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Reading network in dyslexia: Similar, yet different

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ABSTRACT

Dyslexia is a developmental disorder characterized by reading and phonological difficulties, yet important questions remain regarding its underlying neural correlates. In this study, we used partial least squares (PLS), a multivariate analytic technique, to investigate the neural networks used by dyslexics while performing a word-rhyming task. Although the overall reading network was largely similar in dyslexics and typical readers, it did not correlate with behavior in the same way in the two groups. In particular, there was a positive association between reading performance and both right superior temporal gyrus and bilateral insula activation in dyslexic readers but a negative correlation in typical readers. Together with differences in lateralization unique to dyslexics, this suggests that the combination of poor reading performance with high insula activity and atypical laterality is a consistent marker of dyslexia. These findings emphasize the importance of understanding right-hemisphere activation in dyslexia and provide promising directions for the remediation of reading disorders.

1. Introduction

Reading is a complex process: unlike less effortful aspects of language, such as verbal acquisition (Kuhl, 2000), the ability to read needs to be acquired through repetitive and consistent practice. This process draws on phonological awareness, the awareness of the sound structure of words (Høien, Lundberg, Stanovich, & Bjaalid, 1995; Joubert et al., 2004) and on orthographic knowledge, the ability to recognize letter combinations or whole words (Loveall, Channell, Phillips, & Conners, 2013). Both abilities are thought to play an important role in reading acquisition, with the former being a strong predictor of reading fluency (Ziegler & Goswami, 2005).

Functional Magnetic Resonance Imaging (fMRI) studies have repeatedly demonstrated that skilled word reading depends heavily on a left-lateralized cortical network including frontal, temporoparietal and occipitotemporal areas (Cohen & Dehaene, 2004; Pugh, 2006; Richlan, 2012; Rumsey et al., 1997; Turkeltaub, Gareau, Flowers, Zeffiro, & Eden, 2003). The temporoparietal cortex is involved in grapheme-phoneme conversion (Pugh, 2006), while the occipitotemporal (OT) region is important for visual and orthographic encoding (whole word recognition) and includes the visual word-form area (VWFA, Cohen & Dehaene, 2004). The OT region has a strong reciprocal relationship with the left inferior frontal gyrus (IFG; Broca's area), a region associated with articulation and involved in phonological processing (Richlan, 2012). Furthermore, IFG functional activation during a reading task is positively correlated with reading ability (Turkeltaub et al., 2003), further emphasizing its critical role in the development of reading ability. Consistent with these findings, developmental models of reading expertise show that early stages of reading induce bilateral activation (Waldie & Mosley, 2000), subsequently declining to left hemispheric predominance in skilled readers (Shaywitz et al., 2007). Learning to read fluently is also associated with decreasing reliance on right extrastriate and inferotemporal cortices (Turkeltaub et al., 2003).

Some children have great difficulty attaining fluent decoding and, if this persists, may have a specific reading disability (herein called dyslexia). Dyslexia is a persistent and unexplained difficulty in achieving accurate and/or fluent word recognition skills, despite adequate intelligence and opportunity (Lyon, Shaywitz, & Shaywitz, 2003). While many adults who had reading difficulties in childhood are eventually able to read accurately, their reading often remains slow and effortful with persistent spelling and written expression deficits (Habib, 2000).

The primary cognitive deficit in dyslexia can be traced back to deficient phonological coding, which impairs the way that speech sounds are represented, stored and retrieved (Shaywitz & Shaywitz, 2005). Dyslexic children are typically unable to decode written words phonetically, have great difficulty reading nonwords

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but are able to recognize and correctly pronounce familiar words (Castles & Coltheart, 1993). Coltheart (1980) first speculated that this so-called phonological dyslexia might be the developmental form of deep dyslexia. Patients with acquired deep dyslexia are thought to rely on their right hemisphere for reading as a result of left hemisphere damage (typically resulting from left temporal or parietal-occipital lesions). Zaidel and Peters (1981) later proposed that individuals with phonological dyslexia rely on the right hemisphere for reading because of the similarity between their reading errors and the ideographic reading ability of the disconnected right hemisphere.

A disruption in the ability to link graphemes and phonemes in dyslexia has been shown to be related to anatomical (Galaburda & Kemper, 1979; Galaburda, Rosen, & Sherman, 1990; Pernet, Andersson, Paulesu, & Demonet, 2009; Rimrodt, Peterson, Denckla, Kaufmann, & Cutting, 2010; Steinbrink et al., 2008; Temple, 2002) and functional (Helenius, Tarkiainen, Cornelissen, Hansen, & Salmelin, 1991; Shaywitz, Mody, & Shaywitz, 2006; Shaywitz & Shaywitz, 2008) abnormalities. For example, the parietal operculum is less asymmetrical in dyslexics than in controls and the degree of asymmetry is inversely related to phonological task performance (Habib & Demonet, 2000). Adults with dyslexia also show reduced left temporoparietal activity during phonological processing, a pattern opposite of that observed in typical readers (Shaywitz et al., 1998).

Besides weaker activation in the left posterior areas during pseudoword rhyming (Shaywitz et al., 1998) and pseudoword decisions (Waldie, Haigh, Badzakova-Trajkov, Buckley, & Kirk, 2013), individuals with dyslexia also show overactivation in the corresponding areas in the right hemisphere (Waldie et al., 2013), in line with prior research on the neural systems predicting long-term outcomes of dyslexia (Hoeft et al., 2011). That is, Hoeft et al. (2011) found, in their prospective, longitudinal study, that reading improvements in their participants with dyslexia were associated with greater right prefrontal activation during a phonological reading task. Therefore, right-hemisphere activation also appears to be diagnostic of impaired reading performance, in contrast with the traditional focus on left hemisphere activation in the study of reading ability.

Current research trends reflect this new direction in the study of dyslexia. For example, a recent meta-analysis pointed out that right hemisphere activation is largely inconsistent across studies (Richlan, Kronbichler, & Wimmer, 2009), thus highlighting the need to better understand how activity in this area and subregions is associated with reading impairment. As noted, dominant theories have consistently demonstrated that dyslexia develops from deficient phonological coding (Pennington, Van Orden, Smith, Green, & Haith, 1990), which entails how sounds are encoded and retrieved. Although phonological coding is typically thought to be a left lateralized process, with skilled readers showing strong left laterality when processing speech sounds, empirical evidence suggests that individuals with dyslexia recruit a more bilateral neural network to perform the same type of tasks (Shaywitz et al., 1998). This is consistent with structural (Rimrodt et al., 2010; Saygin et al., 2013) and functional (Richlan et al., 2010; Shaywitz & Shaywitz, 2008; Shaywitz et al., 2002) differences between individuals with dyslexia and typical readers, the former group showing less asymmetrical patterns than the latter. The precise underpinnings of the increased right hemisphere activation in dyslexia have yet to be identified, however, given that the interest bilateral studies have sparked is only recent.

The current study was designed to refine our understanding of the asymmetrical neural activation typical in dyslexia, by assessing the relationship between neural activation, both within and outside of the traditional reading areas, and reading performance, either in the presence (dyslexia, comorbid) or absence (dyscalculia, control) of a reading disability. Specifically, we used partial least squares (PLS; Krishnan, Williams, McIntosh, & Abdi, 2011; McIntosh & Lobaugh, 2004), to investigate two independent questions. First, we assessed the similarities and differences between normal readers and individuals with reading difficulties in regards to the regions activated in response to a rhyming task. We predicted that, as shown by others (Hoeft et al., 2006), both groups would activate a set of regions largely restricted to the left hemisphere. In addition, we predicted that group differences would emerge showing the reading difficulty group to have reduced activity in certain regions of the left hemisphere (e.g. McCrory, Mechelli, Frith, & Price, 2004; Paulesu et al., 2001; Shaywitz et al., 2002), as well as increased activity in right hemisphere regions (Waldie et al., 2013).

In addition to investigating group similarities and differences in regions activated by a rhyming task, we assessed whether the relationship between reading ability and BOLD activity differed between the two groups. Here, we predicted that regions within left-hemisphere regions associated with the rhyming task would correlate with reading performance in the control group, but not the reading difficulty group. This is motivated by previous research showing that activity in—and task-related functional connectivity between—left hemisphere regions is linearly related to reading ability in normal readers, but not reading difficulty groups (Hampson et al., 2006; Hoeft et al., 2007; van der Mark et al., 2011). We also predicted that BOLD signal in regions outside the left-lateralized "reading network" would correlate with reading performance in the reading difficulty group (but not the normal reading group). Besides refining theoretical models of reading disorders, identifying patterns of neural activation that correlate with reading performance may also provide an avenue for the development of evidence-based interventions.

2. Methods

2.1. Subjects

Subjects were recruited as part of a larger study, the Auckland Comorbidity Study (Wilson et al., 2015), which included 85 adults, selected from an initial 127 volunteers. From this pool of 85 participants, n = 47 were selected for the current study. All participants with dyslexia reported a history of reading difficulties dating back to primary school, as well as current difficulties. Initial screening included a detailed clinical history, the administration of the Wechsler Abbreviated Scale of Intelligence (WASI), standardized tests of reading, spelling and mathematics (Woodcock Johnson Word ID and Word Attack, and the Wide Range Achievement Test spelling and mathematics), and screening for ADHD using the ASRS (Adult Self Report Scale; ASRS). A second clinical interview was performed to diagnose any participants presenting with high ASRS scores, who were screened out of the current fMRI study.

In the current study, almost all participants (n = 45) were included based on a cutoff criterion; for dyslexia, this was at least one score ≤25th percentile on the three reading and spelling tests (WJ Word ID and Word Attack, and WRAT spelling), as well as another score ≤50th percentile on the same tests. A further two participants were included based on a cutoff + discrepancy criterion (≤35th percentile on one reading/spelling test, and ≥1.5 SD between FSIQ and the average of all the reading/spelling tests). Exclusion criteria for the current study were neurological disorder (except mild depression or anxiety), history of major head injury or non-standard schooling, English as a second language, vision or hearing impairment, Full Scale Intelligence Quotient (FSIQ) < 85, clinical diagnosis of ADHD, fMRI contraindications, or left handedness. The final sample of n = 47 included 11 dyslexics, 11 dyscal-