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Distinct influences of affective and cognitive factors on children's non-verbal and verbal mathematical abilities

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ABSTRACT

Individual differences in children's math performance have been associated with math anxiety, attention problems, working memory (WM), and reading skills, but the mechanisms by which these factors jointly contribute to children's math achievement are unknown. Here, we use structural equation modeling to characterize the relation between these factors and their influence on non-verbal Numerical Operations (NO) and verbal Math Reasoning (MR) in 330 children (M = 8.34 years). Our findings indicate that WM plays a central role in both non-verbal NO and verbal MR, whereas math anxiety and reading comprehension have unique and more pronounced influences on MR, compared to NO. Our study elucidates how affective and cognitive factors distinctly influence non-verbal and verbal mathematical problem solving.

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1. Introduction

An extensive body of research has investigated the roles of cognitive factors such as working memory, attention, and processing speed, in mathematics achievement. In contrast, studies examining the role of affective factors, such as math anxiety, are relatively few, and the mechanisms by which affective and cognitive factors collectively influence different components of mathematical reasoning are poorly understood. In particular, it has been suggested that the impact of affective factors such as math anxiety on early math learning and achievement are also related to numerous cognitive factors such as attention and working memory (WM; Fuchs, Geary, Fuchs, Compton, & Hamlett, 2015). However, previous studies have predominantly examined the effect of each variable in isolation, and mainly in relation to fluency with numerical operations that place little demand on verbally-based math problem solving. Little is known about how these affective and cognitive factors differentially contribute to individual differences in competence in basic non-verbal and verbal math problem solving skills, the latter of which place a greater load on working memory and attention (Bailey, Watts, Littlefield, & Geary, 2014). This question has added significance in light of the introduction of the Common Core curriculum, which places a greater emphasis on applying mathematical knowledge in real world applications. The cognitive and affective demands for these kinds of applications are likely to be different from those invoked in basic numerical fluency and procedural skills.

The overarching goal of the current study was to investigate the distinct, but interrelated, roles of affective and cognitive factors on two components of mathematical problem solving: basic non-verbal computational skills and verbal problem solving. Our specific aims were to investigate the differential roles of (1) math anxiety and WM, (2) attention and WM, and (3) reading achievement and WM in relation to computational skills and word-based problem solving using theoretically-informed structural equation modeling. Here, we first review relevant literature then highlight the open questions in each case. We then describe our use of statistical models to uncover the interrelations among these factors and their impacts on participants' performance on two standardized measures of mathematical achievement: Wechsler Individual Achieve-

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ment Test, 2nd edition (WIAT-II; Wechsler, 2002) Numerical Operations (NO) for basic non-verbal computational skills and Math Reasoning (MR) for more complex, verbally-based problem solving.

1.1. Aim 1: Differential role of math anxiety and working memory in math achievement

1.1.1. Math anxiety

Math anxiety is defined as a negative emotional reaction to situations involving numerical problem solving (Ashcraft, 2002; Richardson & Suinn, 1972). Previous studies have shown that having stressful emotional and anxious responses to math-related situations and problem solving demands were significantly correlated with disruptions in on-line math performance and math achievement (Ashcraft, 2002; Maloney, Risko, Ansari, & Fugelsang, 2010). Most importantly, these performance decrements could not be attributed to general trait anxiety (Wu, Barth, Amin, Malcarne, & Menon, 2012). Recent studies using standardized and age-appropriate math achievement measures have shown that math anxiety is negatively correlated with math achievement, even at the earliest stages of math learning (Ramirez, Gunderson, Levine, & Beilock, 2013; Wu et al., 2012)

1.1.2. Working memory

As described by Baddeley and Hitch (1974) and Baddeley (1992, 2003), WM is a cognitive system that facilitates the acquisition of new knowledge and general problem solving by maintaining and storing information from recent past experience. In both children and adults, mathematics skills are highly dependent on WM because of the multiple procedures involved with calculations, such as carrying and storing numerical values and intermediate computational results, and remembering task rules (Geary, Hoard, Byrd-Craven, & Catherine DeSoto, 2004; see Raghubar, Barnes, & Hecht, 2010 for a review). In young children, lower math achievement scores were associated with lower WM capacity as compared to children with average math achievement (Friso-Van Den Bos, Van Der Ven, Kroesbergen, & Van Luit, 2013; Mabbott & Bisanz, 2008) .

With respect to math anxiety and WM, studies in young adults have shown that math anxiety interferes with the WM processes that support mathematical computations, thereby resulting in a decrement to performance (Ashcraft & Kirk, 2001; Eysenck & Calvo, 1992). This interaction was clarified in a study by Beilock and Carr (2005) that found a differential impact of pressure on math performance as a function of WM capacity. Unfortunately, the preponderance of research examining math anxiety, WM, and math achievement has relied on samples consisting of young adults, and the limited available research in young children is mixed. Regarding the relation between math anxiety and WM, the only available study from Ramirez et al. (2013) showed that math anxiety had a particularly salient effect on math performance in 1st grade children with high WM capacity.

Taken together, these results suggest a differential influence of math anxiety as a function of math problem complexity (Ashcraft & Krause, 2007) as well as a potential role of WM in mediating the relation between math anxiety and early math achievement. Thus, the first aim of the current study is to investigate the distinct role of math anxiety on early math achievement in the context of other cognitive factors and, to characterize how the mediational effect of WM relates differentially to basic computational skills versus word-based problem solving. We hypothesized that the effect of math anxiety on math performance would be mediated by WM and that the strength of the effects would be different for MR compared to NO.

1.2. Aim 2: Differential role of attention and working memory in math achievement

1.2.1. Attention problems

The most relevant evidence for the role of attention problems in math performance comes from studies on children with behavioral disorders that involve attentional weaknesses such as Attention Deficit/Hyperactivity Disorder (ADHD; Capano, Minden, Chen, Schacher, & Ickowicz, 2008; Wu, Willcutt, Escovar, & Menon, 2014). Attentional problems in children diagnosed with ADHD have been shown to interfere with basic computational processes, such as fact retrieval (Zentall, 1990) as well as with more complex math processes (Raghubar et al., 2009). Several explanations for why attention can impair mathematical performance have been suggested in literature, including (1) a lack of continual focus on and rehearsal of repetitive stimuli, as is necessary when internalizing addition or multiplication facts, and (2) an impaired ability to switch between the various processes required to solve math problems. These preliminary results, although based on studies in clinical populations, suggest that attentional difficulties may also differentially influence performance on basic computational and word-based problems in typically-developing children.

1.2.2. Attention problems and working memory

As previously discussed, studies to date have suggested that both attentional and WM problems can have a detrimental effect on math performance. However, their differential roles relative to one another in basic computational as opposed to word-based problem solving skills are still relatively unclear. Lucangeli and Cabrele (2006) found that children with attention difficulties who have trouble inhibiting irrelevant information are also more likely to have lower WM scores and severe difficulties in arithmetic word problem solving due to their tendency to remember tangential instead of target information. In a small exploratory study, Kercood and Grskovic (2009) found that providing a method of organizing information helped children with ADHD increase their recall of relevant information and improve their performance on tasks of mathematical computations. These findings provide initial evidence that WM may mediate the relation between attention and math achievement in children. Therefore, our second aim was to specifically probe the extent to which WM mediates the influence of attention problems on math achievement, and whether it has a differential impact as a function of type of mathematical achievement. Because MR likely places more demands on attentional and cognitive systems than NO, we hypothesized that the effect of attention would not be completely mediated by WM in MR but would be in NO.

Although math anxiety was previously found to positively correlate with attention problems (Wu et al., 2014), the distinct roles of these two factors on early math achievement are still unclear (Schatz & Rostain, 2006; Wine, 1971). No study to date has explored how math anxiety specifically relates to attentional problems in the context of different components of math achievement in a non-clinical sample. Here, we address this question with an exploratory analysis examining whether math anxiety mediates the relation between attentional difficulties and math achievement by testing a direct path from attentional problems to math achievement.

1.3. Aim 3: Reading achievement, working memory and their differential contribution to different components of math achievement

Previous research has found a consistent correlation between dimensional measures of math achievement and reading performance on standardized tests (Dunn & Markwardt, 1970; Wechsler, 2002), in school settings (Vilenius-Tuohimaa, Aunola,

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