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Emergence of the neural network for reading in five-year-old beginning readers of different levels of pre-literacy abilities: An fMRI study☆

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A B S T R A C T

The present study traced the emergence of the neural circuits for reading in five-year-old children of diverse pre-literacy ability. In the fall and winter of kindergarten, children performed a one-back task with letter versus false font stimuli during fMRI scanning. At the start of kindergarten, children with on-track pre-literacy skills (OT) recruited bilateral temporo-parietal regions for the letter > false font comparison. In contrast, children at-risk for reading difficulty (AR) showed no differential activation in this region. Following 3 months of kindergarten and, for AR children, supplemental reading instruction, OT children showed left-lateralized activation in the temporo-parietal region, whereas AR children showed bilateral activation and recruitment of frontal regions including the anterior cingulate cortex. These data suggest that typical reading development is associated with initial recruitment and subsequent disengagement of right hemisphere homologous regions while atypical reading development may be associated with compensatory recruitment of frontal regions.

Over the past 20 years, a number of neuroimaging studies have examined the nature, development, dysfunction, and remediation of cortical circuits for reading. Studies of proficient, adult readers have identified three left-hemisphere regions that comprise a putative reading network. These include dorsal and ventral posterior regions and one anterior region (Pugh et al., 2000, 2001; Schlaggar and McCandliss, 2007). The posterior dorsal region, located at and around the temporo-parietal junction, including the posterior part of the superior temporal gyrus, supramarginal gyrus, and angular gyrus, has been hypothesized to be recruited for phonological processing (Church et al., 2008; Temple, 2002) and the conversion of orthographical (visual) information to phonological (auditory) form (Pugh et al., 2000, 2001; Shaywitz et al., 1998), which involves integration of multi-modal information (Booth et al., 2002; van Atteveldt et al., 2004). The posterior ventral region, localized in the inferior temporal gyrus and known as the visual word form area, has been postulated to support visual word recognition based on orthographical regularities of a given language (Cohen et al., 2000; McCandliss et al., 2003). Finally, the anterior region, centered in and around the inferior frontal gyrus (Pugh et al., 2000, 2001), has been hypothesized to support articulatory recoding, that is, the conversion of phonological information to motoric information of articulatory organs, during reading (Pugh et al., 2000, 2001).

Studies of adults with dyslexia indicate patterns of atypical activation in the posterior dorsal and anterior regions of the reading network. For example, when performing phonological processing tasks with visually presented words or letters, adults with dyslexia show reduced activation relative to normal readers in the left posterior dorsal region (Brunswick et al., 1999; Paulesu et al., 1996; Rumsey et al., 1992, 1997; Shaywitz et al., 1998). In contrast, recruitment in the homologous region in the right hemisphere has been reported in some studies of adults with dyslexia (Pugh et al., 2000; Rumsey et al., 1999). Furthermore, it has been shown that adults with dyslexia who received a phonologically based intervention increased the recruitment of right as well as left posterior dorsal regions in a phonological manipulation task (Eden et al., 2004). With respect to the anterior region, abnormal activations, both over- (Brunswick et al., 1999; Paulesu et al., 1996; Shaywitz et al., 1998) and underactivation (Paulesu et al., 1996), have been reported in adults with dyslexia performing these and similar tasks. Recruitment of the right posterior dorsal region and over-activation of anterior region has been interpreted as reflecting the use of

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compensatory strategies for phonological processing tasks (Brunswick et al., 1999; Eden et al., 2004).

More recently, research has examined the reading network in beginning readers six years of age and older. In typically developing children, the posterior dorsal region is recruited in letter rhyming (Temple et al., 2001) and implicit word reading (Turkeltaub et al., 2003) tasks, while underactivation of this area is reported in children with developmental dyslexia (Hoeft et al., 2006; Shaywitz et al., 2002; Temple et al., 2003). Using magnetoencephalography (MEG), similar findings are reported in a study with 6-7-year-olds with or without a risk for developing reading problems (Simos et al., 2002). Furthermore, several functional magnetic resonance imaging (fMRI) and MEG studies report increased activation in the posterior dorsal region in children with or at risk for dyslexia after successful reading intervention (Shaywitz et al., 2004; Simos et al., 2005, 2007; Temple et al., 2003). A finding from a cross-sectional developmental study of 6-to 22-year-olds (Turkeltaub et al., 2003) suggests that the posterior dorsal region comes to be recruited earlier than other regions in the reading network. Results in the same study also suggest that the development of reading ability involves progressive disengagement of the right-hemisphere homologues of the reading network.

These previous studies provide evidence on the development of reading circuits in children who have already had at least a year of formal schooling and in many cases several years. However, to date no study has examined children under the age of six years. Yet, this is the age when many children are first exposed to print. Thus, examining the neural circuits for reading in children at the age of first school entry provides an opportunity to examine the *emergence* of reading circuits in pre-reading children. Furthermore, given that children's pre-literacy skills at school entry can predict their reading performance many years later, longitudinal studies of children at this age provides the opportunity to examine possible differences in the neural *trajectory* across the first months of reading instruction in children either on track or at risk for later reading failure. Such data can be useful in discriminating patterns of delay from deviance in the development of neural circuits for reading. In the present study, the recruitment of the reading network was examined at the beginning of kindergarten in five-year-old children either on track for reading development (OT group) or at risk for later reading difficulties (AR group) using fMRI. We further examined the changes in the recruitment of the emerging reading network at the end of the first semester of kindergarten in the same children.

It has been reported that early pre-literacy skills such as letter-name knowledge as well as phonemic awareness are important precursors to and predictors of later literacy development (Byrne and Fielding-Barnsley, 1995; Foulin, 2005; Wagner and Torgesen, 1987). In the current study, these pre-literacy skills of the children were assessed using standardized tests upon entrance to kindergarten. Although these children were too young to be diagnosed for dyslexia, those scoring below 35th percentile were considered at risk for later reading difficulties and eligible for district-supported supplemental reading instruction. Thus, the AR group received daily supplemental reading instruction with the Early Reading Intervention (Kame'enui and Simmons, 2003) from school personnel in addition to the regular kindergarten curriculum.

During fMRI data acquisition, children (and adults) performed a one-back task with letter and false font stimuli. This task allowed us to examine the neural systems supporting letter-name knowledge, which is an important predictor of reading development, in children who were not yet able to engage in word-level reading. We expected encoding and maintenance of visual information to be sufficient for task performance such that the task could be performed equally well whether or not children knew letter names. However, knowing letter names would enable encoding and maintenance of letter (but not false font) stimuli in the phonological, as well as visual, form. Therefore, comparing the activation to letter versus false font stimuli allowed us to examine the emergence of the posterior dorsal system involved in phonological processing during the earliest stage of literacy development. We predicted that the recruitment of this region for letters relative to false fonts would emerge earlier in the OT group, who started kindergarten with more letter-name knowledge, than the AR group. We also examined the involvement of the right hemisphere homologue of the posterior dorsal system in these emerging readers. We asked whether right hemisphere activation is limited to AR children, or whether OT children also recruit the right hemisphere homologue initially. As findings from previous studies suggest (Shaywitz et al., 2002; Turkeltaub et al., 2003), the right hemisphere homologue may be recruited during the early stage of literacy development of OT children but later disengaged so that the pattern of recruitment becomes more mature and specialized as children gain further literacy skills.

Method

Participants

Eighteen children and 13 adults participated in this study. Children attended one of three schools in Eugene, Oregon, and were recruited from a larger behavioral study involving the Early Reading Intervention (Kame'enui and Simmons, 2003) described below. Adults were recruited from the University of Oregon community. Both adults and children were healthy, right-handed, native English speakers with no known neurological disorders including ADHD. Fourteen of the 18 children had usable behavioral and neuroimaging data from both Sessions 1 and 2 and were included in the analysis. (See Table 1 for participant information.)

Of the 14 children, seven were considered to be on track for reading development (OT) and seven were considered to be at (some) risk for later reading difficulties (AR). Children's grouping was based on standard school screening procedures conducted at the beginning of the kindergarten year (initial screening), using the Letter Naming Fluency (LNF) and Initial Sound Fluency (ISF) subtests of the Dynamic Indicators of Basic Early Literacy Skills (DIBELS) (Good et al., 2002). DIBELS is a standardized assessment tool for early (pre-)literacy development. LNF is a timed measure of children's ability to name upper- and lower-case letters presented visually in random order. ISF is a timed measure of phonemic awareness, assessing children's ability to recognize and produce the initial phoneme of auditorily presented words.

Children scoring between the 50-75th percentile were identified as the OT group, and children scoring below the 35th percentile on either subtest were identified as AR group in the current study. Predictive validity coefficients of kindergarten DIBELS subtest scores and first grade reading ability measures (e.g., Test of Word-Reading Efficiency, Woodcock Reading Mastery Test-Revised) have been reported to range from .29 to .46 for ISF and .48 to .73 for LNF (Dynamic Measurement Group, 2008). The two groups had similar gender ratios and did not differ significantly in age, socio-economic status (Hollingshead, 1975), level of maternal education, or Stanford-Binet non-verbal fluid reasoning or verbal knowledge, as shown in Table 1.

All children received the school's regular half-day kindergarten curriculum, which included early literacy instruction. In addition, AR children were given 30 minutes of supplemental reading instruction outside of the regular school day using the Early Reading Intervention (ERI) (Kame'enui and Simmons, 2003), followed by 15 minutes of non-literacy activities, including puzzles and small group activities. The ERI focused on the development of phonological awareness and alphabetic skills.

In-scanner task and procedure

Participants performed a one-back task with letters and letter-like stimuli (false fonts) in the scanner (Fig. 1). The stimuli included 10