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Spatial skills as a predictor of first grade girls' use of higher level arithmetic strategies☆

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ABSTRACT

Girls are more likely than boys to use counting strategies rather than higher-level mental strategies to solve arithmetic problems. Prior research suggests that dependence on counting strategies may have negative implications for girls' later math achievement. We investigated the relation between first-grade girls' verbal and spatial skills and the strategies they used to solve arithmetic problems. The present findings are consistent with our hypothesis that individual differences in girls' use of higher-level mental strategies are related to differences in their spatial abilities. Spatial skills positively predicted frequency of use of both higher-level mental strategies (retrieval and decomposition), while verbal skills only contributed to the use of decomposition. Furthermore, the rate of use of the *least* sophisticated counting strategy was *negatively* related to spatial skills.

In mathematics, basic skills are necessary for advanced thinking and problem solving. The ability to efficiently and accurately perform basic arithmetic operations is one such fundamental skill. Multiple strategies (e.g., counting, retrieval) can be used to solve arithmetic problems, some of which are more efficient and sophisticated than others. As early as kindergarten, there are individual differences in the frequency with which children use different strategies. These early differences predict later differences in mathematics competence, particularly for girls (Carr, Hettinger Steiner, Kyser, & Biddlecomb, 2008; Fennema, Carpenter, Jacobs, Franke, & Levi, 1998). Thus, it is important to understand some of the cognitive factors that contribute to individual differences in early strategy use. In the present study, we investigated whether young girls' spatial and/or verbal abilities contribute to their use of higher-level, more sophisticated strategies.

1. Arithmetic strategies

Arithmetic problems can be solved using a variety of strategies. Generally, children use one of four strategies to solve arithmetic problems: count-all, count-on, decomposition, and retrieval. The *count-all* strategy involves counting out each addend and then counting the total (e.g., to solve $5+3$, a child would first count to 5, then count to 3, then finally count from 1 to 8). The *count-on* strategy involves counting up from one addend, the value of the second addend (e.g., to solve $5+3$, a child would count 6, 7, 8). *Decomposition* involves decomposing a problem into simpler problems; for example, to solve $5+6$, a child might first add $5+5$ to get 10 and then add one more to arrive at 11. It often involves multiple steps, including remembering to add or subtract back numbers that were added or taken away from the original addends. The last strategy, *retrieval*, involves recalling the solution to an arithmetic problem from memory.

At any given time, children, and even adults, use a mix of these strategies to solve arithmetic problems. For example, on smaller easier problems, children are more likely to use retrieval, while on larger more difficult problems children are more likely to use count-all or count-on (Ashcraft, 1982; Siegler & Jenkins, 1989). Thus, in the same session, an individual might use count-on to solve one problem, retrieve the answer from memory to answer the next problem, and use decomposition to solve another problem. In addition, there are individual differences within children of the same age in terms of the frequency with which they use different strategies. For instance, if two first graders are asked to solve 10 arithmetic problems, one child might solve all 10 of them by using a count-all strategy, whereas the other might solve 5 of the 10 problems using a count-on strategy and the other 5 by retrieving the answer from memory.

Individual differences in the frequency with which young children use different strategies are important because strategy usage is related to later math achievement (e.g., Carr & Alexeev, 2011). Mental strategies,

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such as decomposition and retrieval, are generally considered higher-level strategies than count-all and count-on for a number of reasons. First, relative to counting strategies, decomposition and retrieval are more efficient; problems solved using decomposition and retrieval are solved more quickly than ones using counting strategies (e.g., Ashcraft & Fierman, 1982). Second, decomposition and retrieval draw on memory based mental procedures that depend on prior knowledge of number facts (Ashcraft & Stazyk, 1981; Geary, 2011), and tend to emerge only after substantial practice solving arithmetic problems (Shrager & Siegler, 1998; Siegler & Jenkins, 1989). Finally, children and adults who frequently use decomposition and retrieval to solve arithmetic problems tend to have higher math performance and overall math achievement scores than those who depend on counting strategies (Carr & Alexeev, 2011; Carr et al., 2008; Fennema et al., 1998; Geary, Hoard, Byrd-Craven, & DeSoto, 2004).

2. Girls' arithmetic strategy use

The negative association between counting strategies and mathematics achievement suggests that a persistent preference for using counting strategies over mental strategies may be problematic. Girls, in particular, seem to be at risk for this problem. At every grade between kindergarten and third grade, girls are more likely than boys to solve problems using counting strategies. In contrast, boys are more likely than girls to solve problems mentally—using decomposition or retrieval (Carr & Davis, 2001; Carr & Jessup, 1997; Carr et al., 2008; Fennema et al., 1998; Jordan, Kaplan, Ramineni, & Locuniak, 2008). Girls' preference for counting strategies persists through primary school and on more complex math operations. They also abandon the use of concrete materials for counting out the answers to arithmetic problems more slowly than boys (Carr & Alexeev, 2011). At least through fifth grade, boys continue to use retrieval strategies more frequently than girls on arithmetic problems (Imbo & Vandierendonck, 2007). In sixth grade, boys are more likely than girls to solve complex division problems mentally than with written algorithms (Hickendorff, van Putten, Verhelst, & Heiser, 2010).

This persistent preference for counting strategies may lead girls to have fewer opportunities to practice decomposition and retrieval, resulting in poorer accuracy when executing these mental strategies. In fact, across multiple ages, boys have been found to be more *accurate* than girls at using mental strategies when the task does not allow strategy choice and instead requires the use of mental calculation. Carr and Davis (2001) found that by first grade, boys were already more accurate than girls at using retrieval. Rosselli, Ardila, Matute, and Inozemtseva (2009) found that at 7-to-10 years of age, and again at 13-to-16 years, boys were more accurate than girls when required to solve addition, subtraction, multiplication, division, and fraction problems mentally.

The girls who demonstrate an early preference for mental strategies similar to that of boys, however, have later mathematics performance that is equal to that of boys. For example, Fennema et al. (1998) found that when tested on math performance in third grade, the subset of girls who had previously chosen to use invented strategies (such as decomposition) in second grade, performed just as well as the boys who had used invented strategies in the previous grade. These findings suggest that it is important to investigate individual differences *within* young girls relating to differences in their strategy choices.

In the literature on disadvantaged groups, within-group study has been important for uncovering factors that may help mitigate that disadvantage and to better understand how to promote the achievement of those who demonstrate cognitive disadvantage. In the present study, we have focused in depth on the different types of strategies young girls use to solve arithmetic problems in order to determine what cognitive factors predict for frequency of higher and lower level strategy use within girls.

3. Spatial and verbal processing and arithmetic performance

Two factors that potentially influence children's strategy choices are spatial and verbal skills. In fact, there is strong evidence from behavioral studies as well as from the field of neuroscience that both spatial and verbal processing are involved in generating the solutions to arithmetic problems (e.g., Dehaene, Spelke, Pinel, Stanescu, & Tsivkin, 1999; Geary, Hamson, & Hoard, 2000; Kurdek & Sinclair, 2001; Lachance & Mazzocco, 2006; LeFevre et al., 2010; McLean & Hitch, 1999).

Object-based spatial skill is one type of spatial processing that has been found to relate to mathematics achievement in children. Object-based spatial measures include assessments of spatial visualization skills (such as the Block Design subtest from the WISC-IV; Coates & Lewis, 1984; Wechsler, 2003), and 2-d mental rotation tasks (such as the subtest of the Levine mental transformation task that requires children to match a picture of two halves of a shape rotated in 2-d space to four choices of possible completed figures; Levine, Huttenlocher, Taylor, & Langrock, 1999). (Note that in the present study, both these measures were used as components of the composite measure of spatial ability.) Recently, Levine and her associates (Gunderson, Ramirez, Beilock, & Levine, 2012) found that mental transformation ability predicted the quality of children's number line representations, and that number line representations mediated the relation between these spatial skills and later mathematics achievement. Other object-based spatial tasks shown to relate to children's math achievement include the ability to reproduce geometric designs (Geary & Burlingham-Dubree, 1989) and discriminating between similar shapes (Lachance & Mazzocco, 2006).

A second aspect of spatial processing that has been found to be related to mathematics achievement in children is spatial working memory. Spatial working memory refers to the capacity to maintain and simultaneously process visual–spatial information for short periods of time (Baddeley, 1992; Baddeley & Hitch, 1974). Studies have shown that children with mathematics disabilities perform worse on tasks measuring visual–spatial working memory than typically functioning control children (D'Amico & Guarnera, 2005; Mammarella, Lucangeli, & Cornoldi, 2010; McLean & Hitch, 1999).

Baddeley and Hitch (1974) proposed an influential multi-component model of working memory in which spatial and verbal information is processed through separate systems. Numerous studies have found evidence that these two systems function independently of one another (e.g., Brandimonte, Hitch, & Bishop, 1992). Moreover, neuropsychological and neuroimaging studies have found distinct anatomical loci for the different working memory components (Henson, 2001; Vallar & Pagagno, 2002).

In the research on children from preschool to adolescence, a large number of studies have examined the relation between spatial working memory and arithmetic performance relative to those of verbal working memory skills. These findings indicate that spatial and verbal processing contributes differently over the time course of acquiring arithmetic skills. Spatial working memory seems to be critical for the learning and application of *new mathematical skills* and concepts, whereas verbal working memory seems to be more important *after a skill has been learned* (LeFevre et al., 2010; Raghubar, Barnes, & Hecht, 2010). For example, spatial working memory has been found to be a unique predictor of first grade, but not second grade, mathematics achievement; whereas, verbal working memory has been found to be a unique predictor of second grade, but not first-grade, mathematics achievement (DeSmedt et al., 2009; McKenzie, Bull, & Gray, 2003). Similarly, LeFevre et al. (2010) found that in younger children, measures of spatial working memory predicted mathematical achievement independently of the linguistic or quantitative pathways. In summary, these different types of findings suggest that with young learners, spatial skills will have a stronger influence than verbal skills on *choice of higher-level arithmetic strategies*, as these students are still in the process of acquiring basic arithmetic knowledge.