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The relationship between phonological and auditory processing and brain organization in beginning readers

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ABSTRACT

We employed brain–behavior analyses to explore the relationship between performance on tasks measuring phonological awareness, pseudoword decoding, and rapid auditory processing (all predictors of reading (dis)ability) and brain organization for print and speech in beginning readers. For print-related activation, we observed a shared set of skill-correlated regions, including left hemisphere temporoparietal and occipitotemporal sites, as well as inferior frontal, visual, visual attention, and subcortical components. For speech-related activation, shared variance among reading skill measures was most prominently correlated with activation in left hemisphere inferior frontal gyrus and precuneus. Implications for brain-based models of literacy acquisition are discussed.

1. Introduction

Reading disability (RD) is a brain-based difficulty in acquiring fluent reading skills, typically associated with phonological deficits, which affects significant numbers of children (Lyon, Shaywitz, & Shaywitz, 2003). Depending, in part, on definitional criteria applied (i.e., achievement, discrepancy, or Response to Intervention) prevalence estimates for RD vary from 5% to 20% (Fletcher, Lyon, Fuchs, & Barnes, 2007; Katusic, Colligan, Barbaresi, Schaid, & Jacobsen, 2001; Shaywitz & Shaywitz, 2003). Definitional questions and related decisions about cut-offs for diagnosis are further complicated by evidence from epidemiological population-based studies that have suggested that RD symptomology reflects normally-distributed behavioral (Jorm, Share, Maclean, & Matthews, 1986; Shaywitz, Escobar, Shaywitz, Fletcher, & Makuch, 1992; Stevenson, 1988) and genetic (Plomin & Kovas, 2005) variation, and thus might be more accurately viewed as a dimensional, rather than a discrete, developmental disorder (Fletcher, 2009). The current study, which seeks to gain new insights into the neurobiology of RD, adopts the dimensional perspective and, with a large cohort of beginning readers (ranging from impaired to highly skilled), examines the relationship between variation on behavioral measures of reading-relevant skills and brain activation for print and speech. To motivate the specific tasks chosen here, we begin by considering findings from behavioral research on reading acquisition and on those cognitive skills that are most associated with variable outcomes in reading acquisition.

2. Behavioral research on typical and atypical reading development

The overwhelming majority of children with RD have pronounced problems in utilizing phonological structures of language and with phonological awareness (PA) in particular (Ball & Blachman, 1991; Vellutino, Fletcher, Snowling, & Scanlon, 2004). PA refers to the metalinguistic understanding that spoken words are made up of smaller units such as syllables and phonemes (Liberman, Shankweiler, Fischer, & Carter, 1974). For pre-literate children and beginning readers, individual differences in PA ability

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(often measured by tasks that examine phoneme deletion or blending skills) are strongly predictive of word reading outcomes over the first few years of schooling (Ball & Blachman, 1991; Foorman, Francis, Fletcher, Schatschneider, & Mehta, 1998; Johnson, Pennington, Lee, & Boada, 2009). Moreover, research indicates that the training of PA skills for high-risk pre-school children can have beneficial effects on subsequent reading trajectories (Byrne et al., 2008; Foorman et al., 1998; Torgesen, Morgan, & Davis, 1992). Findings of this type have been taken to suggest a causal relationship between PA and reading acquisition (Byrne et al., 2008), although it should be noted that PA is also influenced by reading skills during the first few years of reading instruction, which implies a complex reciprocal relationship between PA and reading (Castles & Coltheart, 2004).

The canonical view of how PA comes to impact the development of visual word recognition skills is that it instills in the learner a sensitivity to component features of spoken words, which creates the metacognitive foundation necessary for learning to associate visual representations (graphemes) with the phonemes they represent. The process of learning these relations has been referred to as mastering the alphabetic principle (Liberman & Shankweiler, 1985; Liberman et al., 1974). Deficits in PA and the consequent failure to master the alphabetic principle impede the development of efficient grapheme-to-phoneme decoding routines. These decoding skills are typically assessed by pseudoword reading tests. Pseudoword reading performance is highly correlated with PA and, like PA, is also strongly predictive of word reading outcomes in developing readers (Torgesen, Wagner, & Rashotte, 1999; Torgesen, Wagner, Rashotte, & Rose et al., 1999; Vellutino et al., 2004). These results all suggest that initial phonological processing deficits restrict the development of high quality lexical representations for print, where lexical quality depends upon adequate integration and binding of orthographic with phonological and semantic features (Harm & Seidenberg, 1999; Perfetti & Hart, 2001). Thus, PA and pseudoword decoding are key skills in reading acquisition, and the current study includes measures of these skills in order to uncover key brain–behavior relationships that exist across the continuum of early reading ability.

In seeking to uncover the cause(s) of PA deficits, many investigators have focused on those neurocognitive systems that encode phonological representations (Elbro, 1996; Fowler, 1991; Goswami & Ziegler, 2006) on the assumption that these deficits are specific to this component of language. Others, motivated by the idea that phonological processing deficits might be reducible to abnormalities in basic sensory or sensorimotor processing, have used tasks that measure visual motion processing deficits (Demb, Boynton, Best, & Heeger, 1998; Stein & Walsh, 1997), or auditory processing deficits, at both shorter (Tallal, 1980; Ahissar and Hochstein, 2004) and longer (Goswami, Fosker, Huss, Mead, & Szűcs, 2010) time scales; differences between typically developing (TD) and RD readers have been reported for each of these tasks (although some researchers argue that auditory and visual deficits may be present only in subsets of RD children; cf., Ramus, White, & Frith, 2006). Sperling, Lu, Manis, & Seidenberg (2005) and Sperling, Lu, Manis and Seidenberg (2006) have argued that observed deficits in performance on visual or auditory sensory tasks might arise from attentional mechanisms that impact signal–noise discrimination, resulting in what are termed "noise exclusion" deficits (see Ziegler, Pech-Georgel, George, & Lorenzi (2009) for a similar proposal). At present, the question of whether phonological deficits are language specific or not is still a topic of some debate (Castles, McLean, & McArthur, 2010; Ramus et al., 2006; Snowling & Hulme, 2012). The current study employed exemplars of both language and non-language predictor tasks that have been linked to RD (see below for details) to map out important brain–behavior relations in beginning readers.

3. Brain research on typical and atypical reading development

Much of what is known about systems-level neurobiological differences that discriminate typically from atypically developing readers has come from neuroimaging studies of older children or adults who have either mastered, or failed to master, basic word reading skills (see Pugh et al. (2010) for a review). Functional neuroimaging studies have consistently shown differences between TD and RD readers at those left hemisphere (LH) regions that compose a distributed circuitry for word reading (Brunswick, McCrory, Price, Frith, & Frith, 1999; Meyler et al., 2007; Pugh, Mencl, Jenner et al., 2000; Rumsey et al., 1997; Salmelin, Service, Kiesila, Uutela, & Salonen, 1996; Shaywitz et al., 1998, 2002; Temple et al., 2003). The most common finding is that RD readers tend to under-activate LH posterior areas, especially temporoparietal (TP) and occipitotemporal (OT) networks. This disruption is also evinced as reduced functional connectivity among these regions (Hampson, Olson, Leung, Skudlarski, & Gore, 2004; Horwitz, Rumsey, & Donohue, 1998; Pugh, Mencl, Shaywitz et al., 2000). In addition, RD readers often, but do not always, show evidence of two apparently compensatory responses to their LH posterior dysfunction: an increased functional role for right hemisphere (RH) posterior regions (Sarkari et al., 2002; Shaywitz et al., 1998; Simos et al., 2002) and increased bi-hemispheric frontal lobe activation (Brunswick et al., 1999; Shaywitz et al., 1998; 2002).

Structural neuroimaging studies have identified coarse-grained anatomic differences, such as reduced grey matter volumes in RD, at those regions with reported functional anomalies, including TP (Brambati et al., 2004; Brown & O'Regan, 2001) and OT (Kronbichler et al., 2008; Silani et al., 2005). Diffusion tensor imaging studies also indicate that individuals with RD have anomalous white matter tracts connecting LH reading-relevant cortical networks, possibly reflecting reduced myelination in RD (Beaulieu et al., 2005; Klingberg et al., 2000; Niogi & McCandliss, 2006).

Although extant findings with older children or adults reveal a strong association between reading abilities and the structural and functional integrity of LH posterior cortical systems (especially TP and OT) that support word reading, only a few studies to date have examined these relationships in emergent readers. In one such study, Raschle, Chang, & Gaab (2011) used structural imaging methods and identified reduced gray matter volume at both TP and OT regions in high-risk kindergarten pre-readers; because these anatomical differences pre-date reading experience the authors suggest that neurobiological anomalies may be causally related to later reading difficulties rather than a result of them. Functional activation differences at TP and OT sites have also been observed in low and high-risk kindergarten children (Specht et al., 2009). In a longitudinal study of children (from 7 to 12 years of age at onset) of varying reading levels, Ben-Shachar, Dougherty, Deutsch, and Wandell (2011) report that a region at the left OT sulcus develops increasing specialization for words over the first few years of reading instruction. Moreover, a recent study by Blau et al. (2010) examining high-risk beginning readers (age 6) who were undergoing a training program that reinforced grapheme-to-phoneme mapping skills showed that activation of the left OT depended on these trained skills (see Brem et al. (2010) for similar findings). In another recent study Yamada et al. (2011) examined print processing during a one-back task for letters versus false font stimuli in typically developing and high-risk kindergarten children at the beginning and middle of the school year. High-risk children, relative to typically developing children, showed reduced LH