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Individual differences in cognitive resources and elementary school mathematics achievement: Examining the roles of storage and attention☆

Alana Dulaney [a,*], Marina Vasilyeva [b], Laura O'Dwyer [c]

[a] Program in Applied Developmental and Educational Psychology, Boston College School of Education, 201 Campion Hall, Boston College, Chestnut Hill, MA 02467, USA
[b] Program in Applied Developmental and Educational Psychology, Boston College School of Education, 239 Campion Hall, Boston College, Chestnut Hill, MA 02467, USA
[c] Department of Educational Research, Measurement, and Evaluation, Boston College School of Education, 339 Campion Hall, Boston College, Chestnut Hill, MA 02467, USA

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ABSTRACT

Using data from the NICHD Study of Early Child Care and Youth Development, a longitudinal study of 1,364 children, the present research investigated early cognitive correlates of children's mathematics achievement. Individual differences in mathematics performance prior to kindergarten and growth in achievement across elementary school were modeled as a function of two measures of attention—performance-based and informant-reported—and a measure of short-term memory. At the age of 54 months, children with poor capacities for attention and short-term memory storage had lower mathematics achievement than their peers with larger capacities. These early differences persisted through the fifth grade. Interestingly, the informant-based measure of attention did not predict mathematics achievement or its growth across time. The findings implicate the utility of early performance-based assessments of cognitive resources – storage and attention – in identifying students potentially at-risk for poor mathematical outcomes.

1. Introduction

In carrying out our daily tasks we depend on cognitive resources that allow us to hold and manipulate information in mind in order to reach a goal. For example, tasks as diverse as preparing a dinner or solving a mathematics problem involve processing information, retrieved either from an external source (e.g., a book) or from long-term memory. This, in turn, requires a person to temporarily store relevant information and manipulate it, all while resisting potentially distracting stimuli. Thus, both storage capacity and attentional resources are critical for human behavior and, as reviewed below, they have been shown to play a key role in learning. Yet, a more nuanced understanding of how specific cognitive resources are linked to growth in children's performance is required in order to design tools to identify students at risk for poor academic achievement and to create interventions targeting these students. To this end, the current paper presents the results of a longitudinal investigation that seeks to better understand the relation between children's cognitive resources—storage and attention—assessed prior to school entry and their academic achievement throughout elementary school. We focus specifically on mathematics achievement because of the foundational role early mathematical performance has been shown to play in students' long-term academic outcomes (Duncan et al., 2007) and career aspirations (Mullis, Martin, Foy, & Arora, 2012; National Center for Education Statistics, 2011).

1.1. Storage and attention as working memory resources

The processes of storing information and allocating attention have often been examined within the domain of research on working memory. There are various theoretical accounts of working memory (Baddeley, 2000; Baddeley & Hitch, 1974, 1994; Bayliss, Jarrold, Gunn, & Baddeley, 2003; Engle, Tuholski, Laughlin, & Conway, 1999; Jarrold, Mackett, & Hall, 2014). Whereas the original Baddeley and Hitch (1974) model has been subsequently extended and revised, most scholars agree with the original notion that two of the key resources required for the functioning of working memory are the capacity for temporary storage and controlled attention; these resources work together to enable recalling and manipulating information (Miyake & Shah, 1999). Storage involves mental coding of incoming information, or short-term memory (Baddeley & Hitch, 1974, 1994). While short-term memory requires some attention in order to rehearse stored

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* Corresponding author at: Department of Psychology, University of Chicago, 5848 S University Ave, Chicago, IL 60637, USA. Tel.: +1 773 834 4170.
E-mail addresses: alana.dulaney@bc.edu (A. Dulaney), marina.vasilyea@bc.edu (M. Vasilyeva), laura.odwyer@bc.edu (L. O'Dwyer).

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information (Cowan, 2001), working memory requires a greater level of attention for manipulation of that information.

Multiple studies have documented a relation between working memory and academic performance, both for overall academic achievement and for mathematics achievement in particular (Adams & Hitch, 1997; Alloway & Alloway, 2010; Alloway & Passolunghi, 2011; Andersson, 2007; Bull & Scerif, 2001; De Smedt et al., 2009; Holmes, Adams, & Hamilton, 2008; Lee, Ng, & Ng, 2009). Limitations in working memory have been identified as one of the key cognitive factors (along with domain-specific factors, such as poor underlying numerical representations) linked to general learning disabilities (Alloway, Gathercole, Kirkwood, & Elliot, 2009; Swanson & Ashbaker, 2000; Tillman, Eninger, Forssman, & Bohlin, 2011) and to mathematical learning disabilities (Geary, Hoard, Nugent, & Bailey, 2012; Hitch & McAuley, 1991; McLean & Hitch, 1999; Pickering & Gathercole, 2004; Swanson & Jerman, 2006).

Although there is a large body of evidence indicating a relation between working memory and mathematics performance, researchers have highlighted the importance of understanding the underlying nature of this relation (see Raghubar, Barnes, & Hecht, 2010 for a review). The idea that working memory taps multiple cognitive resources suggests that a deficit in working memory may be due to one or more deficits in these resources. Cowan and Alloway (2009) note that working memory theorists have long been divided in their views on the source of forgetting, debating whether the main source is the control of attention (Engle et al., 1999) or limitations in storage capacity and the rate of storage decay (Baddeley, 1986; Broadbent, 1958; Cowan, 1999; Miller, 1958). Further, there may be differences among individuals in the distribution of cognitive resources (i.e., storage and attention) utilized by the working memory system. For example, some students may have a limited capacity for short-term storage but a strong ability to control attention; the academic difficulties of these students would be driven specifically by this storage limitation, rather than a failure of attention. Conversely, other students might show deficits in working memory performance and academic achievement because of difficulties controlling attention, even if those students have a large capacity for storing information. Achieving greater clarity concerning the distinct contributions of storage and regulatory resources may be instrumental in our ability to design effective interventions that directly target the sources of a child's difficulties.

1.2. Cognitive resources as predictors of later mathematics achievement

A number of studies have examined either attention or short-term memory in relation to children's mathematical achievement. For example, meta-analytic findings have shown that the capacity for attention in preschool and kindergarten predicts mathematical performance later in elementary school (Duncan et al., 2007). Similarly, young children's short-term memory is related to their current and later mathematics achievement (Alloway & Passolunghi, 2011; Andersson, 2010; De Smedt et al., 2009; Purpura & Ganley, 2014; Swanson & Kim, 2007). However, researchers have become increasingly aware of the need to measure both attention and storage components contemporaneously when predicting children's academic performance. This trend is reflected in a series of recent longitudinal investigations of elementary school children's mathematics achievement, which are described below. These studies provide compelling evidence that early working memory could serve as a window into children's mathematics achievement trajectories, by disentangling a number of competing factors. Yet, the findings concerning a specific role of attention are somewhat inconsistent across the studies.

An investigation conducted by Fuchs et al. (2010) with first graders measured attention using teacher ratings on the Strengths and Weaknesses of ADHD-Symptoms and Normal-Behavior (SWAN) scale (Swanson et al., 2004), and measured working memory and numerical knowledge through direct assessment of test performance. The findings showed that attention scores predicted some, but not all of the measures of mathematics performance, after controlling for working memory, which was also a significant predictor. However, in their discussion of these findings, the authors note that their informant-based measure of attention might have been a proxy for academic achievement, as teachers' ratings could have been biased by their knowledge of children's academic performance. Similar results were obtained in a comprehensive longitudinal investigation of growth in children's mathematical ability from kindergarten through grade 5, although the measure of working memory was taken during elementary school (Geary et al., 2012).

In contrast, Swanson (2011) conducted a similar investigation but obtained different results. Growth in children's word problem solving performance was examined from grades 1 through 3, as a function of their working memory, numerical knowledge, phonological processing, and teacher reports of inattentive behavior on the Conners' Teacher Rating Scale-Revised form (Conners, 1997). Working memory predicted growth and grade 3 levels of mathematics performance, but inattentive behavior was not found to be a significant predictor of problem solving performance in grade 3 after accounting for working memory.

To summarize, several existing studies have examined attention separately from working memory measures and have implicated both attention and storage in mathematics performance. Yet, the findings are not entirely consistent, which may be due, in part, to the measures of attention used in these investigations. In particular, a separate measure of attention was based on teacher reports of inattentive behavior. As the investigators have pointed out themselves, the informant-based reports of inattentive behavior may have been a proxy for other variables, such as academic achievement (Purpura & Lonigan, 2009). Performance-based assessment of attention may provide a more accurate measure whereas measures based on informant report might neglect attention deficits in students without behavior problems and thus, may fail to capture the true variability among students (Jaekel, Wolke, & Bartmann, 2013).

Some of these studies have also captured attention via measures of the central executive, which is the component of working memory that is responsible for manipulation of information through controlled attention and inhibition of irrelevant stimuli (Baddeley & Hitch, 1974). The use of instruments testing the central executive component as a measure of attention also presents problems with interpretation, because these instruments typically involve a large storage component in addition to an attention-regulating component, making it hard to ascertain the distinct roles of different cognitive resources (Gathercole & Pickering, 2000; Szmalec, Vandierendonck, & Kemps, 2005). For example, a measure of the central executive commonly used with children is the listening span task (e.g., De Weerdt, Desoete, & Roeyers, 2013; Gathercole & Pickering, 2000; Pickering & Gathercole, 2004; Geary et al., 2012). In this task, children are presented with a series of statements that they must identify as either true or false; at the end of the series, they are asked to recall the last word of each sentence, which clearly requires both storage and attention resources. In order to better understand the distinctive contribution of attention, it would be useful to use tasks with a minimal storage requirement.

Further, in examining children's capacity for storage and attention, it is important to measure them early, preferably even before kindergarten entry. This can help educators identify children who may be at risk for poor mathematics achievement and provide them with additional training and monitoring. Yet, existing studies have primarily examined these cognitive resources in school-aged children, although some have examined either short-term memory, attention, or a composite of executive function in younger children (Clark, Pritchard, & Woodward, 2010; Fuhs, Nesbitt, Farran, & Dong, 2014; Purpura & Ganley, 2014). Moreover, even though several investigations have taken a longitudinal approach, some of them looked at concurrent relations (e.g., Fuchs et al., 2010), and others (e.g., Geary et al., 2012) have used measures of attention and the central executive that were averaged over time. This leaves