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Fractionating the neural correlates of individual working memory components underlying arithmetic problem solving skills in children

Arron W.S. Metcalfe[a,*], Sarit Ashkenazi[a,b], Miriam Rosenberg-Lee[a], Vinod Menon[a,c,d,e,*]

[a] Department of Psychiatry and Behavioral Sciences, Stanford University School of Medicine, Stanford, CA 94305, USA
[b] School of Education, The Hebrew University of Jerusalem – Mt. Scopus, Jerusalem 91905, Israel
[c] Department of Neurology and Neurological Sciences, Stanford University School of Medicine, Stanford, CA 94305, USA
[d] Program in Neuroscience, Stanford University School of Medicine, Stanford, CA 94305, USA
[e] Symbolic Systems Program, Stanford University School of Medicine, Stanford, CA 94305, USA

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ABSTRACT

Baddeley and Hitch's multi-component working memory (WM) model has played an enduring and influential role in our understanding of cognitive abilities. Very little is known, however, about the neural basis of this multi-component WM model and the differential role each component plays in mediating arithmetic problem solving abilities in children. Here, we investigate the neural basis of the central executive (CE), phonological (PL) and visuo-spatial (VS) components of WM during a demanding mental arithmetic task in 7–9 year old children ($N=74$). The VS component was the strongest predictor of math ability in children and was associated with increased arithmetic complexity-related responses in left dorsolateral and right ventrolateral prefrontal cortices as well as bilateral intra-parietal sulcus and supramarginal gyrus in posterior parietal cortex. Critically, VS, CE and PL abilities were associated with largely distinct patterns of brain response. Overlap between VS and CE components was observed in left supramarginal gyrus and no overlap was observed between VS and PL components. Our findings point to a central role of visuo-spatial WM during arithmetic problem-solving in young grade-school children and highlight the usefulness of the multi-component Baddeley and Hitch WM model in fractionating the neural correlates of arithmetic problem solving during development.

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1. Introduction

Working memory (WM) is now increasingly considered to be an important factor in the development of mathematical cognition in general (LeFevre et al., 2005; Raghubar et al., 2010) and arithmetic problem solving skills in particular (Geary et al., 2004; Imbo and Vandierendonck, 2008; Raghubar et al., 2010). A long line of research in adults has established that complex arithmetic problem solving tasks require active maintenance and manipulation of task relevant visuo-spatial and phonological information in WM (Hitch, 1978; LeFevre et al., 2005). In contrast, how different components of WM contribute to the development of arithmetic skills is poorly understood. Baddeley and Hitch's multi-component WM model offers a powerful approach for studying this question. This model has played a prominent role in our understanding of the fundamental constituents of general cognitive abilities (Baddeley,

* Corresponding authors at: Department of Psychiatry and Behavioral Sciences, Stanford University School of Medicine, 401 Quarry Road, CA 94305, USA. Tel.: +1 650 736 0128; fax: +1 650 736 7200.
E-mail addresses: arron@stanford.edu, arron.metcalfe@gmail.com (A.W.S. Metcalfe), menon@stanford.edu (V. Menon).

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1986, 1996, 2003, 2012; Baddeley and Hitch, 1974). Only a few behavioral studies have, however, used such models to examine how different components of WM contribute to arithmetic problem solving skills in children (LeFevre et al., 2005; Raghubar et al., 2010). Emerging behavioral data suggest that individual WM components make unique contributions to the development of arithmetic problem solving skills (De Smedt et al., 2009; Meyer et al., 2010; Simmons et al., 2012). Whether individual WM components rely on different brain systems during arithmetic problem solving is currently not known.

Baddeley and Hitch's multicomponent WM model includes a central executive (CE) responsible for high level control, monitoring and task switching, along with subordinate phonological (PL) and visuo-spatial (VS) components for short term storage and maintenance of verbal and visuo-spatial information (Baddeley, 2012). Behavioral studies have suggested that each WM component plays a different role in arithmetic problem solving. The CE is required for the complex arithmetic procedures of carrying and borrowing (Imbo et al., 2007). The phonological loop is used for active maintenance of intermediate results (Trbovich and LeFevre, 2003). And finally, the visuo-spatial sketchpad is involved in the solution of multi digit operations (Heathcote, 1994), single digit subtraction problems (Lee and Kang, 2002), and has been connected to the representation of quantities in the format of an internal mental number line representation (Rotzer et al., 2009). In children specifically, CE predicts performance on single-digit addition tasks in 5–8 year old children (De Smedt et al., 2009; Meyer et al., 2010; Simmons et al., 2012). Geary et al. (2012) found that starting in grade 1, higher CE scores predicted faster transitions from counting (e.g., 6 + 5 = 6 + 1 + 1 + 1 +1 + 1 = 11) to a more sophisticated decomposition strategy (e.g., 6 + 5 = 5 + 5 + 1 = 10 + 1 = 11). Simmons et al. (2012) found a trend for PL ability predicting multiplication performance in 7–8 year olds and other studies have demonstrated a link between PL ability and math performance tests including word problems in grade 2 (De Smedt et al., 2009; Meyer et al., 2010). VS ability has been found to predict magnitude judgment and number writing skills in 5–8 year old children (Simmons et al., 2012), and arithmetic performance in 6–8 year old children (De Smedt et al., 2009; Meyer et al., 2010).

In contrast to behavioral studies, brain imaging studies of arithmetic cognition in children have not directly examined the role of individual WM components. For the most part, the role of WM has been surmised based on greater prefrontal cortex engagement in children (Cantlon et al., 2009; Grabner et al., 2009; Ischebeck et al., 2007; Rivera et al., 2005). Two recent brain imaging studies have indirectly addressed the link between WM abilities and numerical problem solving skills. Dumontheil and Klingberg (2012) found that activity in the intra-parietal sulcus during a visuo-spatial WM task predicted arithmetic performance two years later in a sample of 6–16 year old children and adolescents. Rotzer et al. (2009) found that compared to typically developing controls, children with low math ability had lower VS abilities as well as lower activity levels in the right inferior frontal gyrus, right anterior intra-parietal sulcus, and right insula during a visuo-spatial WM task. While these studies have provided some evidence for the differential influence of WM components in numerical problem solving abilities in children, their precise neural representations remain unknown. Critically, no previous brain imaging studies have simultaneously examined the role of the three WM components in children's problem solving abilities.

Here we use an individual differences approach to fractionate the neural correlates of individual WM components underlying arithmetic problem solving skills in children. Our central goal is to test the hypothesis that the CE, VS and PL play distinct roles in problem solving. To the extent that these core components of WM engage different brain areas our findings would provide novel support for theories which posit that CE, VS and PL encapsulate distinct cognitive processes. The period encompassing ages 7–9 years is a time of significant developmental change in the acquisition of single digit addition skills as evidenced by shifts from unsophisticated to mature strategy use (Siegler et al., 1995; Siegler and Shrager, 1984) and by dynamic shifts in the role of different WM components (De Smedt et al., 2009; Meyer et al., 2010), making it an ideal period for investigating this question. Based on previous behavioral studies in children, we predicted that VS and CE would emerge as the strongest behavioral predictors of basic arithmetic skills. Studies in patients with brain lesions have emphasized dissociations linking the CE to the lateral prefrontal cortex (Baddeley et al., 1997), the PL to the inferior frontal cortex and supramarginal gyrus (Vallar and Papagno, 2002), and the VS to ventral occipito-temporal and dorsal posterior parietal cortex (Della Sala and Logie, 2002). A recent meta-analysis of verbal and visual WM tasks has pointed to a common fronto-parietal network active across different domains, with differential activation of Broca's area for verbal tasks, premotor cortex for object and location tasks, posterior lateral PFC for maintenance of items in WM and anterior lateral PFC for maintaining task set (Rottschy et al., 2012).

Extrapolating from these WM studies, we hypothesized that the CE, PL and VS components would engage distinct brain systems during arithmetic problem solving. In parallel with the hypothesized behavioral results, we further predicted that VS and CE components would strongly modulate brain activity in distinct fronto-parietal regions, while PL effects would be generally weak.

2. Methods

2.1. Participants

Seventy-four participants (40 female, 34 male) were recruited from a wide range of schools in the San Francisco Bay Area using mailings to schools and postings at libraries and community groups. Our theoretical focus on variability in working memory recruitment during complex arithmetic task performance dictated a tightly constrained focus on 7–9 year old participants (M = 7.8 years, SD = 0.7). All participants were right-handed (Oldfield, 1971) and reported no history of psychiatric illness or medication use. All participants completed the Wechsler Abbreviated Scale of Intelligence (Wechsler, 1999) and met the inclusion

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