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Effects of phonological contrast on auditory word discrimination in children with and without reading disability: A magnetoencephalography (MEG) study

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Abstract

Poor readers perform worse than their normal reading peers on a variety of speech perception tasks, which may be linked to their phonological processing abilities. The purpose of the study was to compare the brain activation patterns of normal and impaired readers on speech perception to better understand the phonological basis in reading disability. Whole-head magnetoencephalography (MEG) was recorded as good and poor readers, 7-13 years of age, performed an auditory word discrimination task. We used an auditory oddball paradigm in which the 'deviant' stimuli (/bat/, /kat/, /rat/) differed in the degree of phonological contrast (1 vs. 3 features) from a repeated standard word (/pat/). Both good and poor readers responded more slowly to deviants that were phonologically similar compared to deviants that were phonologically dissimilar to the standard word. Source analysis of the MEG data using Minimum Norm Estimation (MNE) showed that compared to good readers, poor readers had reduced left-hemisphere activation to the most demanding phonological condition reflecting their difficulties with phonological processing. Furthermore, unlike good readers, poor readers did not show differences in activation as a function of the degree of phonological contrast. These results are consistent with a phonological account of reading disability.

Keywords

Speech perception; Developmental dyslexia; MEG; Children; Phonology

1. Introduction

Poor readers' performance on a variety of tasks such as phoneme identification (Chiappe, Chiappe, & Siegel, 2001; Mody, Studdert-Kennedy, & Brady, 1997), categorical speech perception (Godfrey, Syrdal-Lasky, Millay, & Knox, 1981; Watson & Miller, 1993; Werker & Tees, 1987), nonword repetition (Brady, Shankweiler, & Mann, 1983; Snowling, 1981; Snowling, Goulandris, Bowlby, & Howell, 1986), rapid naming (Bowers & Swanson, 1991; Wolf, Bowers, & Biddle, 2000), and perception of speech in noise (Brady et al., 1983) has been found to be inferior to that of their normal reading peers. There is mounting evidence in favor of a phonological core deficit as a basis of these observed difficulties, that is children with

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reading disabilities appear to have deficient phonological representations (for a review see (Boada & Pennington, 2006), which would account for their grapheme to phoneme correspondence problems. Insofar as the perception of speech requires accurate coding and retrieval of phonological representations, we used a speech perception task to compare the brain activation patterns between normal and impaired readers to better understand the phonological basis in reading disability.

Poor readers' difficulties with speech perception are known to be subtle, typically exacerbated under phonologically demanding conditions (Bonte, Poelmans, & Blomert, 2007; Brady et al., 1983; Godfrey et al., 1981; Mody et al., 1997; van der Leij & van Daal, 1999; Yap & van der Leij, 1993). For example, on categorical perception tasks, poor readers compared to good readers have been found to be less accurate in discriminating between stimuli that cross a phoneme boundary, whereas they tend not to be impaired on within-category discrimination (Boada & Pennington, 2006; Chiappe, Chiappe, & Gottardo, 2004; Godfrey et al., 1981; Reed, 1989; Serniclaes, Sprenger-Charolles, Carre, & Demonet, 2001). This difficulty with discriminating phonetically similar stimuli that are phonologically contrastive has been taken as evidence of poor readers' phonological problems. Studies involving speech discrimination of minimal pairs have also revealed impaired performance in poor readers (Adlard & Hazan, 1998). Children with reading impairments were less accurate than unimpaired readers in discriminating words with a small degree of phonological contrast (initial phoneme differing in one feature) that were also acoustically similar. In the present study, we used words differing in their initial phoneme by one versus three phonetic features, in order to examine the effect of degree of phonological contrast on speech perception in good and poor readers.

Neuroimaging studies have shown that good and poor readers exhibit different neural response patterns during speech perception (Breier et al., 2003; Corina et al., 2001; Heim, Eulitz, & Elbert, 2003; Ruff, Marie, Celsis, Cardebat, & Demonet, 2003). In a categorical perception task using magnetoencephalography (MEG), Breier and colleagues (2003) found that good readers primarily activated left temporoparietal cortex during perception of speech stimuli along a synthetic /ga/-/ka/ voicing continuum, whereas poor readers showed initial right temporoparietal activation followed by later left temporoparietal activation. These results are consistent with the idea that poor readers may use right hemisphere ancillary systems to compensate for underdeveloped left hemisphere language systems (Shaywitz et al., 2002; Simos, Breier, Fletcher, Bergman, & Papanicolaou, 2000; Simos, Breier, Fletcher, Foorman et al., 2000). Studies using functional magnetic resonance imaging (fMRI) have similarly found differences in brain activation between good and poor readers in areas implicated in phonological processing, including left superior temporal and inferior frontal cortices (e.g., (Corina et al., 2001; Georgiewa et al., 1999; Temple et al., 2001).

In the present study we used an oddball task. Oddball paradigms involving occasional 'deviants' among a repeated 'standard' stimulus have been commonly used in EEG and MEG studies of speech perception. Under passive listening conditions, deviant stimuli evoke a mismatch negativity (MMN) response (Näätänen, 1992). However, research on the use of the MMN to investigate speech perception in children with learning disabilities has yielded inconsistent results (Bradlow et al., 1999; Kraus et al., 1996; Lachmann, Berti, Kujala, & Schroger, 2005; Schulte-Körne, Deimel, Bartling, & Remschmidt, 1998). Although some of the conflicting results may partially be accounted for by methodological differences between studies (Boada & Pennington, 2006; Heim et al., 2000), it appears that MMN for speech stimuli may not be a clinically reliable measure (Kurtzberg, Vaughan, Kreuzer, & Fliegler, 1995).

An attended oddball task, however, which actively engages poor readers' phonological processing abilities, may in contrast help to capture the subtle differences between good and poor readers in speech perception. When using this design, two attention-dependent evoked

components, the N2 (or N200) and the P3 (or P300), are typically observed in the EEG waveforms (Lawson & Gaillard, 1981; Näätänen & Picton, 1986; Ritter, Simpson, Vaughan, & Friedman, 1979). The N2 is purported to reflect focused attention, stimulus classification and discrimination, whereas the P3 is generally held to reflect processes associated with dynamic update in working memory, cognitive resource allocation and task involvement (Breznitz & Meyler, 2003). In the present study, we focused on the time range of the N2 response (150-300 ms), given its association with phonological processing (Connolly, Service, D'Arcy, Kujala, & Alho, 2001; Kujala, Alho, Service, Ilmoniemi, & Connolly, 2004). Neural generators contributing to the N2 have been localized to the superior temporal gyrus or prefrontal cortices (Alho et al., 1998; Giard, Perrin, Pernier, & Bouchet, 1990; Opitz, Mecklinger, Von Cramon, & Kruggel, 1999; Pääviläinen, Alho, Reinikainen, Sams, & Näätänen, 1991; Scherg, Vajsar, & Picton, 1989).

There have been a limited number of N2 studies comparing normal and reading-impaired children (Bernal et al., 2000; Bonte & Blomert, 2004; Taylor & Keenan, 1990). In an auditory lexical decision study with alliteration priming, children who were poor readers, showed significantly smaller N1 amplitudes in temporal electrodes, with larger N2 amplitudes in midline electrodes compared to good readers (Bonte & Blomert, 2004). The authors suggest that the smaller N1 responses for the poor readers may be a result of deviant source locations and/or diminished activation related to auditory processing. However, the abnormally large N2 responses for the poor readers compared to the good readers may represent subtle differences in prelexical speech processing between the two groups, reflecting poor readers' difficulties with accessing phonological representations.

The present study aimed at characterizing spatiotemporal differences in brain activation related to phonological processing between good and poor readers during auditory perception of deviant target words that differed in the degree of their phonological contrast (one vs. three feature difference) from a repeated standard word. We predicted that poor readers would show longer reaction times and more errors to phonologically similar than phonologically dissimilar target words when compared to the good reader group. Additionally, we hypothesized that poor readers compared to good readers would show decreased response amplitudes between 150-300 ms to phonologically similar than phonologically dissimilar deviants compared to the standard stimulus, in areas important for phonological processing.

2. Materials and Methods

2.1 Subjects

Two groups of children participated: fifteen good readers (11 females; 7 to 13 years old, mean = 9.7), and fifteen poor readers (8 females; 8-13 years old, mean 10.4). Although the participants in the poor readers group were slightly older, the difference in age between the two groups was not significant (t -test, $p > 0.1$). Written informed assent/consent was obtained from all subjects/parents in accordance with the Human Subjects Committee at Massachusetts General Hospital. All children had English as their primary language and had normal or corrected-to-normal vision, with no history of neurological, psychological or hearing problems. Additionally, all children passed a standard hearing screening at 20 dB for 500 to 4000 Hz, (ANSI, 1989) and were screened for implanted metal devices. Most of the subjects were right-handed, with the exception of three children in each group who were left-handed (Annett, 1970).

Good and poor reader groups were selected on the basis of their performance on the subtests of the Woodcock Reading Mastery Tests-Revised (Woodcock, 1987). Poor readers scored below the 25th percentile on the Word Attack and/or Word Identification subtest of the Woodcock Reading Mastery Tests-Revised. Children in the good reader group were reading

above the 39th percentile on both Woodcock subtests to allow for clear separability between the two groups. Additionally, children in the poor reader group were identified by the school system as reading below grade level, and they were receiving reading remediation. Both groups had scores in the normal range (85-120) on verbal and nonverbal IQ. Nonverbal IQ was assessed using the Test of Nonverbal Intelligence (TONI-3) (Brown, Sherbenou, & Johnsen, 1997); verbal IQ was estimated from the Peabody Picture Vocabulary Test (PPVT-3) (Dunn & Dunn, 1997), a measure of receptive vocabulary that correlates closely with verbal IQ. All children were also tested on rapid naming performance (color naming and object naming subtests) and phonological memory (nonword repetition and memory for digits subtests) of the Comprehensive Test of Phonological Processing (CTOPP) (Wagner, Torgesen, & Rashotte, 1999). Children with a diagnosis of attention deficit hyperactivity disorder (ADHD) were excluded from the study. A summary of the standardized testing scores for the two groups is shown in Table 1. Planned *t*-tests revealed that the groups did not differ significantly on any standardized testing measure other than reading standard score (SS).

2.2 Stimuli

A phonetically-trained native male speaker of American English recorded the standard token (*pat*) as well as three deviant tokens (*bat*, *cat*, *rat*) with neutral intonation in a sound treated room using a unidirectional microphone attached to a PC running the program WaveSurfer (Sjolander & Beskow, 2000) with a 22 kHz sampling rate. To control for acoustic differences between the stimuli, new deviants were constructed by extracting the formant contours (F1, F2, F3, F4) of the initial phonemes of the recorded deviants (i.e., /k/, /b/, /r/) using the sound-editing program XKL (Klatt, 1980). New instances of /k/, /b/, and /r/ were created using the Klatt synthesizer by mimicking the formant contours observed in the natural utterances. The synthesized consonants were appended to the rime of the standard stimulus (/at/), resulting in new deviant tokens (/bat/, /kat/, /rat/) that were controlled for acoustic differences. Care was taken to create smooth transitions between the formant contours of the synthesized consonants and the formant contours of the vowel /a/. As the synthesis of /r/ was more complex than for /b/ and /k/, it was found that the insertion of an additional pole-zero pair at 1750 Hz resulted in a more natural sounding /r/. Small sections of the initial phonemes were modified, so that the duration of each stimulus was maintained at a constant length of 420 ms. Spectrograms of the stimuli are shown in Figure 1.

Several adults and children verified that all of the stimuli sounded natural prior to use in the actual study. The stimuli were chosen, as they were all highly familiar words (word frequency: *pat*-35, *bat*-18, *cat*-23, *rat*-6) (Kucera & Francis, 1967). Two of the deviants differed in one phonetic feature (/kat/ in place of articulation, /bat/ in voicing) from the standard, while the other deviant (/rat/) differed in three phonetic features (voicing, place of articulation, and manner of articulation) from the standard. The deviants will be hereafter referred to as phonologically similar for /bat/ and /kat/, and phonologically dissimilar for /rat/.

2.3 Experimental procedure

During the experiment, subjects were presented with a train of standard (*pat*) stimuli embedded with occasional deviants (*bat*, *cat*, or *rat*) played at a comfortable listening level through headphones. Consecutive stimuli were separated by 300 ms of silence. Subjects were instructed to press a response button as soon as they heard one of the deviant words, to indicate that the deviant was detected. To ensure an adequate signal to noise ratio, each deviant was presented 100 times, and the standard was presented 1000 times for a total of 1300 trials, giving each of the deviants an 8% probability of occurrence. To help the subjects maintain focus, they were instructed to fixate on a cross that was projected on the middle of a screen in front of them. The stimuli were presented in five runs containing an equal number of stimuli (200 standards, and 20 of each deviant). The total recording time for all runs was approximately 25 minutes.

Short five-second breaks after every twenty stimuli, and longer two-minute breaks between runs helped prevent subject fatigue. The order of the stimuli was identical for all subjects. It was pseudorandomized so that at least two but no more than five standards occurred between two deviants. In addition, deviants did not occur within the first five trials of each run or within the first three trials after a break, to allow subjects to build up a memory trace of the standard against which the deviant was to be compared. Subjects were instructed to respond as quickly and accurately as possible using the index finger of their dominant hand.

2.4 Behavioral Measures

Response time (RT) and accuracy measures for each deviant were calculated for each subject. RTs were measured from the onset of the deviant word. Trials with response times less than 200 ms or greater than 1500 ms were counted as incorrect. The choice of these cutoffs was justified given the range of mean RTs was 400-950 ms. The number of missed deviants (i.e., when the button was not pressed), as well as the number of false positives was calculated for each subject. Subjects were provided with 26 practice trials (20 standards, 2 each of the deviants) before beginning the actual experiment, to determine a comfortable listening level and to ensure a complete understanding of the task instructions. The total recording time was about 25 minutes. Pearson product-moment correlation coefficients were also calculated for comparisons of standardized testing measures and performance measures on the oddball task to determine if test scores predicted performance on the oddball task.

2.5 MEG recording

Simultaneous MEG and EEG were recorded using a 306-channel (204 first-order planar gradiometers, 102 magnetometers) VectorView MEG system (Elekta-Neuromag Ltd., Helsinki, Finland), with 19 electrodes of EEG in a cap arranged approximately according to the 10-20 system. The impedances of all EEG electrodes were kept below 5 k Ω . For the source analysis, only the MEG signals were used given the optimization of our analysis tools for this purpose. Horizontal and vertical EOG electrodes were used for detection and subsequent rejection of large eye movements and eye blinks, which cause artifacts in the MEG data. The locations of the electrodes were digitized with a Fastrak digitization device (Polhemus, Colchester, VT). Landmark anatomical features (nasion and preauricular points), along with additional points along the surface of the head were also digitized for the co-registration of the MEG data with the subject's MRI.

Subjects were seated in a comfortable chair facing a screen, with hands resting on a flat surface holding the response pad, and with their head placed under the helmet-shaped bottom of the dewar housing the MEG sensors. A microphone was used for communication with the subject, and all subjects were monitored during the experiment for task compliance and head movements with a video camera inside the magnetically shielded room linked to a display outside of the room.

The MEG and EEG signals were recorded continuously during each of five runs, and sampled at 601 Hz after filtering from 0.03 to 200 Hz. At the beginning of each run, low-level current was fed to each of 4 HPI coils attached to the subject's head for calculation of the head position with reference to the MEG sensors. Stimulus presentations and corresponding brain responses were time locked to trigger pulses sent by the Presentation program and coded by the data acquisition computer. Event-related MEG and EEG responses related to each stimulus condition were averaged. The epoch window used for averaging was 900 ms (100 ms before to 800 ms after the onset of the stimulus). Trials containing eye movements, blinks, or other channel artifacts (peak-to-peak amplitude >150 μ V in EOG, >500 fT/cm in gradiometers) were rejected. The good readers had on average 82 artifact-free epochs per condition, the poor readers 73. This difference was not significant (t -test, $p > 0.1$). The averaged epochs were low-

pass filtered at 40 Hz, and the zero level in each channel was taken to be the mean value in the 100-ms baseline period before stimulus onset. Although the visualization of the MEG and EEG sensor data was important for validating the task design and comparison of our results with previous studies, differences between the groups were primarily assessed using MEG source analysis.

2.6 Structural Magnetic Resonance Imaging

High resolution structural T1-weighted magnetic resonance images (MRIs) were acquired on a 3T Siemens Sonata or Allegra scanner (TR = 2530 ms, TE = 3.25 ms, flip angle = 7°, 128 sagittal slices, slice thickness = 1.3 mm, voxel size = $1.3 \times 1.0 \times 1.3 \text{ mm}^3$). A representation of the cortical surface was constructed from the individual structural MRIs with the Freesurfer software (Dale et al., 1999; Fischl, Sereno & Dale, 1999). Cortical white matter was segmented in the high-resolution MR images, and the estimated border between gray and white matter was tessellated, providing a triangular representation of the surface. The surface was also “inflated” to unfold cortical sulci, providing a convenient viewing of cortical activation patterns (Dale, Fischl, & Sereno, 1999; Fischl, Sereno, & Dale, 1999).

2.7 MEG Source Analysis

Cortical sources of the MEG signals were estimated using a distributed model, the Minimum Norm Estimate (MNE) (Hämäläinen & Ilmoniemi, 1994). The sources were assumed to lie on the cortical surface that was reconstructed from the structural MRI. To calculate the forward model which describes the signal pattern generated by a unit dipole at each allowed location on the surface, a single-compartment boundary element model (BEM) was used (Hämäläinen & Sarvas, 1989). For the BEM, the inner surface of the skull for each subject was determined from the T1-weighted MRI. To compensate for small head movements between runs, a forward solution was generated for each run, and the average was used in the analysis (Uutela, Taulu, & Hämäläinen, 2001). To compensate for the bias of MNE toward superficial sources, the inverse operator was constructed with depth weighting (Lin, Witzel et al., 2006). To avoid numerical instability a regularization parameter, $\lambda^2 = 0.33$ was used when computing the inverse operator (Hämäläinen & Ilmoniemi, 1994). Regularization reduces the sensitivity of MNE to noise and effectively results in a spatially smoothed solution. To allow flexibility of the model against small co-registration errors, the orientations of the dipole elements were not strictly constrained to be perpendicular to the cortical surface, and a “loose orientation constraint parameter” of 0.6 was used (Lin, Belliveau, Dale, & Hämäläinen, 2006). Using the MNE, the activation at each location on the cortical surface was estimated every 5 ms.

To examine differences in the pattern of brain activation between the two groups, noise-normalized MNE, called dynamic Statistical Parametric Map (dSPM) was also calculated (Dale et al., 2000). The dSPM converts the MNE into a statistical test variable that is essentially the signal-to-noise ratio (SNR) of the current estimate at each spatial location. Thus dSPM is useful for visualization of the data as it identifies locations where the MNE amplitudes are above the noise level. Average dSPM for the three deviant-standard subtraction conditions (*bat-pat*, *cat-pat*, *rat-pat*) was calculated in 50-ms time windows from 0 to 500 ms separately for the two groups.

We quantified the observed group differences in the dSPM by defining regions of interest (ROIs) (Wehner, Ahlfors, & Mody, in press). ROIs based on activated cortical regions in each hemisphere were manually drawn on the omnibus (all deviants combined) MNE solution averaged across all subjects. This was an unbiased method to quantify differences between groups and conditions in regions that showed consistent activation across the subjects and conditions. The locations of these ROIs on the individual subjects were determined using spherical morphing of the ROI cortical labels from one subject to another (Fischl et al.,

1999). Two symmetrical 50-ms windows (65-115 ms, 190-240 ms) surrounding the peak latencies associated with the P1/N1 and N2 evoked brain responses were identified from the omnibus solution for the subtraction (i.e., *bat-pat*, *cat-pat*, *ratpat*) conditions. Inclusion of an additional time window from 140-190 ms was warranted after observation of additional activation in the right hemisphere during this time range. Mean MNE values in these time bins were used for statistical comparisons between the two reading groups.

3. Results

3.1 Behavioral Data

The mean reaction times (RTs) and accuracy for the three deviant conditions are shown in Fig. 2 for the two groups of children. Only correct answers were used for the calculation of RTs. The RT and accuracy data were subjected to repeated-measures ANOVAs with condition as the within-subjects factor and group as the between-subjects factor. For accuracy, no main effects or a group $\times$ condition interaction were found (Fig 2A). For the RTs, there was a main effect of condition, $F(2,28) = 42.6, p < 0.0001$, and a marginally significant effect of group, $F(1,28) = 3.1, p < 0.09$ (Fig 2B). No group $\times$ condition interaction was observed. Post-hoc paired *t*-tests revealed that both groups had longer RTs for *bat* compared to *cat* and *rat* and also longer RTs for *cat* compared to *rat* (all *p*-values < 0.05). Since poor readers had slightly faster RTs compared to good readers, we wanted to determine if poor readers also had more false positive responses compared to good readers. To test this, we calculated d' values for each subject. A common metric in signal detection theory, d' is a measure relating percent correct responses to percent false positive responses. A false positive response was defined as pressing the button to the standard word, *pat*. No significant difference was observed in d' values between the two groups (mean d' - good readers: 2.46, poor readers: 2.45, 1-tailed *t*-test: $p > 0.1$).

Differences in the number of missed deviants for the three deviant conditions were examined with *t*-tests for within (paired, 2-tailed), and between (unpaired, 1-tailed) group comparisons. One-tailed *t*-tests were used for between group comparisons, as we had the *a priori* hypothesis that poor readers would miss more deviants than good readers due to their impoverished phonological representations. Within group comparisons revealed that both groups missed more *bat* deviants compared to *rat* deviants (good readers: $p < 0.02$, poor readers: $p < 0.01$). No between-group comparisons were significant.

To ensure that there were no performance (RTs, accuracy, missed deviants, false positives) differences between the two groups related to differences in motivation or vigilance, we compared subjects' performance on run 1 with that on run 5, and found no group differences between any of the performance measures as a function of run.

Correlations between standardized testing scores (PM, RN) and performance (RT and accuracy) on the oddball task were conducted to determine if children with poorer standardized scores also performed differently on the task. No correlations between standardized testing scores and task performance were significant. However, overall accuracy was correlated with overall RT for both groups (good readers: $r = 0.72, p < 0.01$, poor readers: $r = 0.81, p < 0.001$), indicating that children who responded quickly to the deviants also had lower accuracy on the task.

3.2 MEG data

Averaged MEG responses in two gradiometers for the three subtraction conditions for one child are shown in Fig 3A. Prominent responses can be seen in both hemispheres for all conditions at about 150-250 ms. This latency range coincides with the N2 response as seen in the grand-averaged EEG responses for a parietal midline electrode (Fig 3B).

Differences in the spatiotemporal pattern of brain activation for the two groups were compared using consecutive averaged 50-ms time segments of the dSPM solution for the three subtraction contrasts (Fig. 4). Both groups showed activation in the superior temporal cortex typically beginning around 100-150 ms for all contrasts. However, some group differences were also observed. For poor readers, activation persisted throughout the recording epoch. In comparison, good readers showed a response for all conditions between 100-250 ms that diminished during the 250-350 ms time range, before the re-emergence of widespread activation after 400 ms. Brain activity after 400 ms may be partially attributed to reactivation of the auditory word form and the motor response associated with the button press to the deviants, as reaction times were on average 596 ms for the good readers and 514 ms for the poor readers. So as not to confound the later motor response-related activation with earlier activation related to the discrimination of the deviants, we have focused our source analysis on the earlier time range (before 400 ms).

In the phonologically similar *bat-pat* condition, good readers showed activation that began early in the left hemisphere (50-100 ms) and peaked bilaterally around 150-200 ms. In contrast, the poor readers showed bilateral activation that began later (150-200 ms) and was stronger in the right hemisphere. The right hemisphere activation peaked around 200-250 ms and was followed by left hemisphere activation that peaked between 250-300 ms. The other phonologically similar contrast (*cat-pat*) also showed bilateral activation that was stronger in the right hemisphere temporal cortex for the poor readers, whereas the good readers showed a weak bilateral response between 200-300 ms. As opposed to the different patterns of brain activation for the two groups to the phonologically similar contrasts, both groups showed an early (100-150 ms) bilateral response to the phonologically dissimilar (*rat-pat*) contrast. However, even for this seemingly easy contrast, the general pattern of persistent activation for the poor reader group versus a more transient then diminishing response for the good reader group was evident.

3.3 MEG ROI analysis

To quantify the observed differences between the two groups, brain activation was compared within three regions of interest (ROIs) for each hemisphere; superior temporal gyrus (STG), middle temporal gyrus (MTG) and inferior frontal gyrus (IFG), and three time windows (65-115 ms, 140-190 ms, and 190-240 ms) as determined from the MNE solution for the three deviant conditions (Fig. 5). These three regions were selected because they showed activation in the noise-normalized dSPM solution (Fig. 4), and they have been implicated in similar studies of phonological processing. In contrast, some areas that showed activation in the MNE solution (e.g., left temporal pole) but were absent in the dSPM solution were not included as the MNE activation in these areas may have been a noise-related artifact. The MNE time courses for the subtraction contrasts averaged across all subjects within a group for each ROI are shown in Fig. 6.

To examine whether the amplitude or latency of the peak MEG response in the early (65-115 ms) time range differed between the two groups, repeated measures ANOVAs were conducted for the STG ROIs, with condition (*pat*, *bat*, *cat*, *rat*) as the repeated within-subjects factor and group as the between-subjects factor. The dependent measure was either the peak MNE value or the latency of the peak MNE value within the 65-115 ms time window. No main effects of group or group $\times$ condition interactions for the peak MNE value or peak latency were observed, suggesting that the groups did not process the acoustic properties of the stimuli differently. However, the peak MNE value in the left and right STG was significantly larger for the *bat* condition relative to the other conditions irrespective of reading group, evidenced as a main effect of condition (left: $F(3,84) = 7.2$, $p < 0.001$, right: $F(3,84) = 7.3$, $p < 0.001$).

To examine differences between the groups in the later time range, repeated-measures ANOVAs were conducted for each ROI and the two time bins (140-190 ms, 190-240 ms), with

condition (*bat-pat*, *cat-pat*, *rat-pat*) as the within subjects factor and group as the between-subjects factor. As activation during the later time bins did not show clear peaks, we used the mean rather than the peak MNE value within each ROI and time bin as the dependent measure in the ANOVAs. Two significant effects were observed in the left hemisphere STG (Fig. 7). First, a group $\times$ condition interaction, $F(2,56) = 5.2$, $p < 0.01$, was found during the 140-190 ms time range. Post-hoc t -tests ($p < 0.05$) revealed that good readers compared to poor readers showed more activation for the *bat-pat* contrast, whereas poor readers showed more activation than good readers for the *rat-pat* contrast. Good readers also showed more activation for *bat-pat* than to *cat-pat* and *rat-pat* during this time range, whereas the poor readers showed no differences between the conditions (Fig. 8). Second, a main effect of group, $F(1,28) = 5.7$, $p < 0.03$, and a group $\times$ condition interaction, $F(2,56) = 4.1$, $p < 0.03$, were observed within the 190-240 ms time range. Post-hoc t -tests ($p < 0.05$) revealed that poor readers showed more activation than good readers in this ROI and time bin, and had greater activation for the *rat-pat* contrast. No other significant differences were found for the left hemisphere ROIs.

Analysis of the right hemisphere ROIs revealed a main effect of condition for all three ROIs and both time bins except the right IFG during the 190-240 ms time bin. Post-hoc t -tests ($p < 0.05$) revealed that all main effects of condition could be explained as more activation for the *bat-pat* contrast relative to the other contrasts. No main effects of group or group $\times$ condition interactions were observed in any of the right hemisphere ROIs.

3.4 Brain-behavior relationships

To examine the relationship between standardized testing measures (PM, RN) and mean MNE activation within ROIs and time bins, Pearson product-moment correlations were calculated for all subjects combined, and for each group separately. To control for the potential increase in Type 1 errors arising from multiple comparisons (6 ROIs, 3 time bins), significant correlations were those with a corrected p -value $< 0.05/18 = 0.0028$. No across-group or within-group correlations between standardized testing measures and mean MNE activation were significant.

We also calculated correlations between behavioral performance (RT, accuracy) for each deviant and the mean MNE activation associated with discriminating each deviant (e.g., *bat-pat* for *bat* RT) within all ROIs and time bins. Two significant correlations were observed. First, for all subjects combined, accuracy on the *bat* condition negatively correlated ($r = -0.54$, $p < 0.002$) with mean MNE activation for the *bat-pat* contrast in right IFG for the 190-240 ms time range. Therefore, children who were less accurate at detecting phonologically similar stimuli showed more right hemisphere IFG activation during this time range. Second, a negative correlation was observed for the good readers between accuracy on the *bat* condition and mean MNE activation for the *bat-pat* contrast in left IFG during the 140-190 ms time range ($r = -0.77$, $p < 0.001$), and the right IFG during the 190-240 ms time range ($r = -0.78$, $p < 0.001$). A negative correlation ($r = -0.71$, $p < 0.01$) was also observed for the good readers between accuracy to *rat* and mean MNE activation for *rat-pat* within right IFG during the 140-190 ms time range. Therefore, it appears that lower accuracy on the task is generally associated with an increase in inferior frontal (particularly right IFG) activation. No within-group correlations for the poor readers were significant. Additionally, no correlations between RT and MNE activation were significant.

4. Discussion

Differences in the discrimination of spoken words that varied in the degree of phonological contrast were examined in good and poor readers using an attended oddball task. A novel finding in our study was that by manipulating the degree of phonological contrast of a deviant target word to a repeated standard word, we were able to detect differences in spatiotemporal

activation between the two groups that were consistent with a phonological account of reading disability. Both groups had greater difficulty detecting the phonologically similar deviants compared to the phonologically dissimilar deviants, evidenced by longer reaction times, and a larger number of missed deviants for the phonologically similar items. Despite the similar behavioral performance, MEG source analysis revealed different patterns of brain activation for the two groups as a function of phonological contrast. Compared to the good readers, poor readers' delayed and reduced left-hemisphere activation to the most demanding phonological contrast (*bat-pat*), and the overall sustained bilateral activation may reflect their greater difficulty with phonological processing. Below we first discuss patterns of behavioral performance and brain activation that were similar in both groups, and then elaborate on the observed group differences.

4.1 Effects of varying degree of phonological contrast

Both good and poor readers took longer to respond to the phonologically similar deviants relative to the phonologically dissimilar deviant, indicating that phonological contrasts involving one feature were indeed harder to discriminate than those involving three features. Additionally, both groups had more difficulty discriminating a voicing contrast (*bat* vs. *pat*) than a place of articulation contrast (*cat* vs. *pat*), suggestive of disproportionate weightings of different acoustic cues by children (Nittrouer, 1992; Nittrouer & Studdert-Kennedy, 1987).

The good and poor readers also showed similar patterns of brain activation within the STG. In the early time range (65-115 ms), both groups showed larger peak MNE amplitudes to *bat* than to the other deviants, possibly due to the large difference in acoustic energy between the initial phoneme of this deviant (viz., /b/) and that of the standard (viz., /p/) (Fig. 1). Importantly, no group differences in peak MNE amplitude or latency were observed in this early time range, suggesting that both groups processed the acoustic properties of the stimuli similarly.

Previously, Heim and colleagues (2003) found differences in right hemisphere dipole locations between good and poor readers in this early time range using a passive oddball paradigm.

Although we did not examine dipole localization in the present study, the poor readers in our study appeared to show greater and more sustained activity in the right hemisphere compared to the good readers, suggesting that the regions in the right hemisphere may play an important role in speech perception deficits in reading disability.

In the later time ranges, good readers showed a more sustained response to the phonologically similar *bat-pat* condition relative to the phonologically dissimilar *rat-pat* condition. A similar sustained response was observed for the poor readers for all conditions, regardless of the contrast. That good and poor readers showed sustained activation during the *bat* condition may reflect both groups' struggle with this phonologically demanding discrimination. Furthermore, decreased accuracy on *bat* was associated with increased inferior frontal activation in the right hemisphere (all children) or bilaterally (good readers). Inferior frontal regions are known to be involved in phonological processing (Gold & Buckner, 2002; Poldrack et al., 1999). Processing of a phonologically demanding contrast (viz., *bat-pat*), thus appears to have drawn more on these areas (Pugh et al., 2001).

4.2 Differences between good and poor readers

Despite similar behavioral performance, good and poor readers showed different patterns of brain activation in the time range associated with phonological processing. Compared to good readers, the poor readers showed greater activation in the phonological dissimilar (and more contrastive) *rat-pat* condition but reduced activation in the phonologically similar (and less contrastive) *bat-pat* condition in left STG, an area implicated in phonological processing (Binder et al., 2000; Helenius, Salmelin, Richardson, Leinonen, & Lyytinen, 2002; Okada & Hickok, 2006; Poldrack et al., 2001). These results may reflect a difference in the processing

of these conditions by the two groups as a function of their phonological abilities. More specifically, despite both good and poor readers taking longer to respond to *bat* than to *rat*, good readers showed a significant difference in brain activity between these two conditions, whereas poor readers did not. This suggests that good readers were able to take advantage of their superior coding abilities to respond differently to the phonologically similar vs. dissimilar stimulus pairs. Poor readers, in contrast, did not show this difference, perhaps due to their reduced sensitivity to the phonological characteristics of the stimuli (Brady et al., 1983; Liberman, Shankweiler, Liberman, Fowler, & Fischer, 1977). It is worth noting that poor readers showed greater activation than good readers on the phonologically easier (i.e., more contrastive) *rat-pat* condition, which points to their use of phonological processing strategies as in normal readers; however, poor readers' weaker activation under demanding conditions, compared to good readers, suggests a deficiency in their phonological abilities. When discrimination was difficult, the poor readers in our study also showed a bilateral response that was initially larger on the right then peaked later on the left. This sequence of right hemisphere activation followed by activation in the left hemisphere is in line with previous findings in the literature on reading disability (Breier et al., 2003). Widespread synchronization between left and right brain regions has been recently observed in an oddball task (Fingelkurts, Fingelkurts, Krause, Möttönen, & Sams, 2003). Fingelkurts and colleagues observed more left hemisphere connections in healthy adults. Functional connections in young children and/or poor readers may include more right hemisphere regions, as reflected as sustained bilateral activation in the present study. We found no activation differences between the groups in the *cat-pat* condition, despite it having a one-feature contrast as in the *bat-pat* condition, suggesting that further investigation is needed. That both groups had more difficulty with the *bat-pat* contrast than the *cat-pat* contrast may partially explain these findings. In summary, the aberrant brain activation patterns observed in the poor readers in areas and a time range (140-240 ms) previously implicated in phonological processing appear to be consistent with a phonological account of reading disability. However, insofar as these same areas are known to also be involved in non-phonological processes, alternative explanations cannot be excluded.

Examination of the dSPM (Fig. 4) revealed additional activation in brain regions, such as the insula, somatosensory, and inferior temporal cortices, that may have been recruited in the task, but that were not captured by our omnibus ROI analysis. The omnibus ROI-based approach provided us with an unbiased method to statistically compare differences between groups and conditions. However, ROIs were defined only for regions that showed consistent activation across the subjects and conditions. The dSPM complemented the ROI approach by providing statistical maps of cortical activation that were qualitatively compared across conditions and groups.

In theory, it is possible that large head movements during the task may have affected the source estimation. However, we monitored all subjects during the task for compliance, and had no reason to believe that one group moved more than the other group.

The absence of group differences in reaction times or accuracy may be explained in terms of the degree to which the task stressed the phonological processing system. Although subjects had to attend to the stimuli to detect the deviant targets, they did not have to actively identify or label them. Previous research has shown that poor readers have difficulties with such labeling processes (e.g., (Breier et al., 2001; Godfrey et al., 1981; Mody, 2003; Swan & Goswami, 1997). Given the subtle nature of the speech perception deficit in poor readers, perhaps a task that required active phonological coding of the stimuli would have shown more robust group differences. MEG allowed us to observe group neural differences on a task in which the behavioral performance was comparable across groups, providing support for continued use of MEG to understand the development of cognitive processes in children.

5. Conclusion

Both good and poor readers had more difficulty discriminating phonologically similar than phonologically dissimilar spoken words. Whereas the two groups were able to detect the deviants, evident in their similar behavioral performance on the task, the pattern of brain activation was different for the good and poor readers under varying degrees of phonological contrast. Delayed and reduced left hemisphere activation for the poor readers compared to the good readers in the most demanding phonological contrast, which was found in an area and a time range previously implicated in phonological processing, may reflect their greater difficulty with phonological processing. As such the results are consistent with a phonological core deficit in reading disability.

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References

- Adlard A, Hazan V. Speech perception in children with specific reading difficulties (dyslexia). *Quarterly Journal of Experimental Psychology A* 1998;51:153–177.
- Alho K, Winkler I, Escera C, Huotilainen M, Virtanen J, Jääskeläinen IP, Pekkonen E, Ilmoniemi RJ. Processing of novel sounds and frequency changes in the human auditory cortex: magnetoencephalographic recordings. *Psychophysiology* 1998;35:211–224. [PubMed: 9529947]
- Annett M. A classification of hand preference by association analysis. *British Journal of Psychology* 1970;61:303–321. [PubMed: 5457503]
- ANSI. Specifications for audiometers, S3.6. American National Standards Institute; New York: 1989.
- Bernal J, Harmony T, Rodriguez M, Reyes A, Yanez G, Fernandez T, Galan L, Silva J, Fernandez- Bouzas A, Rodriguez H, Guerrero V, Marosi E. Auditory event-related potentials in poor readers. *International Journal of Psychophysiology* 2000;36:11–23. [PubMed: 10700619]
- Binder JR, Frost JA, Hammeke TA, Bellgowan PS, Springer JA, Kaufman JN, Possing ET. Human temporal lobe activation by speech and nonspeech sounds. *Cerebral Cortex* 2000;10:512–528. [PubMed: 10847601]
- Boada R, Pennington BF. Deficient implicit phonological representations in children with dyslexia. *Journal of Experimental Child Psychology* 2006;95:153–193. [PubMed: 16887140]
- Bonte ML, Blomert L. Developmental dyslexia: ERP correlates of anomalous phonological processing during spoken word recognition. *Brain Research: Cognitive Brain Research* 2004;21:360–376. [PubMed: 15511652]
- Bonte ML, Poelmans H, Blomert L. Deviant neurophysiological responses to phonological regularities in speech in dyslexic children. *Neuropsychologia* 2007;45:1427–1437. [PubMed: 17187830]
- Bowers PG, Swanson LB. Naming speed deficits in reading disability: multiple measures of a singular process. *Journal of Experimental Child Psychology* 1991;51:195–219. [PubMed: 2033360]
- Bradlow AR, Kraus N, Nicol TG, McGee TJ, Cunningham J, Zecker SG, Carrell TD. Effects of lengthened formant transition duration on discrimination and neural representation of synthetic CV syllables by normal and learning-disabled children. *Journal of Acoustical Society of America* 1999;106:2086–2096.
- Brady S, Shankweiler D, Mann V. Speech perception and memory coding in relation to reading ability. *Journal of Experimental Child Psychology* 1983;35:345–367. [PubMed: 6842131]

- Breier JI, Gray L, Fletcher JM, Diehl RL, Klaas P, Foorman BR, Molis MR. Perception of voice and tone onset time continua in children with dyslexia with and without attention deficit/hyperactivity disorder. *Journal of Experimental Child Psychology* 2001;80:245–270. [PubMed: 11583525]
- Breier JI, Simos PG, Fletcher JM, Castillo EM, Zhang W, Papanicolaou AC. Abnormal activation of temporoparietal language areas during phonetic analysis in children with dyslexia. *Neuropsychology* 2003;17:610–621. [PubMed: 14599274]
- Breznitz Z, Meyler A. Speed of lower-level auditory and visual processing as a basic factor in dyslexia: electrophysiological evidence. *Brain and Language* 2003;85:166–184. [PubMed: 12735934]
- Brown, L.; Sherbenou, RJ.; Johnsen, SK. Test of Nonverbal Intelligence. Third Edition. PRO-ED, Inc; Austin, TX: 1997.
- Chiappe P, Chiappe DL, Gottardo A. Vocabulary, Context, and Speech Perception Among Good and Poor Readers. *Educational Psychology* 2004;24:825–843.
- Chiappe P, Chiappe DL, Siegel LS. Speech perception, lexicality, and reading skill. *Journal of Experimental Child Psychology* 2001;80:58–74. [PubMed: 11511135]
- Connolly JF, Service E, D'Arcy RC, Kujala A, Alho K. Phonological aspects of word recognition as revealed by high-resolution spatio-temporal brain mapping. *Neuroreport* 2001;12:237–243. [PubMed: 11209927]
- Corina DP, Richards TL, Serafini S, Richards AL, Steury K, Abbott RD, Echelard DR, Maravilla KR, Berninger VW. fMRI auditory language differences between dyslexic and able reading children. *Neuroreport* 2001;12:1195–1201. [PubMed: 11338191]
- Dale AM, Fischl B, Sereno MI. Cortical surface-based analysis. I. Segmentation and surface reconstruction. *Neuroimage* 1999;9:179–194. [PubMed: 9931268]
- Dale AM, Liu AK, Fischl BR, Buckner RL, Belliveau JW, Lewine JD, Halgren E. Dynamic statistical parametric mapping: combining fMRI and MEG for high-resolution imaging of cortical activity. *Neuron* 2000;26:55–67. [PubMed: 10798392]
- Dunn, LM.; Dunn, LM. Peabody Picture Vocabulary Test. Third Edition. American Guidance Service, Inc; Circle Pines, MN: 1997.
- Fingelkurts A, Fingelkurts A, Krause CM, Möttönen R, Sams M. Cortical operational synchrony during audio-visual speech integration. *Brain and Language* 2003;85:297–312. [PubMed: 12735946]
- Fischl B, Sereno MI, Dale AM. Cortical surface-based analysis. II: Inflation, flattening, and a surface-based coordinate system. *Neuroimage* 1999;9:195–207. [PubMed: 9931269]
- Georgiewa P, Rzanny R, Hopf JM, Knab R, Glauche V, Kaiser WA, Blanz B. fMRI during word processing in dyslexic and normal reading children. *Neuroreport* 1999;10:3459–3465. [PubMed: 10599862]
- Giard MH, Perrin F, Pernier J, Bouchet P. Brain generators implicated in the processing of auditory stimulus deviance: a topographic event-related potential study. *Psychophysiology* 1990;27:627–640. [PubMed: 2100348]
- Godfrey JJ, Syrdal-Lasky AK, Millay KK, Knox CM. Performance of dyslexic children on speech perception tests. *Journal of Experimental Child Psychology* 1981;32:401–424. [PubMed: 7320677]
- Gold BT, Buckner RL. Common prefrontal regions coactivate with dissociable posterior regions during controlled semantic and phonological tasks. *Neuron* 2002;35:803–812. [PubMed: 12194878]
- Hämäläinen MS, Ilmoniemi RJ. Interpreting magnetic fields of the brain: minimum norm estimates. *Medical and Biological Engineering and Computing* 1994;32:35–42. [PubMed: 8182960]
- Hämäläinen MS, Sarvas J. Realistic conductivity geometry model of the human head for interpretation of neuromagnetic data. *IEEE Transactions on Biomedical Engineering* 1989;36:165–171. [PubMed: 2917762]
- Heim S, Eulitz C, Elbert T. Altered hemispheric asymmetry of auditory P100m in dyslexia. *European Journal of Neuroscience* 2003;17:1715–1722. [PubMed: 12752389]
- Heim S, Eulitz C, Kaufmann J, Fuchter I, Pantev C, Lamprecht-Dinnesen A, Matulat P, Scheer P, Borstel M, Elbert T. Atypical organisation of the auditory cortex in dyslexia as revealed by MEG. *Neuropsychologia* 2000;38:1749–1759. [PubMed: 11099733]
- Helenius P, Salmelin R, Richardson U, Leinonen S, Lyytinen H. Abnormal auditory cortical activation in dyslexia 100 msec after speech onset. *Journal of Cognitive Neuroscience* 2002;14:603–617. [PubMed: 12126501]

- Klatt D. Software for a cascade/parallel formant synthesizer. *Journal of the Acoustical Society of America* 1980;67:971–995.
- Kraus N, McGee TJ, Carrell TD, Zecker SG, Nicol TG, Koch DB. Auditory neurophysiologic responses and discrimination deficits in children with learning problems. *Science* 1996;273:971–973. [PubMed: 8688085]
- Kucera, H.; Francis, W. Computational analysis of present-day American English. Brown University Press; Providence: 1967.
- Kujala A, Alho K, Service E, Ilmoniemi RJ, Connolly JF. Activation in the anterior left auditory cortex associated with phonological analysis of speech input: localization of the phonological mismatch negativity response with MEG. *Brain Research: Cognitive Brain Research* 2004;21:106–113. [PubMed: 15325418]
- Kurtzberg D, Vaughan HG Jr, Kreuzer JA, Fliegler KZ. Developmental studies and clinical application of mismatch negativity: problems and prospects. *Ear and Hearing* 1995;16:105–117. [PubMed: 7774764]
- Lachmann T, Berti S, Kujala T, Schroger E. Diagnostic subgroups of developmental dyslexia have different deficits in neural processing of tones and phonemes. *International Journal of Psychophysiology* 2005;56:105–120. [PubMed: 15804446]
- Lawson EA, Gaillard AW. Mismatch negativity in a phonetic discrimination task. *Biological Psychology* 1981;13:281–288. [PubMed: 7342998]
- Lieberman, IY.; Shankweiler, D.; Liberman, AM.; Fowler, C.; Fischer, FW. Phonetic segmentation and recoding in the beginning reader. In: Reber, AS.; Scarborough, D., editors. *Toward a psychology of reading: The proceedings of the CUNY Conference*. Erlbaum; Hillsdale, N.J.: 1977.
- Lin FH, Belliveau JW, Dale AM, Hämäläinen MS. Distributed current estimates using cortical orientation constraints. *Human Brain Mapping* 2006;27:1–13. [PubMed: 16082624]
- Lin FH, Witzel T, Ahlfors SP, Stufflebeam SM, Belliveau JW, Hämäläinen MS. Assessing and improving the spatial accuracy in MEG source localization by depth-weighted minimum-norm estimates. *Neuroimage* 2006;15:160–171. [PubMed: 16520063]
- Mody M. Phonological basis in reading disability: A review and analysis of the evidence. *Reading and Writing: An Interdisciplinary Journal* 2003;16:21–39.
- Mody M, Studdert-Kennedy M, Brady S. Speech perception deficits in poor readers: auditory processing or phonological coding? *Journal of Experimental Child Psychology* 1997;64:199–231. [PubMed: 9120381]
- Näätänen, R. *Attention and brain function*. Erlbaum; Hillsdale, NJ: 1992.
- Näätänen R, Picton TW. N2 and automatic versus controlled processes. *Electroencephalography and Clinical Neurophysiology Supplement* 1986;38:169–186. [PubMed: 3466775]
- Nittrouer S. Age-related differences in perceptual effects of formant transitions within syllables and across syllable boundaries. *Journal of Phonetics* 1992;20:351–382.
- Nittrouer S, Studdert-Kennedy M. The role of coarticulatory effects in the perception of fricatives by children and adults. *Journal of Speech, Language, and Hearing Research* 1987;30:319–329.
- Okada K, Hickok G. Identification of lexical-phonological networks in the superior temporal sulcus using functional magnetic resonance imaging. *Neuroreport* 2006;17:1293–1296. [PubMed: 16951572]
- Opitz B, Mecklinger A, Von Cramon DY, Kruggel F. Combining electrophysiological and hemodynamic measures of the auditory oddball. *Psychophysiology* 1999;36:142–147. [PubMed: 10098390]
- Pääviläinen P, Alho K, Reinikainen K, Sams M, Näätänen R. Right hemisphere dominance of different mismatch negativities. *Electroencephalography and Clinical Neurophysiology* 1991;78:466–479. [PubMed: 1712282]
- Poldrack RA, Temple E, Protopapas A, Nagarajan S, Tallal P, Merzenich M, Gabrieli JD. Relations between the neural bases of dynamic auditory processing and phonological processing: evidence from fMRI. *Journal of Cognitive Neuroscience* 2001;13:687–697. [PubMed: 11506664]
- Poldrack RA, Wagner AD, Prull MW, Desmond JE, Glover GH, Gabrieli JD. Functional specialization for semantic and phonological processing in the left inferior prefrontal cortex. *Neuroimage* 1999;10:15–35. [PubMed: 10385578]

- Pugh KR, Mencl WE, Jenner AR, Katz L, Frost SJ, Lee JR, Shaywitz SE, Shaywitz BA. Neurobiological studies of reading and reading disability. *Journal of Communication Disorders* 2001;34:479–492. [PubMed: 11725860]
- Reed MA. Speech perception and the discrimination of brief auditory cues in reading disabled children. *Journal of Experimental Child Psychology* 1989;48:270–292. [PubMed: 2794857]
- Ritter W, Simpson R, Vaughan HG Jr, Friedman D. A brain event related to the making of a sensory discrimination. *Science* 1979;203:1358–1361. [PubMed: 424760]
- Ruff S, Marie N, Celsis P, Cardebat D, Demonet JF. Neural substrates of impaired categorical perception of phonemes in adult dyslexics: an fMRI study. *Brain and Cognition* 2003;53:331–334. [PubMed: 14607175]
- Scherg M, Vajsar J, Picton T. A source analysis of the late human auditory evoked potentials. *Journal of Cognitive Neuroscience* 1989;1:336–355.
- Schulte-Körne G, Deimel W, Bartling J, Remschmidt H. Auditory processing and dyslexia: evidence for a specific speech processing deficit. *Neuroreport* 1998;9:337–340. [PubMed: 9507979]
- Serniclaes W, Sprenger-Charolles L, Carre R, Demonet JF. Perceptual discrimination of speech sounds in developmental dyslexia. *Journal of Speech, Language, and Hearing Research* 2001;44:384–399.
- Shaywitz BA, Shaywitz SE, Pugh KR, Mencl WE, Fulbright RK, Skudlarski P, Constable RT, Marchione KE, Fletcher JM, Lyon GR, Gore JC. Disruption of posterior brain systems for reading in children with developmental dyslexia. *Biological Psychiatry* 2002;52:101–110. [PubMed: 12114001]
- Simos PG, Breier JJ, Fletcher JM, Bergman E, Papanicolaou AC. Cerebral mechanisms involved in word reading in dyslexic children: a magnetic source imaging approach. *Cerebral Cortex* 2000;10:809–816. [PubMed: 10920052]
- Simos PG, Breier JJ, Fletcher JM, Foorman BR, Bergman E, Fishbeck K, Papanicolaou AC. Brain activation profiles in dyslexic children during non-word reading: a magnetic source imaging study. *Neuroscience Letters* 2000;290:61–65. [PubMed: 10925175]
- Sjolander, K.; Beskow, J. Wavesurfer - An open source speech tool; Paper presented at the ICSLP; Beijing, China. 2000.
- Snowling MJ. Phonemic deficits in developmental dyslexia. *Psychological Research* 1981;43:219–234. [PubMed: 7302091]
- Snowling MJ, Goulandris N, Bowlby M, Howell P. Segmentation and speech perception in relation to reading skill: a developmental analysis. *Journal of Experimental Child Psychology* 1986;41:489–507. [PubMed: 3734692]
- Swan D, Goswami U. Picture naming deficits in developmental dyslexia: the phonological representations hypothesis. *Brain and Language* 1997;56:334–353. [PubMed: 9070416]
- Taylor MJ, Keenan NK. Event-related potentials to visual and language stimuli in normal and dyslexic children. *Psychophysiology* 1990;27:318–327. [PubMed: 2236434]
- Temple E, Poldrack RA, Salidis J, Deutsch GK, Tallal P, Merzenich MM, Gabrieli JD. Disrupted neural responses to phonological and orthographic processing in dyslexic children: an fMRI study. *Neuroreport* 2001;12:299–307. [PubMed: 11209939]
- Uutela K, Taulu S, Hämäläinen M. Detecting and correcting for head movements in neuromagnetic measurements. *Neuroimage* 2001;14:1424–1431. [PubMed: 11707098]
- van der Leij A, van Daal VH. Automatization aspects of dyslexia: speed limitations in word identification, sensitivity to increasing task demands, and orthographic compensation. *Journal of Learning Disabilities* 1999;32:417–428. [PubMed: 15510431]
- Wagner, RK.; Torgesen, JK.; Rashotte, CA. Comprehensive Test of Phonological Processing. PRO-ED, Inc; Austin, TX: 1999.
- Watson BU, Miller TK. Auditory perception, phonological processing, and reading ability/disability. *Journal of Speech and Hearing Research* 1993;36:850–863. [PubMed: 8377497]
- Wehner DT, Ahlfors SP, Mody M. The influence of semantic processing on phonological decisions in children and adults: A magnetoencephalography (MEG) study. *Journal of Speech, Language, and Hearing Research*. in press
- Werker JF, Tees RC. Speech perception in severely disabled and average reading children. *Canadian Journal of Psychology* 1987;41:48–61. [PubMed: 3502888]

- Wolf M, Bowers PG, Biddle K. Naming-speed processes, timing, and reading: a conceptual review. *Journal of Learning Disabilities* 2000;33:387–407. [PubMed: 15493099]
- Woodcock. Woodcock reading mastery test: revised. American Guidance Services; Circle Pines, MN: 1987.
- Yap RL, van der Leij A. Word processing in dyslexics: An automatic decoding deficit? *Reading and Writing: An Interdisciplinary Journal* 1993;5:261–279.

Figure 1.
Spectrograms of the stimuli.

Figure 2. Behavioral results: mean reaction times (A) and accuracy (B) for the three deviant conditions for the two groups.

Figure 3.

A) Event-related MEG waveforms for one child. Averaged responses for the three subtraction conditions are shown for one left temporal gradiometer and one right temporal gradiometer. Also shown are magnetic field patterns corresponding to the peak MEG responses between 150-300 ms for the *rat-pat* condition. The white arrows represent equivalent current dipoles indicating approximate locations of the underlying neural activity. B) Grand-average ($n=30$ subjects) EEG waveforms for the three subtraction conditions for the posterior midline Pz electrode. The time range associated with the N2 is indicated.

Figure 4.

MEG source estimates. Dynamic statistical parametric maps (dSPM) averaged in sequential 50-ms time bins from 0-500 ms for the good reader group (top) and the poor reader group (bottom). The group-averaged dSPM for the three subtraction contrasts are shown on the reconstructed cortical surfaces of one child. The lateral surfaces have been inflated for better visualization of activation within the sulci (dark gray) as well as the gyri (light gray). Both left and right hemispheres are shown for all time points.

Figure 5.

Regions of interest (ROIs) for the MEG analysis. Left: Minimum-norm estimates (MNE) for the combined deviant condition, averaged across all subjects ($n=30$) are displayed on inflated lateral views of the left and right hemisphere during the time range of interest (65-240 ms). The maps indicate locations where the maximum values of the MNE exceed the threshold value of 0.1 nAm. The group averaged-MNE data are shown on the reconstructed cortical surfaces of one child. The selected ROIs are outlined: superior temporal gyrus (STG), middle temporal gyrus (MTG), and inferior frontal gyrus (IFG). Right: MNE waveforms for left and right STG ROIs for the combined deviant condition. The latencies of the peaks (90 ms, 165 ms, 215 ms) are shown. Shading indicates the time windows of analysis (65-115 ms, 140-190 ms, 190-240 ms).

Figure 6.

MEG source waveforms. The estimated source strength as a function of time, as obtained from minimum norm estimates (MNE), averaged across all subjects in the good and poor reader groups are shown for all ROIs: superior temporal gyrus (STG), middle temporal gyrus (MTG), and inferior frontal gyrus (IFG). The zero level for each curve is indicated by a horizontal line in the prestimulus period. The vertical lines indicate the onset of the stimulus.

Figure 7. Group MNE activation in the left STG ROI for the *bat-pat* contrast (left) and the *rat-pat* contrast (right). The shading indicates the time windows that showed significant differences between the good readers (gray lines) and the poor readers (black lines).

Figure 8.
Group MNE activation in the left STG ROI (140-190 ms) for the three subtraction conditions.
* $p < 0.05$.

Table 1

Children's Reading Scores

Reading scores for both groups for the Peabody Picture Vocabulary Test (PPVT), the Test of Nonverbal Intelligence (TONI), Reading Standard Score (Word ID/Word Attack subtests of Woodcock), and Phonological Memory (PM) and Rapid Naming (RN) from the Comprehensive Test of Phonological Proficiency (CTOPP). Group means and standard deviations (in parentheses) are provided.

	<u>PPVT</u>	<u>TONI</u>	<u>Reading SS</u>	<u>PM</u>	<u>RN</u>
Good Readers	105 (9.7)	104 (9.6)	114 (9.7)	99 (7.4)	89 (9.7)
Poor Reader	101 (10.4)	98 (9.3)	87 (6.7)	94 (9.3)	91 (9.7)