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Neural correlates of language and non-language visuospatial processing in adolescents with reading disability

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ABSTRACT

Despite anecdotal evidence of relative visuospatial processing strengths in individuals with reading disability (RD), only a few studies have assessed the presence or the extent of these putative strengths. The current study examined the cognitive and neural bases of visuospatial processing abilities in adolescents with RD relative to typically developing (TD) peers. Using both cognitive tasks and functional magnetic resonance imaging (fMRI) we contrasted printed word recognition with non-language visuospatial processing tasks. Behaviorally, lower reading skill was related to a visuospatial processing advantage (shorter latencies and equivalent accuracy) on a geometric figure processing task, similar to findings shown in two published studies. FMRI analyses revealed key group by task interactions in patterns of cortical and subcortical activation, particularly in frontostriatal networks, and in the distributions of right and left hemisphere activation on the two tasks. The results are discussed in terms of a possible neural tradeoff in visuospatial processing in RD.

Introduction

Reading disability (RD) has been characterized as a brain-based neurodevelopmental disorder associated with a failure to acquire fluent reading skills (e.g., Landi et al., 2013; Vellutino et al., 2004). There is a large body of research indicating that language deficits, particularly at the phonological level, underlie many reading difficulties (Lyon et al., 2003; Shankweiler et al., 1995). Moreover, evidence from studies of the neurobiology of reading supports the foundational role of left hemisphere language networks for the development of fluent reading skills (Diehl et al., 2011; Pugh et al., 2005) with relative anomaly in RD in comparison to typically-developing (TD) readers across these networks (Pugh et al., 2010).

Although much of the previous research on RD has focused on the neurocognitive basis of phonological deficits (Vellutino et al., 2004), there remains interest in the potential contributions of visual processing abilities to reading and its disorders (Demb et al., 1998; Eden et al., 1996; Stein, 2001, 2003; Vidyasagar, 2013). With regard to visual processing and RD, difficulties with some aspects of visuospatial processing have been reported, including: 1) visuospatial attention (Facoetti et al., 2010; Vidyasagar and Pammer, 2010; Vidyasagar, 2013); 2) motion processing, thought to arise from an abnormal magnocellular system (Demb et al., 1998; Eden et al., 1996; Stein, 2001); and 3) perceptual signal-to-noise attentional mechanisms that impact the quality of sensory processing not only for vision, but for auditory processing as well (e.g., Sperling et al., 2004, 2006). While deficits have been the general focus, paradoxically there have been several reports suggesting relative strengths in RD for certain non-language visuospatial processing tasks including configural processing and visuospatial cue learning (Howard et al., 2006; Schneps et al., 2012; von Károlyi, 2001; von Károlyi et al., 2003). If such advantages do indeed exist for some tasks,

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this might be taken to argue against a global visual processing deficit in RD and could reflect a type of tradeoff between reading and other visual processes. At present this issue has received very little attention in neurocognitive studies (but see Gilger et al., 2013; Gilger and Hynd, 2008; Olulade et al., 2012).

Current neurocognitive theories are generally aimed at accounting for patterns of deficits that present in RD children, whether phonological (e.g., Fowler and Swainson, 2004; Goswami and Ziegler, 2006), visual (e.g., Stein, 2001), auditory (Gaab et al., 2007; Goswami et al., 2002), attentional (Facoetti et al., 2010; Ziegler et al., 2009), or involving domain general procedural learning mechanisms (Nicolson and Fawcett, 2007). No current theory, to our knowledge, directly predicts RD processing advantages in any domain, visuospatial or otherwise; though, at a more general level, we note that Geschwind and Galaburda (1987) did propose the existence of a "pathology of superiority," where a predisposition to the neural deficits specific to reading could lead other areas of the brain to compensate for these deficits. Recent neurobiological studies have also suggested that individuals with RD use different neural networks to process visual stimuli (Olulade et al., 2012) and that strengths could be related to compensation for reading difficulties (Gilger et al., 2013). In any event, if relative advantages are found, all current major theories would be challenged to provide an account of these advantages.

Cognitive research on enhanced visuospatial processing in individuals with RD

Anecdotal reports and historical characterizations of RD have long been taken to suggest that some individuals with RD appear to have pronounced strengths in some kinds of visuospatial processing tasks. Prevalence estimates of children who are both gifted and learning disabled vary widely, with some estimates as high as 2–5% of school-age children, although prevalence estimates on these populations are plagued by varying definitions of giftedness and learning disability (Davis and Rimm, 1985; McCallum et al., 2013; Nielson, 2002; Ruben and Reis, 2005). Several groups have asserted that there are higher rates of individuals with RD in professions where certain visuospatial skills are at a premium, such as art, architecture, engineering, and mechanics (Winner et al., 1991; Winner and Casey, 1993; Winner, 2000; Wolff and Lundberg, 2002). More recently, it has been suggested that genetic factors (although poorly understood currently) might undergird tradeoffs in individuals with superior nonverbal IQ and language/reading-based deficits, or "twice-exceptional" individuals (Craggs et al., 2006; Gilger et al., 2013).

Findings across controlled experimental studies that attempted to identify visuospatial processing strengths in the cognitive profiles of individuals with RD have been decidedly mixed (Diehl et al., 2011; Gilger et al., 2013). Thus, some studies looking at non-language visuospatial tasks have reported that individuals with RD have some superior abilities (Bannatyne, 1971; Howard et al., 2006; Rugel, 1974; Swanson, 1984; Schneps et al., 2012; von Károlyi et al., 2003; von Károlyi, 2001), others find comparable abilities (Bacon et al., 2007; Koenig et al., 1991; Rudel and Denckla, 1976; Rugel, 1974; Siegel and Ryan, 1989; Sinatra, 1988; Smith et al., 1977; Winner et al., 2001), while others have suggested diminished skills (Bacon et al., 2007; Bannatyne, 1971; Benton, 1984; Eden et al., 1995; Johnston and Weismer, 1983; Morris et al., 1998; Naidoo, 1972; Rourke, 1985). Even when examined from the point of view of a single common neurocognitive task that has been used on several different samples (mental rotation; Vandenberg and Kuse, 1978), findings for that single test have been inconsistent (e.g., Olulade et al., 2012; Winner et al., 2001). Of course, all of these studies differ in important regards, including the specific tasks/skills studied and the criteria applied in defining RD; as such, direct comparisons are difficult. There are also methodological concerns related to studies that have found processing advantages (Winner et al., 2001). Clearly, more controlled cognitive research is needed to answer these questions, and it has been argued that neuroimaging might yield unique insights into this complex question by directly examining brain pathways for reading and language relative to other visuospatial skills (Gilger and Hynd, 2008).

Recent research on implicit visuospatial learning in individuals with RD has suggested a possible visuospatial processing strength. Howard et al. (2006) found that adults with RD actually showed advantages relative to typically developing (TD) peers on a visuospatial cue learning task but impaired learning on a non-visuospatial sequential serial reaction time (SRT) task. Correlational analyses indicated that performance on cue learning was negatively correlated with reading skills, whereas SRT learning was positively correlated with reading skills (it should be noted that several other studies have also reported deficits on sequence learning tasks (Szmalec et al., 2011; Stoodley et al., 2006)). Thus, while implicit sequence learning, a type of procedural learning thought to be dependent on frontostriatal networks (e.g., Jenkins et al., 1994; Thomas et al., 2004; Willingham et al., 2002) has been shown to be deficient in RD (Howard et al., 2006), implicit learning for configural visuospatial patterns (thought to be medial temporal lobe dependent; Preston and Gabrieli, 2008) is not only spared, but also could be a relative strength in RD (Howard et al., 2006).

Two other studies recently reported that children with RD show relative processing advantages in another non-language visuospatial configural processing task (von Károlyi, 2001; von Károlyi et al., 2003) and these directly motivated the current report. von Károlyi (2001) used stimuli that could potentially be viewed as 3-D (called possible and impossible figures; Carrasco and Seamon, 1996; Schacter et al., 1990). During the task participants needed to quickly determine whether or not a stimulus (see Fig. 1) could exist in a 3-D space (possible, see Fig. 1a) or not (impossible, see Fig. 1b). This task (hereafter referred to as the impossible figures task) requires the ability to see the gestalt of a figure quickly in order to get it to "pop out" of the page in 3-D. von Károlyi (2001) found that RD readers were reliably faster at this task but comparable on accuracy (suggesting that the latency advantage did not simply reflect a speed/accuracy tradeoff). These findings were later replicated by the same authors with a second, independent sample (von Károlyi et al., 2003); given the replication study, we employed the impossible figures tasks in the current neuroimaging report. It is important to note that both studies had small effect sizes, and the TD comparison groups had slightly (but not significantly) higher accuracy scores. Still, given that individuals with RD are often slower at processing tasks (e.g., Wolf et al., 2000), findings that show enhanced speed in RD without an accuracy tradeoff are intriguing.

Why should there be an RD advantage on this type of task? Von Károlyi and colleagues hypothesized that this relative strength might be related to a global configural processing bias, as the ability to recognize possible figures is thought to be related to this process (e.g., Schacter, 1992). Other studies have also reported the presence of a global bias for processing in individuals with RD, meaning that individuals with RD seem to display a bias toward processing the gestalt over an image's parts, although data from these studies indicate that this bias is similar to the one shown by TD peers (Keen and Lovegrove, 2000; Matthews and Martin, 2009); this bias could, in principle, account for latency advantages in the impossible figures task.

Is there a neural signature for reading vs. visuospatial processing tradeoffs?

An extensive literature attests to the claim that language processing is typically left hemisphere (LH) dominant, whereas the right hemisphere (RH) systems plays a relatively heightened role for many aspects of non-language visuospatial processing (e.g., Hellige, 1996; Hellige and Michimata, 1989; Pallier et al., 2011). With respect to brain organization for reading, neuroimaging studies have found that TD readers develop a largely LH organized neurocircuity for print with inferior frontal, temporoparietal and occipitotemporal components (Pugh et al., 2000a, 2000b). Individuals with RD exhibit reduced activation (and functional connectivity) across LH posterior networks (see Richlan