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Visuo–spatial working memory is an important source of domain-general vulnerability in the development of arithmetic cognition

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A B S T R A C T

The study of developmental disorders can provide a unique window into the role of domain-general cognitive abilities and neural systems in typical and atypical development. Mathematical disabilities (MD) are characterized by marked difficulty in mathematical cognition in the presence of preserved intelligence and verbal ability. Although studies of MD have most often focused on the role of core deficits in numerical processing, domain-general cognitive abilities, in particular working memory (WM), have also been implicated. Here we identify specific WM components that are impaired in children with MD and then examine their role in arithmetic problem solving. Compared to typically developing (TD) children, the MD group demonstrated lower arithmetic performance and lower visuo-spatial working memory (VSWM) scores with preserved abilities on the phonological and central executive components of WM. Whole brain analysis revealed that, during arithmetic problem solving, left posterior parietal cortex, bilateral dorsolateral and ventrolateral prefrontal cortex, cingulate gyrus and precuneus, and fusiform gyrus responses were positively correlated with VSWM ability in TD children, but not in the MD group. Additional analyses using *a priori* posterior parietal cortex regions previously implicated in WM tasks, demonstrated a convergent pattern of results during arithmetic problem solving. These results suggest that MD is characterized by a common locus of arithmetic and VSWM deficits at both the cognitive and functional neuroanatomical levels. Unlike TD children, children with MD do not use VSWM resources appropriately during arithmetic problem solving. This work advances our understanding of VSWM as an important domain-general cognitive process in both typical and atypical mathematical skill development.

1. Introduction

Recent research in mathematical cognition has led to theories that emphasize the foundational role of quantity representations on an internalized mental number line (Ansari, 2008; Cohen Kadosh & Walsh, 2009; Feigenson, Dehaene, & Spelke, 2004). The link between quantity and space requires domain-general visuo-spatial processes (De Smedt et al., 2009; Holmes & Adams, 2006; Rasmussen & Bisanz, 2005). The study of developmental disorders can provide a unique window into the role of WM in mathematical cognition, notably by pinpointing the specific source of domain-general vulnerabilities in cognitive abilities such as WM. Mathematical disability (MD) is a specific deficit in number and mathematics ability in the presence of preserved intellectual and verbal ability (Butterworth, Varma, & Laurillard, 2011; Rubinsten & Henik, 2009; von Aster & Shalev, 2007). MD is often described as a domain-specific disability arising from deficits in the representation of numerical information resulting in abnormal basic numerical processing mechanisms (Butterworth et al., 2011; Wilson & Dehaene, 2007). Children with MD show poor performance on a broad range of basic numerical tasks including

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magnitude judgment (Ashkenazi, Rubinsten, & Henik, 2009; Geary, Hamson, & Hoard, 2000; Mussolin et al., 2010; Piazza et al., 2010; Price, Holloway, Rasanen, Vesterinen, & Ansari, 2007) and enumeration (Geary, Bow-Thomas, & Yao, 1992; Geary & Wiley, 1991; Knootz & Berch, 1996; Landerl, Bevan, & Butterworth, 2004; Schleifer & Landerl, 2011). Importantly, they also lag behind their typically developing (TD) peers in basic arithmetic problem solving skills (Geary et al., 1992; Shalev, Auerbach, Manor, & Gross-Tsur, 2000; Shalev, Manor, & Gross-Tsur, 2005).

In addition to these basic number processing deficits, there is growing evidence to suggest that domain-general working memory (WM) deficits also contribute to MD (Geary, Hoard, Byrd-Craven, Nugent, & Numtee, 2007). Critically, despite growing behavioral evidence for the involvement of WM in numerical cognition, the role of specific WM components and their underlying neural basis is poorly understood. It is well known that WM is not unitary; specifically, the multicomponent view of WM proposes a general cognitive model for the storage and manipulation of information that includes a central executive for high level monitoring and control, and a subsidiary phonological loop and visuo-spatial sketchpad for short term storage and maintenance of verbal, and visuo-spatial information, respectively (Baddeley, 1996, 1998; Baddeley, Emslie, Kolodny, & Duncan, 1998; Baddeley & Hitch, 1974; Baddeley & Logie, 1987). Each element of the multicomponent WM model is potentially important for arithmetic problem solving. The visuo-spatial sketchpad is involved in the solution of multi-digit operations (Heathcote, 1994), and its activity is thought to reflect the representation of quantities on a mental number line (Rotzer et al., 2009). The phonological loop helps in the maintenance of intermediate arithmetic results (Trbovich & LeFevre, 2003). The central executive is needed for sequencing complex arithmetical procedures that involve intermediate steps such as carrying and borrowing (Imbo, Vandierendonck, & Vergauwe, 2007).

Previous behavioral studies have used MD to draw links between working memory and mathematical ability, but no consensus has yet emerged for the relative importance of different WM components and their role in normal versus aberrant development of arithmetic cognition. Geary (1990) hypothesized that WM deficits increase the difficulty of early learning instances, leading to a failure to develop long-term memory associations for basic numerical facts (Geary, 1990; Geary et al., 1992). This hypothesis is consistent with behavioral observations that, relative to their TD peers, children with MD have difficulties in retrieval of arithmetic facts, use less mature arithmetic strategies (Geary, 2004) and have deficits in multiple WM components, including verbal WM and visuo-spatial working memory (VSWM) (Swanson & Jerman, 2006).

The relative importance of each WM component and its role in normal versus aberrant development of arithmetic cognition in not well understood. Several studies have focused on the central executive and verbal WM as strong contributors to arithmetic deficits, but these studies have tended to rely on WM measures based on verbal manipulation of numerical information such as counting or backward Digit Recall (Geary et al., 2000; Geary, Hoard, & Hamson, 1999; Landerl et al., 2004; Wu et al., 2008). Other studies that have controlled for this potential confound have not found a reliable link between verbal WM and math ability. Instead, researchers have found comparable performance on verbal WM tasks, such as word span, between MD and TD groups (Hitch & McAuley, 1991; Passolunghi & Siegel, 2001, 2004; Siegel & Ryan, 1989). This has led some researchers to suggest that participants with MD have a number-specific verbal WM deficit (Siegel & Ryan, 1989). In contrast, Swanson & Jerman (2006) found that VSWM deficit was the only factor that differentiated MD children from children with reading difficulties. Consistent with this view, Rotzer et al. (2009) found that children with MD (age range 9–11, mean = 10.4) had lower scores on a Corsi Block Tapping test (a standard measure of VSWM ability) than TD children. This study also found that children with MD had lower activity levels in the right inferior frontal gyrus, right intraparietal sulcus (IPS), and right insula during a VSWM task. Moreover, right IPS activity was positively correlated with VSWM ability. However, VSWM was not evaluated in the context of arithmetic problem solving. Importantly, there have been no studies directly examining the link between VSWM and brain activity during arithmetic processing in either TD children or children with MD despite the large potential elucidating this link could have on our theoretical understanding of the role of VSWM in arithmetic and numerical cognition.

Here we examine the specific role of VSWM in arithmetic problem solving. We use standardized measures of WM to first examine whether VSWM is a specific locus of deficits in MD children who are otherwise well-matched on cognitive abilities to a group of typically developing (TD) peers. We then contrast the role of VSWM on brain responses during arithmetic processing in both groups of children, allowing us to examine fundamental questions about the specific role of VSWM in normal function while at the same time investigating how WM deficits impact arithmetic problem solving deficits in children with MD. We build upon a previous study in which we examined deficits in brain activation and multivariate representations underlying arithmetic problem solving in 2nd and 3rd graders (ages 7–9) with MD who were matched on age, sex, IQ and reading ability to TD controls (Ashkenazi, Rosenberg-Lee, Tenison, & Menon, 2012). We reported earlier that TD children showed strong modulation of univariate and multivariate brain response in parietal and prefrontal cortex with increasing arithmetic complexity. In contrast, MDs demonstrated weak modulation of brain response in the right IPS, superior parietal lobule, supramarginal gyrus (SMG), and bilateral dorsolateral prefrontal cortex in relation to arithmetic complexity. In the current study, we examine whether WM has a differential effect on brain responses during arithmetic problem solving in the two groups, and whether these effects are modulated by different levels of arithmetic complexity. Note that in contrast to our previous study (Ashkenazi et al., 2012), the samples in the current study were improved by including 2 left handed TD subjects in order to better match TDs to our difficult-to-obtain MD sample that also included two left handed participants.

The Working Memory Test Battery for Children (WMTB-C) (Pickering & Gathercole, 2001) was used to measure the three different components of WM in the TD and MD groups. The central executive was assessed using two subtests: (1) Counting Recall, and (2) Backward Digit Recall. The phonological loop was tested using Digit Recall and visuo-spatial sketch-pad was tested using Block Recall, a variant of the Corsi Block Test. Mathematical abilities were assessed using two standardized measures (Wechsler, 2001): (1) Numerical Operations, which emphasizes counting and computation, and (2) Mathematical Reasoning, which emphasizes word problems. Our primary focus is the relationship between individual VSWM abilities and arithmetic-related brain activity at the whole brain level, and in theoretically motivated region-of-interests (ROI). For the latter analysis, ROIs were selected based on a previous study that demonstrated correlation between behavioral VSWM abilities and brain activation during a VSWM task (Klingberg, Forssberg, & Westerberg, 2002). This study revealed that, in children and adults VSWM abilities and VSWM task activations were positively correlated with left IPS activity levels (Klingberg et al., 2002).

We predicted that children with TD would show a strong relationship between VSWM ability and brain response in multiple frontal and parietal regions during arithmetic problem solving. Based on previous behavioral studies we predicted that even after matching on IQ and reading, VSWM would be a specific source of