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Brief report

Children's use of decomposition strategies mediates the visuospatial memory and arithmetic accuracy relation

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This study examined the mediating role of children's use of decomposition strategies in the relation between visuospatial memory (VSM) and arithmetic accuracy. Children (N = 78; Age M = 9.36) completed assessments of VSM, arithmetic strategies, and arithmetic accuracy. Consistent with previous findings, VSM predicted arithmetic accuracy in children. Extending previous findings, the current study showed that the relation between VSM and arithmetic performance was mediated by the frequency of children's use of decomposition strategies. Identifying the role of arithmetic strategies in this relation has implications for increasing the math performance of children with lower VSM.

Statement of contribution

What is already known on this subject?

- The link between children's visuospatial working memory and arithmetic accuracy is well documented.
- Frequency of decomposition strategy use is positively related to children's arithmetic accuracy.
- Children's spatial skill positively predicts the frequency with which they use decomposition.

What does this study add?

- Short-term visuospatial memory (VSM) positively relates to the frequency of children's decomposition use.
- Decomposition use mediates the relation between short-term VSM and arithmetic accuracy.
- Children with limited short-term VSM may struggle to use decomposition, decreasing accuracy.

It is well established that children with better working memory demonstrate higher mathematical achievement than those with poorer working memory (cf., Raghubar, Barnes, & Hecht, 2010). However, efforts to boost math performance by improving working memory have been largely unsuccessful (Melby-Lervåg, Redick, & Hulme, 2016). Given the difficulty of changing children's working memory, a more promising approach might be to identify factors that account for the relation between working memory and mathematics, and that can be improved with training. With regard to arithmetic performance, a likely candidate is children's strategy choice. The use of advanced

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strategies, such as decomposition, is associated with greater accuracy (Carr & Alexeev, 2011; Geary, Hoard, Byrd-Craven, & Desoto, 2004), and the use of these strategies can be increased via instruction (e.g., Powell, Fuchs, Fuchs, Cirino, & Fletcher, 2009). Thus, the goal of this study was to determine whether the relation between working memory and children's accuracy on mental arithmetic problems is mediated by arithmetic strategies. This kind of investigation is not only of practical significance for instruction, but also of theoretical significance, in that it contributes to the understanding of how children's working memory and math performance are related.

Strategies represent an important aspect of arithmetic mastery. Greater use of advanced arithmetic strategies – namely decomposition strategies – is related to higher accuracy on multidigit problems, compared to less-advanced counting strategies (Carr & Alexeev, 2011; Laski *et al.*, 2013; Shrager & Siegler, 1998). Decomposition is a mental strategy that involves transforming a problem into smaller problems with known solutions (e.g., 68 + 27 = [60 + 20] + [8 + 7] = 80 + 15 = 75). Although decomposition is more efficient than counting, it also requires more mental effort, which may deter some children from using it. Children are known to adaptively use a variety of strategies in their calculations and may rely on less efficient strategies, such as counting, if they do not feel capable of effectively implementing a more advanced strategy (Siegler, 1996). Indeed, many children continue to revert to rudimentary counting procedures well into elementary school (Geary *et al.*, 2004).

A child's capacity for holding information in short-term memory – the storage component of working memory (Baddeley & Hitch, 1974; Gathercole, Pickering, Ambridge, & Wearing, 2004) – may contribute to his or her selection of decomposition because it requires maintenance of intermediate solutions and procedures. Visuospatial memory (VSM), in particular, can serve as a mental sketch pad for storing problem information (Heathcote, 1994). Consistent with this idea, children who demonstrate better spatial reasoning – which involves VSM resources (Miyake, Friedman, Rettinger, Shah, & Hegarty, 2001) – use decomposition more frequently than those with poorer spatial reasoning (Laski *et al.*, 2013). Therefore, it is possible that children with higher VSM use decomposition strategies more frequently than those with lower VSM. We tested this hypothesis in this study, focusing on children's use of decomposition strategies when solving multidigit arithmetic problems. Further, based on previous findings, we predicted that greater use of decomposition would be associated with higher arithmetic accuracy. Simultaneously testing these relations in the context of a single study allowed us to explore our primary research question: Whether the frequency with which children use decomposition mediates the relation between VSM and arithmetic accuracy?

Method

Participants

Participants were 78 typically developing children attending public and private elementary schools in the north-eastern United States and who were not receiving any special education services at the time of the study. To capture a wide range of mathematical skill and experience in mentally solving multidigit problems, we recruited children from two grade levels – 47 second graders (22 females; age $M = 8.40$ years, $SD = 0.43$) and 31 fourth graders (15 females; age $M = 10.32$ years, $SD = 0.39$). The curriculum for second graders focused on mastery of addition and subtraction up to 20 and of base-ten place value, as well as mastery of combinations adding up to 10. The fourth-grade curriculum emphasized understanding place value and mastery in multidigit arithmetic, including multiplication and division. Decomposition strategies were included in the curriculum at both grade levels.

Measures and procedure

Each child completed all tasks individually with a trained researcher at a quiet location at school. Children first completed a memory task and an arithmetic task in counterbalanced order, then an arithmetic strategies assessment.

Memory

The memory task, adapted from Trbovich and LeFevre (2003), consisted of 16 trials, half visuospatial and half verbal. Whereas accuracy on visuospatial trials represented our primary predictor variable (VSM), accuracy on verbal trials served a covariate in our analysis. Trial types were mixed and randomized across individuals. On each trial, a stimulus was presented for 4 s, after which the computer screen turned red and remained so for 15 s. Then, children were asked to reproduce the stimuli.

Verbal. Verbal stimuli consisted of audio recordings of five-letter strings. Vowels were excluded, and every consonant was presented at least once across trials, with no repetitions within a string. The use of rhyming consonants (e.g., P, B) was limited to two within a string. On each trial, the goal was to recall aloud the letters in the correct order. Following the coding used by Imbo and LeFevre (2010), children received one point for each letter recalled in correct order, and final scores were calculated as proportion correct (Cronbach's $\alpha = .94$).

Visuospatial. Visuospatial stimuli consisted of three black dots displayed within a white square. Dots were configured within a 6×6 matrix. On each item, no two dots were in the same column/row, and the three dots never formed a straight line. The goal on each trial was to reproduce the dot locations, which the child did by clicking within the square. Each click produced a response dot, and the computer recorded its coordinates. Responses were given one point if any portion of the response dot was within the correct cell of the 6×6 matrix. Final scores were calculated as proportion correct (Cronbach's $\alpha = .88$).

Arithmetic

Two parallel sets of arithmetic problems were administered; the first assessed accuracy and the second assessed strategy selection. Each set comprised eight problems (four addition and four subtraction), in mixed order, randomized across children. Each problem was displayed for 15 s, had a sum <100, and included one double-digit and one single-digit number. Final scores were calculated as proportion correct (Cronbach's $\alpha = .78$).

We assessed strategies separately from accuracy because the child's accuracy could have been affected by their explanation (Crowley & Siegler, 1999). Thus, on eight additional problems, children were asked for a retrospective report of their strategy. Strategies were categorized as counting, decomposition, or other/guess/non-response. A counting code was given if the child's report or overt behaviours (e.g., finger counting, subvocal counting) indicated counting during their calculations. A decomposition code was given if the child described transforming the problem into several other problems. When the child's reported strategy was unclear or was reported as guess, it was coded as 'other'. Seven children reported using a retrieval strategy on one to three trials. Given the rarity of these reports and that use of retrieval on mixed-digit arithmetic is unlikely, these responses were categorized as 'other'. Final scores represented the proportion of problems on which a particular strategy was used.

Results

Accuracy on all tasks was normally distributed, and the mean accuracy was similar across tasks (Table 1). Children used decomposition strategies on 55% of trials, counting strategies on 26%, and guessing/unknown/other strategies on 20%. The pattern of bivariate correlations was the same for both grades. Therefore, we present correlations collapsed across grades in Table 1. VSM was positively correlated with arithmetic accuracy and with frequency of decomposition use, but was uncorrelated with frequency of counting use ($p = .23$). Consistent with previous findings, use of decomposition was positively correlated with arithmetic accuracy.

Mediation analysis

The mediation analysis was conducted using bias-corrected bootstrapping (5,000 samples) through the SPSS macro 'PROCESS' (Preacher & Hayes, 2004), which tests the significance of the mediation effect based on estimation of confidence intervals and is recommended for smaller samples (Preacher & Hayes, 2008). The mediation effect is considered statistically significant if the 95% CI excludes zero (Preacher & Hayes, 2008).

Given similar patterns of correlational findings across grades, we conducted main analyses on the complete sample, using age as a covariate to control for maturation. Further, we used verbal memory as a covariate to ensure that the observed effects are unique to VSM. Regression results (Table 2) supported our hypotheses: VSM predicted the frequency of decomposition, which, in turn, predicted arithmetic accuracy. Finally, decomposition mediated the relation between VSM and arithmetic accuracy, $M = 0.17$, 95% CI (0.04, 0.38) (Figure 1).

Table 1. Zero-order correlations and descriptive statistics

	Correlations				Descriptives		
	1	2	3	4	*M*	*SD*	Min–Max
1. Age					9.11	1.09	7.24–11.01
2. Arithmetic accuracy	.40**				0.61	0.27	0.00–1.00
3. Verbal memory	.33**	.39**			0.59	0.21	0.10–1.00
4. Visual memory	.21**	.24**	.19		0.46	0.14	0.13–0.83
5. Decomposition	.25**	.47**	.18	.30**	0.55	0.41	0.00–1.00

Note. $^{**}p < .001$.

Table 2. Regression coefficients for the mediation model

	Predicting frequency of decomposition					Predicting arithmetic accuracy				
	b	*SE*	*t*	*p*	Effect size *r*	*b*	*SE*	*t*	*p*	Effect size *r*
Constant	−.47	0.38	−1.22	.225	.14	−.24	0.22	−1.09	.28	.12
Age	.07	0.04	1.50	.139	.17	.05	0.03	2.14	.036	.24
Verbal memory	.16	0.23	0.70	.487	.08	.31	0.13	2.49	.015	.27
Visuospatial memory	.71	0.32	2.19	.032	.24	.08	0.19	0.4	.693	.05
Decomposition						.24	0.07	3.58	<.001	.38

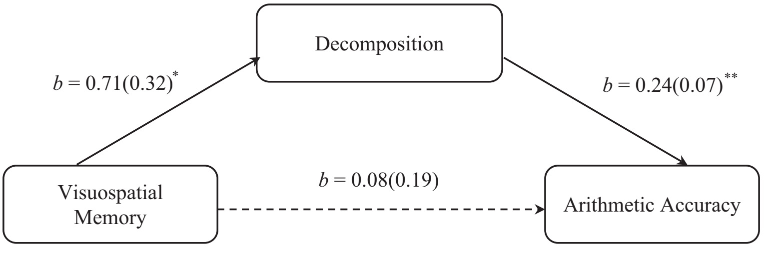

Figure 1. Mediation of the visuospatial memory and arithmetic accuracy relation. Solid lines indicate significant effects; dashed line indicates non-significant effect. *$p < .05$; **$p < .001$.

Discussion

The present study identified a process – use of decomposition strategies – that is more proximally related to arithmetic accuracy and more malleable than VSM and showed that this process mediated the relation between VSM and arithmetic accuracy. Although the causality of this relation cannot be inferred from the correlational design, our finding is consistent with the hypothesis that children with greater VSM are more inclined to use decomposition strategies, which, in turn, facilitates arithmetic accuracy.

It is important to note that both VSM and verbal memory positively correlated with arithmetic accuracy. Indeed, verbal memory is thought to play an important role in arithmetic calculations, as there is evidence that individuals generally represent numbers verbally – as number words in language areas of the brain – when performing mental arithmetic (Dehaene, Spelke, Pinel, Stanescu, & Tsivkin, 1999). However, in contrast to VSM, verbal memory was not correlated with the use of decomposition. This could be because implementation of any arithmetic strategy would require one to maintain some verbal number words in memory, and thus, it is unlikely that decomposition would require more verbal memory resources than other strategies. Decomposition is a unique strategy in that it involves keeping track of a series of calculations and intermediate solutions. The VSM may serve as a mental sketch pad for storing numerals visually and mapping out calculations, just as one would do on a physical piece of paper (Heathcote, 1994). Representing this information visually on a mental sketch pad, rather than verbally through subvocal rehearsal, might reduce the chance of forgetting important problem information while processing multistep calculations.

Another possible explanation for the VSM-decomposition correlation is that implementation of decomposition strategies and the VSM task both required executive working memory resources, as VSM tasks have been found to draw more heavily on executive resources than verbal memory tasks in adults (Salway & Logie, 1995). Although children also draw on executive resources during VSM tasks, the extent of executive involvement is smaller in younger children (age 8) than in older children (age 11; Ang & Lee, 2010). Additionally, it is unknown whether children use executive resources more for VSM tasks than for verbal memory tasks.

A potential limitation of the present study is that, due to the practical time constraints of gathering data in schools, we were precluded from administering a standardized measure of general cognitive ability. However, it is reasonable to assume that age and verbal memory combined, which we included as covariates in our analysis, would account for much of the variance in arithmetic strategies and accuracy that would have otherwise been explained by general cognitive ability.

One avenue for future research would be to determine how to support the use of decomposition strategies in children with poorer VSM. Our finding that children with poorer VSM use decomposition less frequently may be indicative of an underlying difficulty with executing this strategy due to lack of cognitive resources. Rather than (or in addition to) trying to expand children's VSM capacity, another path to boosting arithmetic accuracy may be to provide low-VSM children with external memory supports, such as base-10 counting blocks, when using decomposition (Hiebert & Wearne, 1992) and gradually fade out the use of these external representations to help children develop strategies for keeping track of intermediate solutions and procedures (cf. Fyfe, McNeil, Son, & Goldstone, 2014). A key consideration in future research should be to explore how the effects of such approaches on promoting decomposition and arithmetic accuracy vary for children with different VSM capacities.

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