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Functional neuroanatomical evidence for the double-deficit hypothesis of developmental dyslexia

Elizabeth S. Norton [a], Jessica M. Black [b], Leanne M. Stanley [c,d], Hiroko Tanaka [c,e], John D.E. Gabrieli [a,f], Carolyn Sawyer [c,g], Fumiko Hoeft [c,h,i,*]

[a] Department of Brain and Cognitive Sciences and McGovern Institute for Brain Research, Massachusetts Institute of Technology, Cambridge, MA 02139, USA
[b] Graduate School of Social Work, Boston College, Chestnut Hill, MA 02467, USA
[c] Child and Adolescent Psychiatry, Department of Psychiatry, University of California, San Francisco, CA 94143, USA
[d] Pacific Graduate School of Psychology, Palo Alto University, Palo Alto, CA 94304, USA
[e] Department of Neuropsychology, Children's Healthcare of Atlanta, and Emory University School of Medicine, Atlanta, GA 30322, USA
[f] Institute for Medical Engineering & Science, Cambridge, MA 02139, USA
[g] Department of Pediatrics, Duke University School of Medicine, Durham, NC 27710, USA
[h] Haskins Laboratories, New Haven, CT 06511, USA
[i] Department of Neuropsychiatry, Keio University School of Medicine, Tokyo 160, Japan

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ABSTRACT

The double-deficit hypothesis of dyslexia posits that both rapid naming and phonological impairments can cause reading difficulties, and that individuals who have both of these deficits show greater reading impairments compared to those with a single deficit. Despite extensive behavioral research, the brain basis of poor reading with a double-deficit has never been investigated. The goal of the study was to evaluate the double-deficit hypothesis using functional MRI. Activation patterns during a printed word rhyme judgment task in 90 children with a wide range of reading abilities showed dissociation between brain regions that were sensitive to phonological awareness (left inferior frontal and inferior parietal regions) and rapid naming (right cerebellar lobule VI). More specifically, the double-deficit group showed less activation in the fronto-parietal reading network compared to children with only a deficit in phonological awareness, who in turn showed less activation than the typically-reading group. On the other hand, the double-deficit group showed less cerebellar activation compared to children with only a rapid naming deficit, who in turn showed less activation than the typically-reading children. Functional connectivity analyses revealed that bilateral prefrontal regions were key for linking brain regions associated with phonological awareness and rapid naming, with the double-deficit group being the most aberrant in their connectivity. Our study provides the first functional neuroanatomical evidence for the double-deficit hypothesis of developmental dyslexia.

1. Introduction

Reading provides one of the most significant gateways to knowledge (Gabrieli, 2009) and is a critical skill in modern societies. However, dyslexia affects approximately 5–17% of children, making it the most common learning disability (Shaywitz, 1998). Dyslexia is a developmental condition characterized by marked yet unexpected difficulty in learning to read despite sufficient cognitive ability, effort, and opportunity (Shaywitz & Shaywitz, 2005). Dyslexia is typically diagnosed in second or third grade (or later), once children have failed to learn to read as expected; therefore, children may be exposed to repeated academic failure before diagnosis (Fletcher, Lyon, Fuchs, & Barnes, 2006; Shaywitz, Gruen, & Shaywitz, 2007). Children with dyslexia can experience a host of social and emotional problems secondary to reading and associated academic difficulties (Brooks, 2001; Fletcher et al., 2006; Gerber et al., 1990), and both dyslexia and its associated negative outcomes can persist into adulthood (Raskind, Goldberg, Higgins, & Herman, 1999).

Despite the prevalence and severe consequences of dyslexia, its underlying causes are not fully understood. It is widely believed that dyslexia reflects an underlying weakness in phonological processing, specifically phonological awareness (PA; the ability to recognize and manipulate the sound structure of words) (Bradley & Bryant, 1978; Snowling, Goulandris, & Defty, 1996; Wagner & Torgesen, 1987). PA is important for mapping sound-to-letter correspondences for decoding and spelling and is associated with

* Corresponding author at: Child and Adolescent Psychiatry, Department of Psychiatry, University of California, 401 Parnassus Avenue, Box 0984-F, San Francisco, CA 94143, USA. Tel.: +1 650 245 7016; fax: +1 415 476 7163.
E-mail address: fumiko.hoeft@ucsf.edu (F. Hoeft).

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later reading skills such as orthographic awareness and comprehension (Torgesen, Wagner, Rashotte, Burgess, & Hecht, 1997).

Deficits in PA alone do not account for all cases of dyslexia (Lovett, Steinbach, & Frijters, 2000). Rapid automatized naming (RAN) deficits are also evident in a subset of individuals with developmental dyslexia (Ackerman & Dykman, 1993; Badian, 1995; Bowers, Steffy, & Tate, 1988; Katzir, Kim, Wolf, Morris, & Lovett, 2008; Scarborough, 1998). RAN, sometimes referred to as naming speed or rapid naming, is the speed with which one can name a series of visually-presented familiar stimuli such as letters, numbers, colors and objects out loud (Denckla & Rudel, 1976), and reflects the automaticity of processes which are also important for reading (Norton & Wolf, 2012).

The double-deficit hypothesis (Wolf & Bowers, 1999) posits that RAN is an independent core deficit that can cause reading difficulties, in addition to or in the absence of the phonological processing deficits seen in many individuals with developmental dyslexia. According to this theory, impairments in either RAN or PA can cause reading difficulties, and individuals with a "double-deficit" have more severe deficits in reading than those with single deficits (Wolf & Bowers, 1999). Individuals with a RAN deficit may perform in the typical range on untimed tests of word reading accuracy, but they show particular impairment on timed relative to untimed reading measures (Waber, Forbes, Wolff, & Weiler, 2004; Wolf, Bowers & Biddle, 2000).

Some researchers hold that RAN fits under the umbrella of phonological processing skills (Wagner, Torgesen, Laughon, Simmons, & Rashotte, 1993; Wagner & Torgesen, 1987); however, there are several lines of evidence suggesting that RAN and PA deficits are independent (for review see Norton & Wolf, 2012 and Wolf & Bowers, 1999). Correlations between RAN and phonological tasks are modest in both typical readers and individuals with dyslexia, and RAN and PA load onto separate factors in factor analyses (Powell, Stainthorp, Stuart, Garwood, & Quinlan, 2007). Further, a proportion of poor readers demonstrate RAN deficits in the absence of phonological deficits (Lovett, 1987; Wolf et al., 2002).

Wolf and Bowers noted that the double-deficit hypothesis was proposed not to fully explain all reading difficulties, but rather to move the field forward in considering the possible subtypes and multiple etiologies of dyslexia. Many studies have found support for the double-deficit hypothesis in English (Compton, DeFries, & Olson, 2001; King, Giess, & Lombardino, 2007; Lovett et al., 2000; McBride-Chang & Manis, 1996; Miller et al., 2006) as well as in other languages (e.g., Dutch: Boets et al., 2010; Chinese: Ho, Chan, Lee, Tsang, & Luan, 2004; Greek: Papadopoulos, Georgiou, & Kendeou, 2009; and Finnish: Torppa, Georgiou, Salmi, Eklund, & Lyytinen, 2012). A meta-analysis of the literature on the double-deficit hypothesis identified several limitations of past research including problems with inconsistencies regarding the presence of a single deficit in RAN, and the inherent problems in trying to establish the independence of two skills that are positively correlated (Vukovic & Siegel, 2006; see also Schatschneider, Carlson, Francis, Foorman & Fletcher, 2002). This meta-analysis emphasized the importance of further sound research before conclusions can be made about the double-deficit hypothesis, and indeed, better clinical and educational decisions could be made if the relations among phonological processing, RAN, and dyslexia were better understood.

Heretofore the functional neural mechanisms underlying the double-deficit hypothesis have never been explored, perhaps in part because the pathophysiology of dyslexia is still not fully understood. There is, however, increasing evidence to suggest that the reading difficulties experienced by individuals with dyslexia have neurobiological substrates, and that there may be observable differences in the brain basis of phonological vs. RAN deficits. Functional magnetic resonance imaging (fMRI) studies have identified brain regions critical to skilled reading, and differential functioning has been observed in dyslexia in each region (reviewed in Gabrieli 2009, Maisog, Einbinder, Flowers, Turkeltaub & Eden, 2008, and Richlan, Kronbichler & Wimmer, 2009).

The brain's "reading network" is typically described as including three main regions: left hemisphere occipito-temporal, temporo-parietal, and inferior frontal areas. The occipito-temporal region encompasses the visual word form area (VWFA) of the fusiform gyrus, which is believed to support the automatic identification of printed words (Schlaggar & McCandliss, 2007). The temporo-parietal region (including the inferior parietal lobule, or IPL) is involved in phonological storage and retrieval (Vigneau et al., 2006), as well as the integration of orthography and phonology (Newman & Joanisse, 2011). Anomalous function in this brain region would be expected to compromise the phonological and phonological-to-orthographic mapping processes essential for developing successful reading. Decreased functional activation and connectivity in these left posterior brain systems (temporo-parietal and occipito-temporal regions) seems to be related to the pathophysiology of dyslexia rather than to current level of reading ability (Hoeft et al., 2006, 2007; Saygin et al., 2013). The left inferior frontal gyrus (IFG), particularly the pars triangularis (IFGtri) and opercularis (IFGop) aspects of IFG, is important for articulation and naming (Fiez & Petersen, 1998; Gaillard et al., 2001; Gaillard, Balsamo, Ibrahim, Sachs, & Xu, 2003; Shankweiler et al., 2008) and phonological processing (Pugh et al., 2000; Vigneau et al., 2006). Findings regarding the IFG's role in dyslexia have been mixed, showing both hypo- and hyperactivation in poor readers (Brunswick, McCrory, Price, Frith, & Frith, 1999; Georgiewa, 1999; Maisog et al., 2008; Richlan et al., 2009; Richlan, 2012). In contrast to the reduced connectivity among posterior reading regions in dyslexia, connectivity to inferior frontal areas is increased (Finn et al., 2013).

Phonological processing has been repeatedly associated with inferior frontal and temporo-parietal regions of the reading network. The brain basis of naming speed, however, is not yet well understood. Only one published study has asked participants to complete a rapid naming task during fMRI, and found that as compared to rest, silent rapid naming elicited a diffuse and bilateral pattern of activation (Misra, Katzir, Wolf, & Poldrack, 2004). Perhaps in part because of the challenge of adapting RAN tasks to the MRI environment, other studies have examined how RAN skill measured outside the scanner correlates with neuroanatomical (Eckert et al., 2003; He et al., 2013) and neurofunctional patterns (Turkeltaub, Gareau, Flowers, Zeffiro, & Eden, 2003). Although many regions were related to rapid naming in these studies, commonly reported regions across studies included the left IFG and right cerebellar hemisphere. These same regions uniquely differentiate readers who have a RAN deficit from those who do not. In a study that used multivariate analyses to classify brains as belonging to a group with dyslexia or a control group, the best classifiers were IFG pars triangularis and right cerebellum (Eckert et al., 2003); importantly, 94% of the individuals correctly classified as having dyslexia had a RAN deficit. In another study, the most accurate classifier of whether an individual had dyslexia was right cerebellum (Pernet, Poline, Demonet, & Rousselet, 2009).

Though it is not commonly considered part of the "reading network," atypical cerebellar function has been proposed as a primary cause of dyslexia (Nicolson, Fawcett, & Dean, 2001). Meta-analyses of neuroimaging studies of dyslexia reveal that the right cerebellar lobule VI is associated with both structural and functional abnormalities in dyslexia (Linkersdörfer, Lonnemann, Lindberg, Hasselhorn, & Fiebach, 2012). Right cerebellar lobule VI plays a role in motor, linguistic, and working memory processes (Stoodley & Schmahmann, 2009), and has connections to left IPL and IFG, which may support the automaticity required for fluent