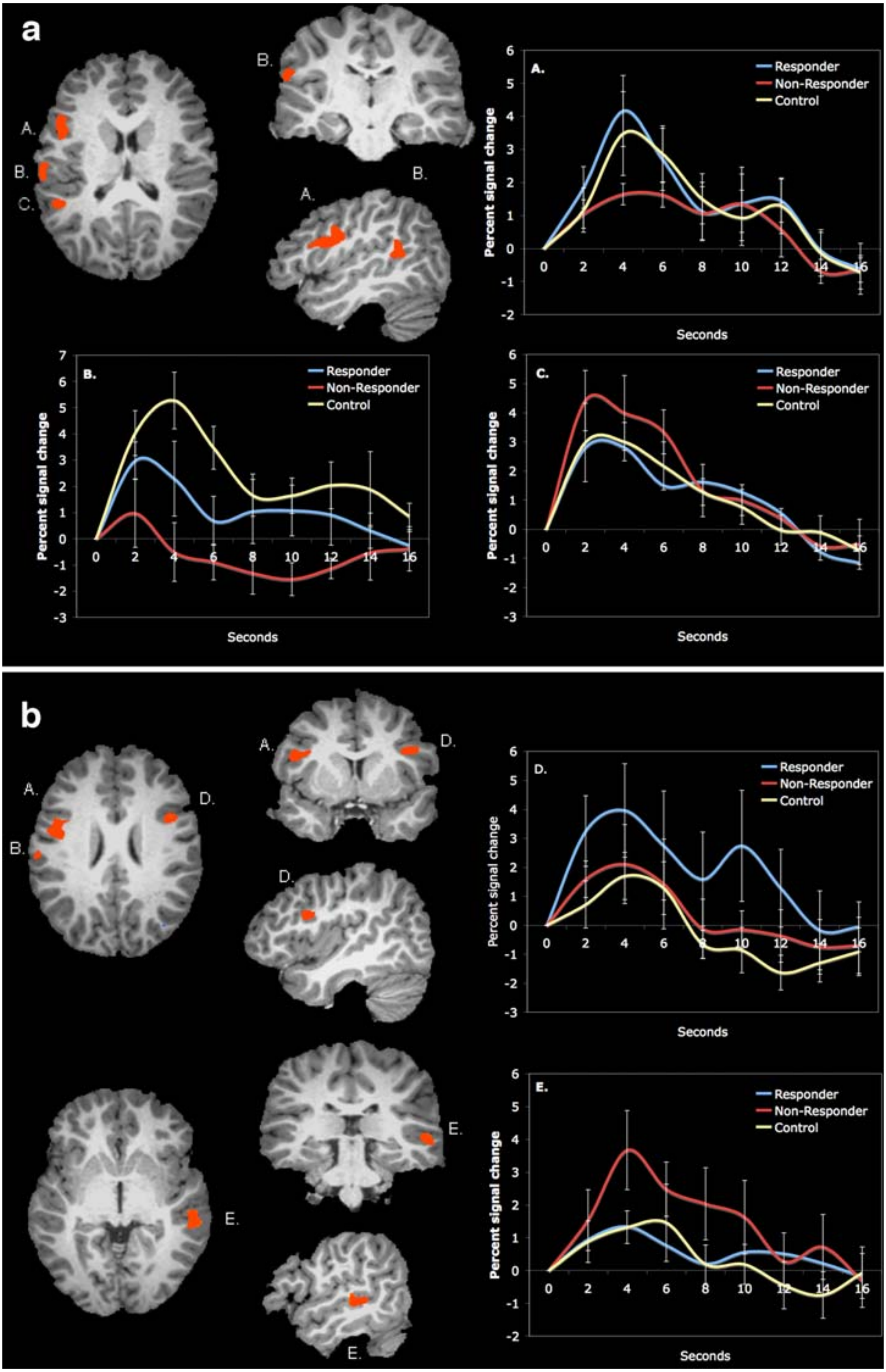
Functional images were analyzed and overlaid onto anatomical images with Analysis of Functional Neuroimages (AFNI) software (Cox, 1996). The first three volumes from the EPI run collected prior to the magnetic field stabilizing were discarded and the slices within the remaining volumes in the EPI were time shifted. Next, functional images were aligned to the first volume in the EPI sequence using three-dimensional rigid body registration. Linear trends in the EPI data were removed and the EPI data were spatially smoothed with a Gaussian filter with a full-width half-maximum value of 6 mm. AFNI's deconvolution was used to estimate hemodynamic response functions (HRF) for phoneme–grapheme events and tone–symbol events relative to the fixation point baseline (Glover, 1999). The estimated HRF began at the onset of the event and included 16 s of signal. The estimated HRFs were converted to Talairach coordinate space (Talairach & Tournoux, 1988).

## Results

### Group analysis of functional data

Initial comparisons were conducted at the voxel level to identify areas that showed different levels of activation for phoneme–grapheme events when compared to the tone–symbol events. The initial analysis contrasted the average area under the HRF curve for phoneme–grapheme events with tone–symbol events. The resulting *t*-values were then subjected to false discovery rate to correct for multiple pairwise comparisons (Benjamini & Hochberg, 1995).

**Fig. 2** **a** The brain of a single participant was spatially normalized to Talairach space and is presented with different functional regions of interest (ROI). All of the regions depicted showed increased activation for phoneme trials when compared to tone trials. Additionally, the average hemodynamic response function (HRF) evoked by phoneme trials in participants in the three groups is depicted for each ROI. Standard *error bars* are provided at each time point plotted in the HRFs. The left inferior frontal lobe (−42, 3, 27) did not show reliable differences between the three different groups (*A.*). The left inferior parietal lobe (−41, −33, 22) showed increased activation in control participants compared to treatment non-responders (*B.*). The left superior temporal lobe (−48, −44, 16) did not show reliable differences across the three different participant groups (*C.*). **b** The right inferior frontal lobe (41, 9, 26) was associated with greater activation in treatment responders than non-responders and control participants (*D.*). The right middle temporal lobe (46, −32, −3) showed greater activation in treatment non-responders than the treatment responders and control participants (*E.*) ▶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The areas that reliably differentiated between the phoneme–grapheme symbol and tone–symbol events are depicted in Fig. 2a and b on the spatially normalized brain of a single participant. Both the left ($x=-42$, $y=3$, $z=27$) and right ($x=41$, $y=9$, $z=26$) inferior frontal lobes showed greater activation during phoneme–grapheme events than tone–symbol events, $z(16)=4.01$, $q<.05$; $z(16)=7.52$, $q<.05$, respectively. Additionally, the left superior temporal lobe ($x=-48$, $y=-44$, $z=16$) and the left inferior parietal lobe ($x=-41$, $y=-33$, $z=22$) showed greater activation during phoneme–grapheme events, $z(16)=3.84$, $q<.05$; $z(16)=5.75$, $q<.05$, respectively. Also, the left fusiform gyrus ($x=-33$, $y=-46$, $z=-8$), often referred to as the visual word form area (e.g., Cohen, Dehaene, & Naccache, 2000; Dehaene, Le Clec'H, Poline, Bihan, & Cohen, 2002), exhibited greater activation during phoneme–grapheme than tone–symbol events, $z(16)=6.25$, $q<.05$. Finally, increased activation was observed in the right middle temporal lobe ($x=46$, $y=-32$, $z=-3$) during phoneme trials, $z(16)=4.01$, $q<.05$.

The activation map contrasting phoneme–grapheme trials with tone–symbol trials was spatially clustered to generate functional regions of interest (ROI). The resulting cluster map was then used to extract average HRF evoked by the phoneme–grapheme events from each ROI. The average HRF evoked in each ROI is presented in Fig. 2a and b. The figures contain separate average HRF functions for treatment responders, treatment non-responders, and non-impaired readers. The maximum amplitude of each participant's response function was calculated and served as the dependent variable in a series of ANOVAs conducted to test for differences across the three groups of participants. All reported significant differences had a $p$-value of less than .05.

There were no statistically reliable differences in the amplitude of the HRFs between the three groups in the left superior temporal lobe, the left fusiform gyrus, or the left inferior frontal gyrus. In contrast, the groups differed in peak levels of activation in left inferior parietal lobe, $F(2, 15)=5.15$, MSE=3.84. Non-impaired readers showed significantly more activation in the left inferior parietal lobe than the treatment non-responders, $t(10)=4.01$. The difference between non-impaired readers and the treatment responders was not reliable, nor was there a difference between the treatment responders and non-responders in the left inferior parietal lobe.

In addition, there were statistically significant different peak levels of activation between the groups in the right inferior frontal gyrus, $F(2, 15)=4.13$, MSE=6.67. The treatment responders had significantly more activation in the right inferior frontal lobe than both the treatment non-responders and non-impaired readers, $t(10)=2.60$; $t(10)=2.80$, respectively. There was, however, no difference between the treatment non-responders and non-impaired readers in right inferior frontal activation. Finally, there were different levels of activation observed between the groups in the right middle temporal lobe. Treatment non-responders demonstrated significantly greater levels of activation in the right middle temporal lobe than either the treatment responders or non-impaired readers, $t(10)=2.96$; $t(10)=3.65$. The treatment responders and non-impaired readers did not differ in right middle temporal lobe activation.

## General discussion

The present study adds to a growing body of research addressing the pattern of brain activation associated with response to intervention. Using a cross-sectional design, we conducted an fMRI study in an attempt to differentiate between children with developmental dyslexia who responded well to intervention from those who did not respond as well to intervention. Although a longitudinal design was not used in the present study, the study replicates prior longitudinal studies investigating the impact of intervention on brain activation associated with performing a reading-related task (e.g., Eden et al., 2004; Shaywitz et al., 2003, 2004; Simos et al., 2002, 2007). Moreover, the present results are intriguing because, even though the poor responders could not adequately decode words after receiving intensive reading intervention, their phonological awareness and brain activation suggest that the reading intervention rehabilitated phonological processing to some extent. As previously highlighted, prior to receiving treatment, all children with dyslexia enrolled in this study had below-average phonological awareness. Yet, both treatment responders and non-responders had average phonological awareness after receiving treatment and the equivalent levels of activation observed between the three groups in the left superior temporal lobe, an area associated with phonological awareness, confirm the behavioral observations. More importantly, the behavioral and fMRI data clearly indicate that something other than phonological awareness differentiates treatment responders and non-responders in the present study.

Treatment non-responders in this study were identified based on their continued inability to adequately decode real and pseudowords. Given the importance of the left inferior parietal lobe in decoding words (Hoeft et al., 2007; Horwitz, Rumsey, & Donohue, 1998), it is noteworthy that, in comparison to non-impaired readers, treatment non-responders had significantly less activation in the left inferior parietal lobe. The left inferior parietal lobe is commonly thought of as an area that links orthographic and phonological representations of language allowing for regular words to be decoded (Hoeft et al., 2007; Horwitz, Rumsey, & Donohue, 1998). Prior to intervention, children diagnosed with dyslexia struggle to decode words and typically exhibit decreased activation in the left inferior parietal lobe when compared to typical readers (Horwitz et al., 1998; Shaywitz et al., 2002, 2004). In the present study, treatment responders, who had average scores on measures of decoding after treatment, demonstrated activation in the left inferior parietal lobe equivalent to that of non-impaired readers when performing the phoneme–grapheme mapping task. Conversely, treatment non-responders showed significantly less activation in the left inferior parietal lobe when compared to non-impaired readers. However, care should be taken in interpreting this result because first, a word decoding task was not used to evoke brain activation and second, the responders did not exhibit significantly greater activation than the non-responders.

In addition to normalization of brain function in the left temporal parietal junction, previous researchers have observed decreased recruitment of right hemisphere brain regions to accompany response to intervention. In contrast, children who continue to struggle with reading after treatment have been observed to increasingly activate right superior temporal lobe, inferior parietal lobe, and middle temporal regions (Shaywitz et al., 2004; Simos et al., 2002, 2007). Partially replicating these previous studies, the non-responders in this study demonstrated increased activation in the right middle temporal lobe in comparison to treatment responders and non-impaired readers. However, in contrast to the commonly observed lateralization of function to the left hemisphere reading circuitry that accompanies response to intervention, treatment responders in our study exhibited greater activation in the right inferior frontal lobe than non-responders and non-impaired readers when performing the phoneme–grapheme mapping task. While this finding is inconsistent with several previous studies, it is not without precedent. The activation evoked from a cross-modal letter identification task like the one used in this study was observed to be positively correlated with children’s reading ability after receiving intervention (Shaywitz et al., 2004).

How can it be that response to intervention is associated with both increased and decreased activation in the right inferior frontal lobe? One possible explanation for such discrepant findings is the simple fact that the pattern of observed activation depends on the behavioral tasks used to evoke brain activation (Simos et al., 2007). For example, Simos et al. (2007) observed non-responders to demonstrate increased activation in right inferior frontal regions from baseline to post-treatment when decoding non-words, but they did not observe a similar increase in activation to be present in treatment responders using magnetic source imaging. Moreover, Shaywitz et al. (2003) also observed persistently poor reading ability to be accompanied by right inferior frontal brain activation when young adults performed a non-word decoding task similar to the one used by Simos et al. (2007) but did so using fMRI. The results from these two studies are exactly opposite of one another. Such conflicting results highlight the importance of carefully noting the specific tasks and task demands when comparing results observed in one study with those of another study.

The results of this study must also be interpreted within the context of several important methodological limitations. As has been discussed by previous researchers (e.g., Simos et al., 2007), the specific task used to evoke brain activation greatly impacts the brain circuitry that is activated. A limitation of the present study was the use of a single fMRI task. The inclusion of non-word decoding, real word reading, and sight word reading tasks would have made the results of the present study more generalizable. Additionally, the design was cross-sectional and therefore results can only be interpreted as correlational. Questions about causation behind observed differences in neurological activation in different groups of children can only be answered with a longitudinal design tracking behavioral and neurological changes during and after treatment. A third issue about the study design concerns the relatively long lag time between completion of treatment and participation in this study. The behavioral data in Table 1 indicate that both groups maintained their respective treatment effects over the post-treatment period; thus, the group comparisons made in this study are still valid. However, there is some longitudinal evidence that activation profiles continue to change up to 1 year after treatment, specifically in the occipitotemporal region associated with word reading ability (e.g., Shaywitz et al., 2004). The result is that conclusions about group activation profiles immediately post-treatment cannot be determined from this design. The results of this study could be interpreted as documenting group differences in the context of longer-term outcomes of relatively stable variation in treatment response. Another important design limitation was the small sample size. Although there was sufficient power to detect group differences in this study, questions about how well the results may generalize to the population as well as any analyses of individual differences (e.g., correlations of changes in behavioral and neurological measures) require larger samples of participants.

Finally, although the groups with dyslexia were balanced in terms of phonological awareness and decoding, the outcome measures of interest, there were significant group differences in word recognition before treatment. In fact, the intervention gains in Table 1 indicate dissociation between word recognition and phonological decoding growth in this sample of ‘non-responders’. Real word reading growth in the non-responders was almost equivalent to those observed in the treatment responders while at the same time they continued to struggle with non-word decoding. The meaning of this discrepancy is not clear, but it must be acknowledged that the ‘non-responders’ in this study did respond to treatment, but they still exhibited more severe deficits in word recognition ability both at baseline and after treatment. Thus, the observed differences between the treatment responders and non-responders in this sample could be attributed in part to pre-existing differences in reading ability. However, it is worth noting that, because the measure of decoding used non-words to assess decoding skills, it is unlikely word identification could fully account for the differences that persisted between the group's decoding abilities and the more basic phonics skill targeted by the fMRI task used in the present study. A significantly larger sample would permit statistically partialling out those pre-existing differences to better assess the impact of the differences in deficit severity on brain function.

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