Published in final edited form as:

Neuroreport. 2011 October 5; 22(14): 674–678. doi:10.1097/WNR.0b013e328349ecf7.

Neural correlates of sentence reading in children with reading difficulties

Panagiotis G. Simos^a, Roozbeh Rezaie^{b,CA}, Jack M. Fletcher^c, Jenifer Juranek^b, and Andrew C. Papanicolaou^b

^aDepartment of Psychology, University of Crete, Rethymno, Crete, 74100, Greece

^bDepartment of Pediatrics, Children's Learning Institute, University of Texas Health Science Center at Houston, Houston, Texas, 77030, USA

^cDepartment of Psychology, University of Houston, Houston, Texas, 77204, USA

Abstract

In contrast to word-level skills, the neural basis of sentence comprehension in children with reading difficulties is not well understood. Using magnetic source imaging, we investigated the spatiotemporal dynamics of regional activity associated with silent passage reading in non-impaired and students with reading difficulties. The latter exhibited underactivation of the temporo-parietal and visual cortices, bilaterally, as well as of the left posterior cingulate region. Late activity in left temporo-parietal and ventral occipito-temporal regions was found to be a significant predictor of individual reading ability in non-impaired, but not in students with reading difficulties. These findings support the notion that reduced temporo-parietal activation during word reading in context, is a hallmark of the functional deficit in reading disability.

Keywords

Dyslexia; comprehension; temporoparietal cortex; magnetoencephalography

Introduction

It is well-established that poor word-level skills, namely phonological decoding and word recognition, form the core deficits in the most common type of reading disability [1]. Nevertheless, the ultimate goal of reading instruction is for students to develop adequate text comprehension skills which bear, at least conceptually, a stronger predictive relationship with overall academic achievement and subsequent professional success, in relation to word-level reading skills [2]. Importantly, the majority of children experiencing reading difficulties at word-level reading skills also exhibit reading comprehension difficulties [3]. Only recently, however, have brain imaging studies investigated signs of aberrant brain function during text comprehension tasks in students with reading difficulties. In particular, functional magnetic resonance imaging (fMRI) studies have reported reduced degree of hemodynamic activity in the left superior temporal, left sensorimotor, and right

^{CA}Corresponding Author: Roozbeh Rezaie, Department of Pediatrics, Children's Learning Institute, University of Texas Health Science Center at Houston, Houston, Texas, 77030, USA. Roozbeh.Rezaie@uth.tmc.edu; Tel: +1 713 797 7570; Fax: +1 713 797 7590..

Publisher's Disclaimer: This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final citable form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

supramarginal regions [4], and also in the left inferior parietal, middle temporal, medial and superior frontal areas [5] during reading of connected text in students with reading difficulties. Others have reported trends in the opposite direction, with reading impaired students exhibiting *greater* activity in the left middle and superior temporal gyri, insula, and the right temporal, inferior parietal and post-central regions [6].

The disparity among fMRI studies of sentence comprehension associated with reading difficulties may be attributed to methodological differences, including the mode of presentation (one-word at a time vs. whole sentence) known to affect the distribution of hemodynamic responses, even in skilled readers [7]. Here, we applied magnetoencephalography (MEG), to investigate the spatiotemporal dynamics of regional activity associated with comprehension of words in context, controlling for word-level reading skill of the participants by titrating the readability level of printed passages based on word reading efficiency scores. Specifically, we predicted that struggling readers would show reduced late activity (i.e. after 200 ms post-stimulus onset) in regions known to be involved in decoding and word recognition, and in brain areas hosting neurophysiological processes supporting verbal working memory and visual attention. Furthermore, given the close relationship between word-level reading skills (word reading fluency and spelling) and text comprehension, we predicted that within group variability in the degree of late activity in these regions would be a significant predictor of individual reading ability.

Materials and Methods

Participants

The target group consisted of 22 struggling readers scoring at or below the 16th percentile (standard score of 85) on the Basic Reading Composite (average of Word Attack and Letter-Word Identification subtest score of the Woodcock-Johnson-III [8]). A second group of 22 children, who had never experienced difficulties in reading, served as the comparison group (≥ 94 on the Basic Reading Composite). All 44 participants had Full Scale IQ scores > 80 on the Wechsler Abbreviated Scale of Intelligence [9]. None of the participants had a history or current diagnosis of attention, hyperactivity/impulsivity problems as indicated by T scores on the Attention Problems scale of the Child Behavior Checklist (CBCL) [10] below 55 or a score lower than 1.6 on the Inattention and Hyperactivity-Impulsivity scales of the SNAP-IV [11] indicating low risk for ADHD [12] (see Table, Supplemental Digital Content 1 which shows the behavioral and demographic profiles of study participants). The study was performed in accordance with the Declaration of Helsinki and approved by the Institutional Review Board. All participants provided informed consent and were financially compensated for their time.

Procedure

Each participant was tested on a silent passage reading task, involving a 300-word passage, presented one word at a time at a constant rate of one word/700 ms (without a blank interval in between). A blank screen presented for 1.5 s indicated the end of each period. Participants were asked to “read each word carefully without sounding them out to understand what the passage says and press a key when they read a word that did not fit with the rest”. There were 40 semantically incongruous in each passage, but only data associated with semantically appropriate words are reported here. Three different passages were created varying in readability (word length and frequency) and were matched to each participant's word reading efficiency score. Stimuli were presented through an LCD projector at the center of a back-projection screen located approximately 60 cm in front of the participant, and subtended 1.0°–3.0° and 0.5° of horizontal and vertical visual angle, respectively.

MEG data acquisition and analysis

Magnetoencephalography recordings were obtained with a whole-head neuromagnetometer array (4-D Neuroimaging, Magnes WH3600) equipped with 248 first-order axial gradiometer coils and housed in a magnetically shielded chamber. The magnetic flux measurements were digitized at 290 Hz, filtered off-line with a bandpass filter between 0.1 and 20 Hz and subjected to a noise reduction algorithm that is part of the 4D-Neuroimaging software. The single-trial event-related time series were averaged after excluding those containing eye movement or other myogenic or mechanical artifacts.

The intracranial origin of EFs was analyzed using a minimum norm estimate (MNE) model to obtain estimates of the time-varying strength of intracranial currents (MNE Software, v. 2.5; <http://www.nmr.mgh.harvard.edu/martinos/userInfo/data/sofMNE.php>), and described in detail elsewhere [13]. Estimated current sources were anatomically constrained by a high-resolution T1-weighted MRI-derived surface model of each participant's brain. A fully-automated cortical surface reconstruction procedure was used to generate a single-compartment boundary element model with triangular tessellations. Each vertex of the brain surface was treated as a potential current dipole perpendicular to the cortical surface during the forward calculations. The inverse solution was subsequently reduced to obtaining an estimate of the scalar distribution of dipole strength across current sources within orientation-specific cortical patches of vertices.

Data analyses

Minimum norm estimates of current amplitude waveforms were first obtained for each predetermined ROI, using the automated gyral-based labeling system of Desikan and colleagues [14] implemented in the Freesurfer software [15]. Based on previous reports on the cortical areas that constitute major components of the brain mechanism for reading in children [16–18], the following ROIs were examined (in both hemispheres): superior (STG) and middle temporal gyri (MTG), supramarginal gyrus (SMG), angular gyrus (ANG), inferior (IFG), rostral middle frontal cortex (rMFG), and fusiform gyrus (FFG). Based on some reports of significant activation in the cuneus (CUN) and posterior cingulate cortex (pCNG) associated with reading in context, activation in two these ROIs was also estimated [19]. For each 4 ms time point, a current estimate measure for each voxel was used to compute the two dependent measures used in the analyses outlined: (1) the average current across all voxels defining each of the ROIs listed above and across all of the 4 ms time points comprising 3 successive 150-ms time bins (50–200, 200–350, and 350–500 ms); and (2) the latency (in ms after stimulus onset) when averaged current reached peak amplitude within the entire recording epoch. This approach aimed at determining if reading group differences in the degree of regional activity were time- and hemisphere-dependent, and identifying ROIs and time bins where activity correlated with measures of reading ability.

Statistical Analyses

Preliminary analyses indicated that group differences (with typical readers showing greater degree of activity) were present as early as between 0–50 ms after stimulus onset (as indicated by a Group main effect, $F[1,42] = 6.95$, $p < .01$). In order to correct for group differences in peristimulus activity, current estimates in all time bins between 50 and 500 ms were adjusted by subtracting the average current during 0–50 ms (to ensure that no stimulus-evoked activity was included) in the corresponding ROI for each participant. The average, adjusted current for each 50 ms time bin and each ROI was then submitted to an ANOVA with Area (9), Hemisphere (2), and Time bin (3) as the within subjects variables, and Group served as the between subjects variable. Significant interactions involving Group (e.g., Time $\times$ Area $\times$ Group) were further evaluated by examining lower-order interactions (e.g., Time $\times$ Group or Hemisphere $\times$ Group) which, if significant (at a Bonferroni-adjusted alpha level

of .006), were explored by testing Group simple main effects at each hemisphere or time bin. All ANOVA results were evaluated using the Huynh-Feldt method as a precaution against inhomogeneity of variance problems.

The second set of analyses consisted of partial correlations between reading measures and peak latency or average current in each ROI and time bin. Age and verbal IQ were entered in these analyses as covariates.

Results

Although groups differed, as expected, on the rate of correct responses to target (semantically incongruous) words, we did not observe floor effects among students with reading difficulties ensuring that all participants maintained adequate recognition and comprehension of the sentences. Response rates were $82 \pm 10\%$ and $71 \pm 14\%$ for the control and experimental groups, respectively ($p < .01$).

The omnibus ANOVA on the degree of activity data revealed a significant Time $\times$ Hemisphere $\times$ ROI $\times$ Group interaction. Three-way ANOVAs performed at each ROI revealed significant interactions involving Group in SMG, controlling for age, $F(1,41) = 10.01$, $p < .003$, $\eta^2 = .18$. The main finding was bilaterally reduced degree of activity for struggling readers in this region between 200 and 500 ms after the onset of each word in the passage. Similar trends in pCNG (more apparent in the left hemisphere, $p < .008$), CUN ($p < .007$), and MTG ($p < .019$) approached significance throughout the epoch. These results are displayed graphically in Fig. 1.

Correlation coefficients were computed between estimates of neurophysiological activity for each latency bin and ROI and each of the three achievement measures. These analyses were performed separately for each group of children and evaluated at $p < .01$. As an additional precaution against potentially spurious, statistically significant correlations, activity in a particular ROI was considered to be associated with achievement only if correlation coefficients were higher with WJ-LWID than with verbal or performance IQ.

Significant positive correlations for typical readers were obtained between WJ-III Letter Word Identification scores and degree of activity in left hemisphere temporo-parietal and ventral occipitotemporal regions (STG, MTG, SMG, and FFG between 50–350 ms). Correlations with spelling ($r < .50$) and WJ-III Word Attack scores ($r < .30$) were generally smaller and failed to reach significance. For the group of struggling readers, none of the correlations were significant ($r < .30$ in all cases).

Each of the MNE estimates of activity listed in the previous paragraph were entered as independent variables in a series of multiple regression analyses (see Table, Supplemental Digital Content 2 which shows the behavioral and demographic profiles of study participants). The dependent variable in each of these analyses was Letter-Word Identification score. Age was always entered in the first step of the analysis, degree of activity measures in the second step, and peak latency measures in the third step of each model. For typical readers degree of activity in left posterior temporal cortices (STG, MTG, STG, and FFG) accounted for 30% of the variance in Letter-Word Identification scores ($R^2 = .30$, $F[4,36] = 4.30$, $p < .006$). Entering verbal IQ in the first step along with age did not affect the overall regression results or the individual beta weights of the remaining independent variables. The prediction models for Word Attack scores were not significant. For the students with reading difficulties prediction models for each of the three achievement measures did not reach significance ($p > .2$ in all cases).

Discussion

Using MEG, we investigated brain activation profiles associated with silent reading of words comprising short passages in a group of struggling readers and a comparable group of typical readers, employing a paradigm that balanced demands for phonological decoding and word recognition between groups. The most pronounced group differences featured underactivation of the temporo-parietal cortex (SMG) bilaterally, in students with reading difficulties relative to non-impaired students. Given that reduced activity in SMG is typically noted in the context of phonological decoding tasks [20], and appears to be affected by the explicit phonological processing demands of the activation task, the present finding most likely reflects impaired engagement of the corresponding circuit in poor readers. In addition, a tendency toward reduced activity in MTG, an area closely linked to lexical/semantic processing [21], was also found here and in the context of a word recognition task [22]. Notably, these recent MEG studies [20, 22] involved larger but overlapping samples which included the participants of the present study, permitting direct comparisons across studies. Failure to identify loci of brain activity that were positively associated with reading performance in RD children [e.g., 20, 22–24] may reflect underdeveloped functional organization of cortical networks to support reading. Another contributing factor may be the restricted range of achievement scores and reduced score variance suppressing the value of correlation coefficients.

We observed two additional sites of underactivation in RD students, namely the CUN and the pCNG. Importantly, both these areas are frequently reported as activation sites regardless of whether the task involves reading or not [e.g., 25], presumably reflecting engagement of circuits responsible for general cognitive functions, such as attention and orientation. This finding is in agreement with the notion that print-independent cognitive functions are linked to normal development of reading comprehension, in addition to word-level reading and language skills. These include language skills (morphosyntactic awareness and vocabulary), working memory, inferential ability and other related executive functions, such as attention control [3]. Based on the present data and lack of previous related findings, we cannot conclude, however, whether these effects reflect a true functional deficit in RD or if they are secondary to a breakdown in print-related cognitive functions and related neural circuits.

Brain-achievement associations may shed some light on the potential role of these regions within the brain circuit normally responsible for reading comprehension (given that significant correlations were restricted to non-impaired readers). In addition to the left SMG and MTG, increased degree of activity in the left STG and FFG in response to words in context was associated with higher word recognition abilities. Importantly, these regional brain-achievement associations were stronger for word reading than for pseudoword reading or general verbal ability tests. The profile of brain-achievement associations is, therefore, consistent with a role of these temporo-parietal and ventral occipito-temporal cortices in lexical/semantic processing of print [22]. Notably, when contrasting activations associated with sentence reading to a simple fixation condition, several additional areas may show significant hemodynamic activity, including ventral occipito-temporal cortex [17].

Conclusion

The similarity between current and previous findings of reduced temporo-parietal activation during processing of words and pseudowords out of context highlights the importance of activity in this cortical region as a hallmark of the functional deficit in reading disability. Furthermore, the positive association between degree of activity in this region and measures of word reading accuracy is generally consistent with the established role of word-level

reading skills for text comprehension. This does not, however, preclude the possibility that the temporo-parietal region is not additionally involved in syntactic processes or even verbal working memory.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

This study was supported by grant P50 HD052117-03 awarded to JMF from the National Institute of Child Health and Human Development (NICHD).

References

1. Gabrieli JD. Dyslexia: a new synergy between education and cognitive neuroscience. *Science*. 2009; 325:280–3. [PubMed: 19608907]
2. Snow, C.; Burns, M.; Griffin, P. Committee on the Prevention of Reading Difficulties in Young Children. National Research Council; 1998.
3. Fletcher, J.; Lyon, G.; Fuchs, L.; Barnes, M. Learning disabilities: From identification to intervention. Guilford Press; New York: 2007.
4. Meyler A, Keller TA, Cherkassky VL, Lee D, Hoeft F, Whitfield-Gabrieli S, et al. Brain activation during sentence comprehension among good and poor readers. *Cerebral Cortex*. 2007; 17:2780–7. [PubMed: 17317678]
5. Schulz E, Maurer U, van der Mark S, Bucher K, Brem S, Martin E, et al. Reading for meaning in dyslexic and young children: distinct neural pathways but common endpoints. *Neuropsychologia*. 2009; 47:2544–57. [PubMed: 19433099]
6. Rimrodt SL, Clements-Stephens AM, Pugh KR, Courtney SM, Gaur P, Pekar JJ, et al. Functional MRI of sentence comprehension in children with dyslexia: beyond word recognition. *Cerebral Cortex*. 2009; 19:402–13. [PubMed: 18515796]
7. Lee D, Newman S. The effect of presentation paradigm on syntactic processing: An Event-Related fMRI study. *Human Brain Mapping*. 2010; 31:65–79. [PubMed: 19554559]
8. Woodcock, R.; McGrew, K.; Mather, N. Woodcock-Johnson III Tests of Achievement. Riverside; Itasca, IL: 2001.
9. Wechsler, D. Wechsler Abbreviated Scale of Intelligence (WASI). The Psychological Corporation; San Antonio, TX: 1999.
10. Achenbach, T. Manual for the Child Behavior Checklist/4–18 & 1991 Profile. University of Vermont, Department of Psychiatry; Burlington, VT: 1991.
11. Swanson, J. School-based assessments and interventions for ADD students. K.C. Publications; Irvine, CA: 1992.
12. Chen W, Faraone S, Biederman J, Tsuang M. Diagnostic accuracy of the Child Behavior Checklist scales for attention-deficit hyperactivity disorder: a receiver-operating characteristic analysis. *Journal of Consulting and Clinical Psychology*. 1994; 62:1017–25. [PubMed: 7806710]
13. Hamalainen MS, Ilmoniemi RJ. Interpreting magnetic fields of the brain: minimum norm estimates. *Medical Biological Engineering and Computing*. 1994; 32:35–42.
14. Desikan RS, Ségonne F, Fischl B, Quinn BT, Dickerson BC, Blacker D, et al. An automated labeling system for subdividing the human cerebral cortex on MRI scans into gyral based regions of interest. *Neuroimage*. 2006; 3:968–80. [PubMed: 16530430]
15. 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]
16. Jobard G, Crivello F, Tzourio-Mazoyer N. Evaluation of the dual route theory of reading: a metaanalysis of 35 neuroimaging studies. *Neuroimage*. 2003; 20:693–712. [PubMed: 14568445]
17. Maisog J, Einbinder E, Flowers D, Turkeltaub P, Eden G. A Meta-analysis of functional neuroimaging studies of dyslexia. *Annals of the N.Y. Academy of Science*. 2008; 1145:237–59.

18. Schlaggar BL, McCandliss BD. Development of neural systems for reading. *Annual Review of Neuroscience*. 2007; 30:475–503.
19. Vigneau M, Beaucousin V, Herve P, Duffau H, Crivello F, Houde O, et al. Meta-analyzing left hemisphere language areas: Phonology, semantics, and sentence processing. *Neuroimage*. 2006; 30:1414–32. [PubMed: 16413796]
20. Simos P, Rezaie R, Fletcher J, Juranek J, Passaro A, Li Z, et al. Functional disruption of the brain mechanism for reading: Effects of comorbidity and task difficulty among children with developmental learning problems. *Neuropsychology*. In press.
21. Booth J, Burman D, Meyer J, Gitelman D, Parrish T, Mesulam M. Modality independence of word comprehension. *Human Brain Mapping*. 2002; 16:251–61. [PubMed: 12112766]
22. Rezaie R, Simos PG, Fletcher JM, Juranek J, Cirino P, Li Z, et al. The timing and strength of regional brain activation associated with word recognition in children with reading difficulties. *Frontiers in Behavioral Neuroscience*. 2011; 5:1–12. [PubMed: 21267359]
23. Hoeft F, Meyler A, Hernandez A, Juel C, Taylor-Hill H, Martindale JL, et al. Functional and morphometric brain dissociation between dyslexia and reading ability. *Proceedings of the National Academy of Science (USA)*. 2007; 104:4234–39.
24. Pernet C, Anderson J, Paulesu E, Demonet JF. When all hypotheses are right: A multifocal account of dyslexia. *Human Brain Mapping*. 2009; 30:2278–92. [PubMed: 19235876]
25. Gates L, Yoon M. Distinct and shared cortical regions of the human brain activated by pictorial depictions versus verbal descriptions: an fMRI study. *Neuroimage*. 2005; 24:473–86. [PubMed: 15627589]

Fig. 1.

Time course of neurophysiological activity associated with reading words in text in the supramarginal gyrus (SMG) where significant group differences were found. Non-significant trends ($p < .007$) in the same direction (with typical readers displayed greater degree of activity) were also noted in the cuneus (bilaterally) and in the left posterior cingulate gyrus.