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Effective brain connectivity in children with reading difficulties during phonological processing

Fan Cao [a], Tali Bitan [a,b], James R. Booth [a,c,*]

[a] Department of Communication Sciences and Disorders, Northwestern University, 2240 Campus Drive, Evanston, IL 60208, USA
[b] Department of Communication Sciences and Disorders, Haifa University, Haifa, Israel
[c] Department of Radiology, Evanston Northwestern Healthcare, Evanston, IL, USA

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Abstract

Using Dynamic Causal Modeling (DCM) and functional magnetic resonance imaging (fMRI), we examined effective connectivity between three left hemisphere brain regions (inferior frontal gyrus, inferior parietal lobule, fusiform gyrus) and bilateral medial frontal gyrus in 12 children with reading difficulties (M age = 12.4, range: 8.11–14.10) and 12 control children (M age = 12.3, range: 8.9–14.11) during rhyming judgments to visually presented words. More difficult conflicting trials either had similar orthography but different phonology (e.g. pint-mint) or similar phonology but different orthography (e.g. jazz-has). Easier non-conflicting trials had similar orthography and phonology (e.g. dime-lime) or different orthography and phonology (e.g. staff-gain). The modulatory effect from left fusiform gyrus to left inferior parietal lobule was stronger in controls than in children with reading difficulties only for conflicting trials. Modulatory effects from left fusiform gyrus and left inferior parietal lobule to left inferior frontal gyrus were stronger for conflicting trials than for non-conflicting trials only in control children but not in children with reading difficulties. Modulatory effects from left inferior frontal gyrus to inferior parietal lobule, from medial frontal gyrus to left inferior parietal lobule, and from left inferior parietal lobule to medial frontal gyrus were positively correlated with reading skill only in control children. These findings suggest that children with reading difficulties have deficits in integrating orthography and phonology utilizing left inferior parietal lobule, and in engaging phonological rehearsal/segmentation utilizing left inferior frontal gyrus possibly through the indirect pathway connecting posterior to anterior language processing regions, especially when the orthographic and phonological information is conflicting.

Keywords: Functional magnetic resonance imaging (fMRI); Dynamic Causal Modeling (DCM); Reading difficulties; Orthography; Phonology

1. Introduction

Converging behavioral evidence suggests that a central problem in children with reading difficulties is a deficit in phonological processing, especially in identifying and manipulating the sound structure of a word (Bruck, 1992; Stanovich & Siegel 1994). Neuroimaging studies show that children with reading difficulties exhibit abnormal activation in left temporo-parietal regions and in left inferior frontal gyrus during reading tasks (Shaywitz et al., 2002). Abnormal activation in left superior temporal gyrus and inferior frontal gyrus could be the underlying neural basis of the deficits that children with reading difficulties have in phonological processing and abnormal activation in left inferior parietal cortex (including inferior parietal lobule and angular gyrus) could be the underlying neural basis of deficits that children with reading difficulties have in mapping between orthographic and phonological representations (Booth et al., 2002).

Most functional neuroimaging studies aim to identify network components that are selectively engaged by cognitive tasks. However, a network could shift from one behavioral goal to another not because of differences in the

* Corresponding author. Address: Department of Communication Sciences and Disorders, Northwestern University, 2240 Campus Drive, Evanston, IL 60208, USA. Fax: +1 847 491 4975.
E-mail address: j-booth@northwestern.edu (J.R. Booth).

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distribution of activations, but because of differences in the interactions among its components (Damasio, 1989; McIntosh, 2000; Mesulam, 1981, 1998). Analyses of effective connectivity (the modulatory influence that one brain region exerts upon another), and its non-directional counterpart known as functional connectivity (based on correlation of brain activation between regions), have, in fact, shown that network components can display task-dependent alterations in their interactions that are independent of amount of activation (Chaminade & Fonlupt, 2003; Homae, Yahata, & Sakai, 2003; Horwitz, Rumsey, & Donohue, 1998; McIntosh et al., 1994; Pugh et al., 2000). Components of distributed networks serve multiple roles including the integration of convergent inputs, the binding of distributed information, the relay of information from one region to another, and the control of neural activity within other network components (Mesulam, 1998).

Although most neuroimaging studies have sought to identify particular brain areas within which activation patterns discriminate controls from those with reading difficulties, a deeper understanding of the neurobiology of reading difficulties may emerge from examining connectivity among multiple brain regions that function cooperatively to process information during reading. Two studies have found that functional connectivity with left angular gyrus is dysfunctional in adults with reading difficulties. Adults with reading difficulties (18–40 years) did not show a correlation of left angular gyrus with left inferior frontal gyrus or with left fusiform gyrus as controls did during single word naming (Horwitz et al., 1998). Another study found that functional connectivity of left angular gyrus with occipital and temporal sites was disrupted during nonword rhyming in dyslexics (16–54 years) (Pugh et al., 2000). The findings of less intense activation and weaker functional connectivity of left inferior parietal cortex in adults with reading difficulties are consistent with reported group differences in brain morphology. Voxel-based morphology studies have found less white matter in left temporo-parietal cortex and less gray matter in left inferior parietal cortex in adults (18–33 years) and children (10–12 years) with reading difficulties (Eckert et al., 2005; Silani et al., 2005). Diffusion tensor imaging studies also found that fractional anisotropy of left temporo-parietal cortex was significantly correlated with reading ability in adults (26–36 years) and children (7–13 years) with good to poor reading, indicating that a reduction of density, myelination and directional coherence may underlie reading problems in adults and children with reading difficulties (Deutsch et al., 2005; Klingberg et al., 2000).

In a previous study, Cao, Bitan, Chou, Burman and Booth (2006) reported that controls showed greater intensity of activation than children with reading difficulties in left inferior frontal gyrus, fusiform gyrus, and inferior parietal lobule during rhyming judgments to conflicting word pairs (e.g. pint-mint, jazz-has) presented in the visual modality, but there were no group differences in intensity of activation for non-conflicting word pairs (e.g. dime-lime, staff-gain) despite group differences in accuracy (Cao et al., 2006). This finding is consistent with behavioral research on children with reading disorder that shows a larger conflict effect in visual and auditory rhyming tasks as compared to controls (McPherson, Ackerman, & Dykman, 1997; Rack, 1985). Rhyming judgment to visually presented words is a relatively complex task that involves decoding orthographic stimuli, phonological rehearsal, phonological segmentation, and making an explicit determination of whether words rhyme. Cao et al. (2006) interpreted abnormal activation in left fusiform gyrus as reflecting an orthographic processing deficit, abnormal activation in left inferior parietal lobule as reflecting a deficit in mapping between orthographic and phonological representations, and abnormal activation in left inferior frontal gyrus as reflecting a deficit in phonological rehearsal/segmentation and/or top-down modulation of posterior processes (Cao et al., 2006). The current study examined whether differences in conflicting as well as non-conflicting trials are associated differences in effective connectivity. We used Dynamic Causal Modeling (DCM) to examine the directional influence that one brain region has on another (Friston, Harrison, & Penny, 2003). DCM is distinguished from alternative approaches by accommodating non-linear and dynamic aspects of neuronal interactions, and by framing the estimation in terms of perturbations that accommodate to experimentally designed inputs (Friston et al., 2003). We chose to use a rhyming task because several previous studies using this task have consistently implicated left inferior frontal gyrus and left temporo-parietal regions in phonological processing (Crosson et al., 1999; Kareken, Lowe, Chen, Lurito, & Mathews, 2000; Lurito, Kareken, Lowe, Chen, & Mathews, 2000; Paulesu et al., 1996; Pugh et al., 1996; Rumsey et al., 1992; Xu et al., 2001). Based on previous neuroimaging work on the rhyming task, our regions of interest (ROIs) included left inferior frontal gyrus, left inferior parietal lobule, left fusiform gyrus and bilateral medial frontal gyrus for the DCM analysis (Bitan et al., 2005; Bitan et al., 2006; Bitan, Burman, et al., 2007). However, based on functional connectivity studies (Horwitz et al., 1998; Pugh et al., 2000), our a priori connections of interest were modulatory effects into and out of left inferior parietal lobule. We expected children with reading difficulties to have disrupted effective connectivity especially for conflicting word pairs.

2. Materials and methods

2.1. Participants

Twelve children with reading difficulties (M age = 12.4, range: 8.11–14.10; 10 males) and 12 age-matched children (M age = 12.3, range: 8.9–14.11; 8 males) participated in this study. One child with reading difficulties and one control were African–American. The other participants were Caucasian. The number of participants in this study is generally accepted as the minimum for a meaningful fMRI