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Cognitive Predictors of Timed and Untimed Early Arithmetic Performance

Olivia N. Wassing
King's University College, owassing@uwo.ca

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Olivia N. Wassing

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Thesis Advisor: Dr. Marcie Penner-Wilger

Abstract

Children perform worse on timed than untimed arithmetic tasks (e.g., Tsui & Mazzoco, 2006), yet children are evaluated on both types of tasks early in their education. The purpose of present study was to investigate whether the set of cognitive predictors differs for performance on timed versus untimed arithmetic tasks. The cognitive predictors of interest in the current study, visuo-spatial short-term memory (STM), phonological working memory (WM), and phonological awareness, were chosen as they have been previously shown to be important in early arithmetic development. Participants in the study were drawn from the Count Me In project and consisted of 116 children tested in Grade One (62 male, *M* = 82.98 months), 88 of whom also participated in Grade Two (41 male). Results demonstrated that in Grade One there was no difference in the set of cognitive predictors between performance on the timed and untimed arithmetic tasks (i.e., phonological awareness and visuospatial STM; R^2 = .238 and .198 respectively). In Grade Two, however, the predictor sets varied for performance on the timed (i.e., phonological awareness and phonological WM; R^2 = .251) and untimed (i.e., phonological awareness and visuospatial STM; R^2 = .306) arithmetic tasks. Overall, phonological awareness was the dominant predictor for both tasks in Grade One and Grade Two, accounting for 8.1-12.7 % of unique variance in arithmetic performance. Therefore, consideration should be given to including phonological awareness in diagnostic tests to identify children at risk of mathematical difficulties.

Cognitive Predictors of Timed and Untimed Early Arithmetic Performance

Arithmetic is one of the primary academic skills children learn in their early education. Next to learning to read and write, arithmetic skills are a priority of childhood education. Furthermore, the basic arithmetic skills that children are initially taught have been demonstrated to be the building blocks for further math achievement (Geary & Brown, 1991; Geary, Hoard, Nugent, Bailey, 2013; Watts, Duncan, Siegler, Davis-Kean, 2014). For example, proficiency in simple addition is predictive of the development of more complex addition, and the early development of multiplication skills (Geary & Brown, 1991), and arithmetic ability in Senior Kindergarten is strongly related to arithmetic performance at age 15 (Watts et al., 2014). During these early educational years (i.e., Senior Kindergarten to Grade 3), children are introduced to arithmetic in an array of forms. Children need to master the four arithmetic operations (i.e., addition, subtraction, multiplication and division), which can be presented in written or verbal format, and may or may not involve time pressure (e.g., mad minutes). However, until recently, much of the previous research regarding arithmetic achievement typically investigated the predictors of *general* arithmetic achievement (e.g., Alloway et al., 2005; Berg, 2008; Bull, Espy, &Wiebe, 2008; De Smedt et al., 2009; Leather & Henry, 1994; Navarro et al., 2011; Swanson, 2004). A limited number of studies have focused on the complex relations between different forms of arithmetic presentation and underlying cognitive abilities (e.g., Cowan & Powell, 2014; De Smedt, Taylor, Archibald, & Ansari, 2010; Fuchs et al., 2006; Jordan, Whylie, & Mulhern, 2010; LeFevre et al., 2010; Schwenck, Dummert, Endlich, & Schneider, 2015; Sowinski et al., 2015). This research, concerning the predictors of arithmetic achievement, is necessary for the understanding of different arithmetic deficits that children can potentially encounter. Furthermore, it is necessary to help understand why some children perform better on different types of arithmetic tasks compared to others, which can help in the creation of diagnostic tests to identify arithmetic deficits and hopefully lead to effective interventions. For the purpose of the present study, we were specifically interested in whether the relations between cognitive predictors and arithmetic performance differ depending on the presence or absence of time pressures incorporated into the arithmetic tasks.

The effect of time pressure on arithmetic performance, and more general academic performance, has been investigated in previous studies (e.g., Dreyden & Gallagher, 1989; Kellogg, Hopko, & Ashcraft, 1999; Schwartz, Evans, & Agur, 2015; Tsui & Mazzocco, 2006). In general, individuals tend to perform worse on timed tasks versus untimed tasks, perhaps due to a speed-accuracy trade-off, the effort to strike a balance between the demands of speed and accuracy (Bogacz, Wagenmakers, Forstmann, & Nieuwenhuis, 2010). Another explanation that has been considered is anxiety, regarding arithmetic (Tsui & Mazzocco, 2006) and other tests (Schwartz et al., 2015). Ashcraft and Kirk (2001) have suggested that anxiety can act like a secondary task, consuming one's attentional resources potentially used for the test at hand, such as arithmetic. Interestingly, some research has demonstrated that some individuals perform better on timed tasks, compared to others (Jordan & Montani, 1997). Unfortunately, there is little research on this topic that is specific to children in their early education (e.g., Jordan & Montani, 1997; Tsui & Mazzocco, 2006). Further research is needed to address to the questions of why there is a difference between timed and untimed achievement, specifically regarding early education. One possible place to look for answers to these questions is at the cognitive level, which has not been explicitly investigated in the previous research.

Various cognitive abilities have been revealed in previous research to be related to general arithmetic performance (e.g., Berg, 2008; Cowan & Powell, 2008; De Smedt, Taylor, Archibald, & Ansari, 2010; Geary, 2011; LeFevre et al., 2010). Furthermore, it has been revealed that there are potentially different subtypes of mathematic learning disorders, including a semantic/long-term memory subtype, which often co-occurs with language-based disabilities; a procedural/working memory subtype, with an impaired strategy use and problem solving; and a visual-spatial-motor-subtype (Geary, 1993). All three of the subtypes reflect an arithmetical deficit, accompanied by other deficits, due to neuronal damage or a cognitive deficit. Therefore, more research is needed that is focused on cognitive level and what roles it may play in different aspects of arithmetic to further understand the deficits faced by these individuals, as well as how to identify and intervene to improve their learning experience.

For the interests of this present study, three cognitive abilities were utilized in our investigation and include visuo-spatial short-term memory, phonological working memory (i.e., phonological loop) one component of Baddeley and Hitch's (1974) multicomponent working memory model, and phonological awareness. All of the aforementioned cognitive abilities have consistently been demonstrated to play an important role in early arithmetic performance (e.g., Alloway et al., 2005; Geary, 2011; Jordan et al., 2010).

In the present study, the relation of visuo-spatial short-term memory to timed and untimed arithmetic tasks was investigated. However, it is important to note the methodological confusion between visuo-spatial working memory (i.e., visuo-spatial sketchpad) and visuo-spatial short-term memory. In the present study, the forward Corsi Blocks task, was used as a measure of visuo-spatial short-term memory. For the Corsi Blocks task, children witness sequences of increasing length and are then asked to replicate the sequence in the order presented. However, it is important to note, previous research has utilized this task, and similar ones (e.g., Rabbits), to assess visuo-spatial working memory (e.g., Cirino, 2011; LeFevre et al., 2010; Simmons, Singleton, & Horne, 2008; Sowinski et al., 2015). The issue is that visuo-spatial working memory encompasses the capabilities of temporarily maintaining and *manipulating* visuo-spatial information (Baddeley, 2001). Yet, using the forward version of the Corsi Blocks task merely involves the ability of temporarily maintaining, and no manipulation, of visuo-spatial information. To assess visuo-spatial working memory with the Corsi Blocks task one would have to utilize the reverse version, since it involves maintaining and manipulating the information. Therefore, for the purpose of the present study, previous research that utilized the forward Corsi Blocks task as a measure for visuo-spatial working memory will be discussed as visuo-spatial short-term memory.

Previous research indicates visuo-spatial short-term memory offers a unique contribution to early arithmetic performance when problems are presented visually (e.g., Berg, 2008; Cirino, 2011; De Smedt et al., 2009; Geary, 2011; LeFevre et al., 2010; Simmons, Singleton, & Horne, 2008; Simmons, Willis, & Adams, 2012; Soto-Calvo, Simmons, Willis, & Adams, 2015; Szucs, Devine, Soltesz, Nobes, & Gabriel, 2013, 2014). However, visuo-spatial short-term memory is reported to not be related to, or a significant predictor of, arithmetic tasks in some studies (e.g., Passolunghi & Lanfranchi, 2012; Passolunghi, Lanfranchi, Altoe, & Sollazzo, 2015). In contrast, Lefevre et al., (2010) reported that visuo-spatial short-term memory was related to, and predicted unique variability for, six out of seven arithmetic outcomes under investigation, including both timed and untimed arithmetic tasks. Other studies have reported that visuo-spatial short-term memory is a unique predictor of arithmetic fluency tasks for adding small sums (timed tasks; Cirino, 2011; Sowinski et al., 2015). Furthermore, visuo-spatial short-term memory at the beginning of Grade One has been reported as a significant predictor of standardized arithmetic tests administered halfway through Grade One (De Smedt et al., 2009).

Visuo-spatial short-term memory has also been found to be a significant, unique predictor of concurrent general success in arithmetic, even when chronological age and processing speed are controlled for (Berg, 2008). Therefore, it appears that visuo-spatial short-term memory plays an important role in arithmetic performance, specifically regarding visually presented problems. Phonological working memory is a specialized component concerning the maintenance and manipulation of speech-based information, and is one of three components of the multicomponent working memory model (Baddeley, 2001). The role of phonological working memory in arithmetic has been assumed to be the retaining of information in a verbal form during calculations, such as the operands and intermediate sums (DeStefano & LeFevre, 2004; Heathcote, 1994; Trbovich & LeFevre, 2003). Additionally, phonological working memory has generally been demonstrated to play a significant role in early arithmetic (Alloway et al., 2005; De Smedt et al., 2009; Hecht et al., 2001; Mannamaa, Kikas, Peets, & Palu, 2013; Passolunghi & Lanfranchi, 2012; Passolunghi et al., 2015); although, its role depends on the task requirements such as arithmetic problems being presented verbally or as number words, and presented horizontally (DeStefano & LeFevre, 2004). For instance, Passolunghi and Lanfranchi (2012) and Passolunghi et al., (2015) reported that phonological working memory abilities at the beginning of Kindergarten predict performance on a Numerical Competence test, an untimed test, which consists of number words, counting, and general understanding of numbers. Phonological working memory was not predictive of the standardized test of arithmetic achievement, primarily based on spatial abilities such as use of a child's mental number line. In contrast, other studies have found that phonological working memory is a predictor of standardized arithmetic tests (e.g., Alloway et al., 2005; De Smedt et al., 2009). De Smedt et al., (2009), reported that phonological working memory ability at the beginning of Grade One was a significant predictor of a standardized arithmetic achievement test at the beginning of Grade Two.

It is important to note that previous research has demonstrated that the predictive value of phonological working memory is potentially dependent on the child's age or grade (Hecht, Torgesen, Wagner, & Rashotte, 2001). When following children from Grade Two to Grade Five, Hecht et al., (2001) reported that phonological working memory in Grade Two predicted performance in Grade Three and Grade Five regarding mathematic computation, an untimed task. Overall, converging results demonstrate the unique contribution of phonological working memory to early arithmetic.

The final cognitive predictor under investigation is phonological awareness. Phonological awareness is defined as one's awareness of, and access to, the sound structure of oral language (Wagner & Torgesen, 1987). Previous research suggests that phonological awareness is a unique contributor not only to language and reading, but also arithmetic (e.g., Alloway et al., 2005; Cirino, 2011; Hecht et al., 2001; Jordan et al., 2010; Leather & Henry, 1994; LeFevre et al., 2010; Simmons et al., 2008; Soto-Calvo et al., 2015; Sowinski et al., 2015; Schwenck et al., 2015; Szucs et al., 2014). Hecht et al., (2001) investigated the relation between various phonological processing abilities and general arithmetic achievement in elementary school children from second to fifth grade. From examining phonological working memory, rate of access (of phonological information in long-term memory), and phonological awareness, the only unique predictor of growth in arithmetic skills for all the reported time intervals was phonological awareness, over and above the influence of the other phonological skills. However, this study only focused on the relation between phonological awareness, other phonological abilities, and general arithmetic achievement. In contrast, De Smedt, Taylor, Archibald, and

Ansari (2010) investigated the complex relation between phonological awareness and various arithmetic skills involving different operations (i.e., addition, subtraction and multiplication), whether questions were small (i.e., single-digit) or large (i.e., double-digit) in size, and whether there were time pressures incorporated or not. This study revealed that phonological awareness was significantly related to accuracy in arithmetic; specifically to computerized, timed, small problem sizes that involved addition, subtraction, and multiplication. In contrast, phonological awareness was not related to the study's paper-and-pencil arithmetic task that included no time pressures; therefore, De Smedt et al., (2010) suggested that the relation between phonological awareness and arithmetic achievement may be limited to computerized arithmetic with time pressures. Furthermore, the findings were rationalized that phonological awareness takes part in retrieval accuracy, which is displayed in small problems sizes for addition, subtraction, and multiplication (e.g., 3 + 4, 11 x 4; De Smedt et al., 2010). However, there was a lack of variance explained by phonological awareness for large problems of subtraction and addition, so phonological awareness was rationalized to not take part in procedural accuracy, which is displayed in large problem sizes for addition and subtraction (e.g., 21 – 13; De Smedt et al., 2010). Another unique finding from the study revealed that only for multiplication, phonological awareness was related to both small and large size problems. De Smedt et al., (2010) consider this result to support the hypothesis posited by Dehaene, Piazza, Pinel, and Cohen (2003) that multiplication potentially relies on a verbal code, whereas other forms of arithmetic rely on different codes (e.g., quantity code).

Phonological awareness has also been investigated as one (i.e., linguistic pathway) of three pathways to arithmetic performance on seven different outcomes, including timed and untimed tasks, and standardized arithmetic achievement tests (LeFevre et al., 2010).

Interestingly, in comparison to De Smedt et al., (2010), the linguistic pathway (i.e., phonological awareness) was reported to be a unique predictor of all seven outcomes, and was the dominant predictor for six. It appears to be conclusive among the previous research that phonological awareness is a unique predictor of arithmetic performance; however, like the other cognitive predictors, this ability seems to be related to arithmetic in specific, complex ways.

Overall, the research regarding the cognitive predictors of arithmetic performance demonstrates that visuo-spatial short-term memory, phonological working memory, and phonological awareness are related to arithmetic performance. However, little research has been conducted regarding the complex relations between these cognitive abilities and arithmetic performance. The complex role that cognitive abilities can play in arithmetic performance is evident based on studies including De Smedt et al. (2010) that focus on a single cognitive ability and different presentations of arithmetic, or LeFevre et al., (2010) that look at many predictors and various arithmetic outcomes. The purpose of the present study is to investigate the contributory set of cognitive abilities that predict arithmetic performance between tasks with or without time pressures.

Current research regarding the relations between cognitive predictors and arithmetic performance, as well as differences in findings across arithmetic measures/tasks utilized that included time pressures or not, led to the predictions for the present study. First, it was predicted that there would be a difference in the set of cognitive predictors between timed and untimed tasks in arithmetic, both concurrently and longitudinally, as there is a consistent difference in performance on these types of tasks. Second, for timed arithmetic, it was predicted that visuo-spatial short-term memory and phonological awareness would be revealed as significant predictors of timed arithmetic performance concurrently and longitudinally, as demonstrated in previous research (e.g., De Smedt et al., 2010; LeFevre et al., 2010). And third, for untimed arithmetic, it was predicted that visuo-spatial short-term memory and phonological working memory would predict arithmetic performance, based on previous research (e.g., Hecht et al., 2001; LeFevre et al., 2010).

To test the above predictions, data from the Count Me In project in 2005 to 2007 was investigated. Children were tracked from Senior Kindergarten to Grade Two. For the purpose of the present study, the cognitive predictors (i.e., visuo-spatial short-term memory, phonological working memory, and phonological awareness) and arithmetic outcomes (i.e., timed and untimed arithmetic) were examined concurrently in Grade One, and longitudinally with the cognitive predictors from Grade One to the arithmetic outcomes in Grade Two, to further illuminate the relations between cognitive abilities and arithmetic performance.

Methods

Participants

Participants in the study consisted of 116 children tested in Grade One (62 male, M = 82.98 months), 88 of whom also participated in Grade Two (41 male). Participants were drawn from the Count Me In project that took place from 2004 until 2007, and included children from seven schools from three Canadian cities, including Winnipeg, Ottawa, and Peterborough. Each year parental consent was received for all children that participated in the study.

Materials

Corsi Blocks Forward Task. Children completed a computerized measure of visuospatial short-term memory, modeled after the forward version of the Corsi blocks task (α = .777; Berch, Krikorian, & Huha, 1998). In this task, children viewed a frog jumping in a sequence from one lily pad to another and included nine lily pads dispersed on the laptop screen

(Destefano & LeFevre, 2003; α = .699, N = 191). After watching the frog, the children indicated the sequence by pointing. The experimenter then clicked on each location after the child pointed. The length of the sequences began with two lily pads and increased to a maximum of seven, with two sequences for each length. If a child missed both sequences of a given length, the task was terminated. The dependent variable was the maximum sequence length that was correctly completed.

Digit Span Reverse Task. Children completed the Digit Span Reverse, a measure phonological working memory. In this task, children were asked to recall a series of spoken digits, but in the reverse order to which they were presented (α = .84; Orsini et al., 1987). The numbers were presented to the child in a series, starting with a length of two digits. The task terminated when the child incorrectly completed both series of a particular length. For this task, the dependent variable was the maximum sequence length that was completed correctly.

Phoneme Elision. Children completed the Phoneme Elision subtest of the Comprehensive Test of Phonological Processing (CTOPP) that was utilized as a measure of phonological awareness (α = .92; Wagner, Torgesen, & Rashotte, 1999). In this task, children heard a word and then were asked to say the word back to the researcher, but omitting a sound (e.g., brat without the / r /). The dependent variable was the grade standardized scores of the Phoneme Elision.

Timed arithmetic. Children completed an addition fluency task, a timed arithmetic task that was completed on a laptop. The task involved 16 single-digit addition trials, with sums less than 10. Each trial of the task was initiated by the child by pressing the 'GO' button on the screen. The child spoke their answer out loud, and when this occurred the experimenter pressed a key to stop the timer and type in the child's response. The children were instructed to answer the questions as quickly as possible without making many errors. The dependent variable was a composite measure that scaled the response times (i.e., RTs) based on accuracy (refer to Data Analysis).

Untimed arithmetic. Children completed the calculation subtest of the Woodcock Johnson Psycho-Educational Battery-Revised (WJ-R) as a measure of untimed arithmetic achievement (α = .928; Woodcock & Johnson, 1989). This calculation measure involves all four operations (addition, subtraction, multiplication, and division), although most of the questions attempted by the children consisted of addition and subtraction. The task was terminated when six incorrect answers were made, or when the child indicated to the researcher that they did not know how to solve the remaining questions. The dependent variable was the number of problems successfully completed.

Procedure

In May of each school year, children were individually tested by trained research assistants. The testing took place during school hours, so children were taken out for testing during class time and brought to a separate, quiet room in the school. Before testing took place, children were verbally informed about the study and were asked for their assent to take part in the study. Computer and pencil-and-paper tasks were given in two separate sessions for each child. Each session lasted between 15 and 30 minutes (approximately one hour of testing time per year), with sessions extended as necessary. The order of tasks was consistent each year. In the first session, children completed the computer-based tasks including, arithmetic fluency, Corsi, and digit span tasks. During the second session, children completed the pencil-and-paper and other non-screen tasks including the Woodcock Calculation and Phoneme Elision tasks.

After each session the children were verbally debriefed regarding the testing they had just completed and were offered compensation (e.g., a pencil or sticker)

Design

The present study is both a cross-sectional/concurrent (Grade One) and longitudinal (Grade One to Grade Two) study. The study consisted of a within-subjects design since each participant was asked to complete all of the aforementioned tasks. Additionally, all variables of interest were continuous variables. The measures utilized for assessing our predictor variables that were all administered in Grade One included, Corsi Blocks Forward, Digit Span Reverse and Phoneme Elision tasks. The measures used to assess our criterion variables of timed or untimed arithmetic performance were administered in both Grade One and Grade Two and included the Woodcock-Johnson Calculation and Arithmetic Fluency tasks.

Data Analysis

Bivariate correlations between all measures were conducted, as shown in Table 1. . Following the correlational analysis, a composite measure was created for the arithmetic fluency task to scale the response times based on accuracy. To do this, the Inverse Efficiency composite measure was utilized, in which participants' median response times are divided by their proportion of correct responses (Townsend & Ashby, 1983). By doing this, a participant who had poor accuracy would then have an increased response time, while a participant who had perfect accuracy on the arithmetic fluency task their response time would remain unchanged. Lastly, individual multiple regression analyses were conducted for each of the criterion tasks and involved all of the aforementioned predictors. Thus, a total of four multiple regressions were conducted, two for the concurrent analysis and two for the longitudinal analysis

Results

First, a correlational analysis was conducted for all variables under investigation in the study, both concurrently and longitudinally. Bivariate correlation coefficients, along with means and standard deviations for all variables, are reported in Table 1. In Grade One, performance on both the timed and untimed arithmetic tasks were significantly related to phonological awareness, phonological working memory, and visuospatial short-term memory. However, in Grade Two, performance on the timed arithmetic task was related to phonological awareness and phonological working memory, while performance on the untimed arithmetic task was related to phonological awareness and visuo-spatial short-term memory. Interestingly, phonological awareness was significantly related to all of the concurrent and longitudinal arithmetic outcomes.

Concurrent Results (Grade 1)

To determine the set of concurrent cognitive predictors for timed arithmetic performance, a multiple regression analysis was conducted with phonological awareness, phonological working memory, and visuo-spatial short-term memory entered as predictors in a single-step and Grade One arithmetic fluency as the criterion variable. The analysis revealed that phonological awareness, $\beta = -.37$, $t(112) = 4.33$, $p < .001$, and visuospatial short-term memory, $\beta = -.20$, $t(112) = 2.43$, $p = .017$, were significant predictors of arithmetic fluency, whereas phonological working memory was not a significant predictor, $\beta = -.13$, $t(112) = 1.51$, $p = .134$ (refer to Figure 1A). The three predictors accounted for 23.8% of the variance of the arithmetic fluency task, $R^2 = .238$, $F(3,112) = 11.69$, $p < .001$, with phonological awareness accounting for 12.7% and visuospatial short-term memory accounting for 4.0% of unique variance.

To determine the set of concurrent cognitive predictors for untimed arithmetic performance, a multiple regression analysis was conducted with phonological awareness,

Table 1

Correlations between all variables with Means and Standard Deviation, including both Grade One and Grade Two variables

	Predictors			Outcomes			
	PA	VSSTM	PWM	Timed (G1)	Untimed (G1)	Timed (G2)	Untimed (G2)
PA	-	.16	.21*	-.43**	.36**	-.40**	.43**
VSSTM		-	.01	-.26**	.29**	-.17	.37**
PWM			-	-.21*	.18*	-.34**	.19
Timed (G1)				-	-.64**	.65**	-.61**
Untimed (G1)					-	-.53**	.59**
Untimed (G2)						-	-.58**
Untimed (G2)							-
M	10.97	4.13	2.84	4735.49	7.91	2528.70	11.85
SD	2.58	1.11	0.81	2612.78	2.85	1016.23	2.80

Note: Numbers in parenthesis following the outcome variables refer to the Grade the task was administered. For all predictors and tasks from Grade One (G1) the mean and standard deviations reflect concurrent sample (N = 116), while the Grade Two (G2) tasks reflect the longitudinal sample (N = 88).
* p < .05. ** p < .01.

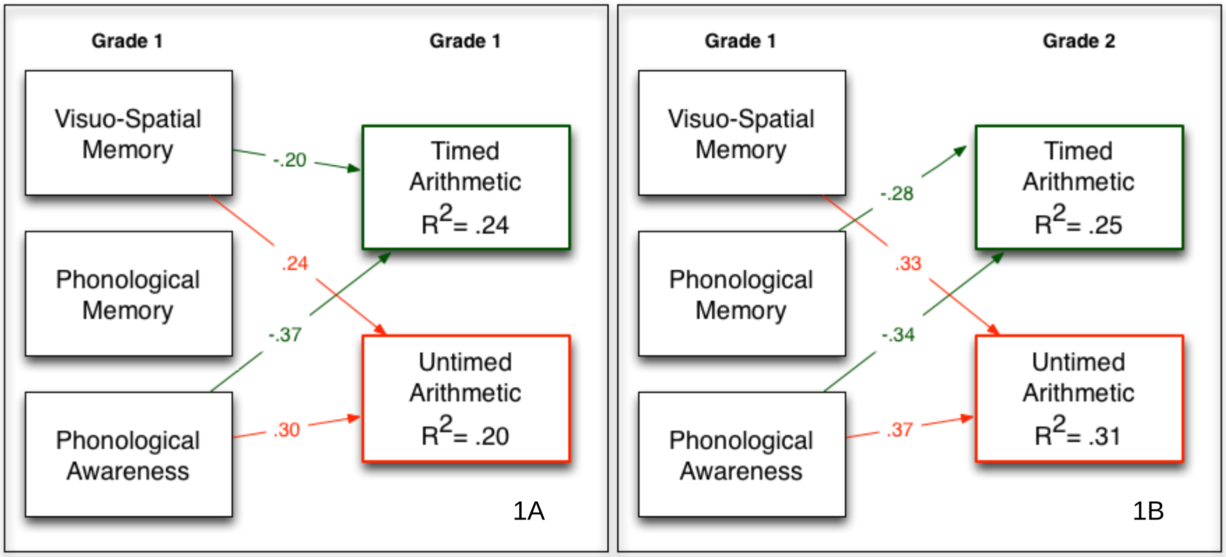

Figure 1A. The significant beta coefficients and corresponding R^2 for Grade One timed and untimed arithmetic tasks. All statistics shown are significant at $p < .05$.

Figure 1B. The significant beta coefficients and corresponding R^2 for Grade Two timed and untimed arithmetic tasks. All statistics shown are significant at $p < .05$.

phonological working memory, and visuo-spatial short-term memory entered as predictors in a single-step and Grade One Woodcock Johnson Calculation as the criterion variable. The analysis revealed that phonological awareness, β = .30, *t*(112) = 3.36, *p* = .001, and visuospatial short-term memory, β = .24, *t*(112) = 2.82, *p* = .006, were significant predictors of children's performance on the Woodcock Johnson Calculation subtest, whereas phonological working memory was not a significant predictor, β = .12, *t*(112) = 1.36, *p* = .176. The three predictors accounted for 19.8% of the variance of the Woodcock Johnson Calculation subtest, $R^2 = .198$, $F(3, 112) = 9.19$, $p < .001$, with phonological awareness accounting for 8.1% and visuospatial short-term memory accounting for 5.7% of unique variance.

Longitudinal Results (Grade Two)

To determine the set of longitudinal cognitive predictors for timed arithmetic performance, a multiple regression analysis was conducted with phonological awareness, phonological working memory, and visuo-spatial short-term memory entered as predictors in a single-step and Grade Two arithmetic fluency as the criterion variable. The regression analysis revealed phonological awareness, β = -.34, *t*(84) = -3.48, *p* = .001, and phonological working memory, β = -.28, *t*(84) = -2.94, *p* = .004, to be significant predictors of calculation fluency, whereas visuospatial short-term memory was not a significant predictor, β = -.13, *t*(84) = -1.36, *p* = .179 (refer to Figure 1B). The three predictors accounted for 25.1% of the variance of the arithmetic fluency task, $R^2 = .251$, $F(3, 84) = 9.37$, $p < .001$, with phonological awareness accounting for 10.8%, and phonological working memory accounting for 7.7% of unique variance.

To determine the set of longitudinal cognitive predictors for untimed arithmetic performance, a multiple regression analysis was conducted with phonological awareness, phonological working memory, and visuo-spatial short-term memory entered as predictors in a single-step and Grade Two Woodcock Johnson Calculation as the criterion variable. The regression analysis revealed phonological awareness, β = .37, $t(84) = 3.93$, $p < .001$, and visuospatial short-term memory, β = .33, $t(84) = 3.57$, $p = .001$, to be significant predictors of the Woodcock Johnson Calculation subtest, whereas phonological working memory was not a significant predictor, β = .14, $t(84) = 1.51$, $p = .136$. The three predictors accounted for 30.6% of the variance of the Woodcock Johnson Calculation subtest $R^2 = .306$, $F(3, 84) = 12.36$, $p < .001$, with phonological awareness accounting for 12.7% and visuospatial short-term memory accounting for 10.5% of unique variance.

Discussion

In the present study, the results revealed that performance on the timed arithmetic task (i.e., arithmetic fluency) in Grade One was predicted by phonological awareness and visuo-spatial short-term memory, with phonological awareness being the most robust predictor. Furthermore, in Grade Two, performance on the timed arithmetic task was predicted by phonological awareness and phonological working memory, with phonological awareness as the most robust predictor. Additionally, concerning the untimed arithmetic task (i.e., Woodcock-Johnson Calculation), in both Grade One and Grade Two, performance on the task was predicted by phonological awareness as well as visuo-spatial short-term memory. Similar to the timed arithmetic task, phonological awareness was the most robust predictor for performance on both the Grade One and Grade Two untimed arithmetic task.

Considering the hypotheses for the present study, the first hypothesis was that the performance on the timed and untimed arithmetic tasks would have a different set of predictors, concurrently and longitudinally. The results did not support this hypothesis concurrently (i.e., Grade One), since both the timed and untimed tasks were predicted by phonological awareness and visuo-spatial short-term memory. In contrast, the hypothesis was supported longitudinally (i.e., Grade Two) since phonological awareness and phonological working memory predicted the timed arithmetic task, and phonological awareness and visuo-spatial short-term memory predicted the untimed arithmetic task. Overall, the first hypothesis was supported longitudinally with a different set of predictors between the two arithmetic tasks, but was not supported concurrently.

The second hypothesis was that the timed arithmetic task would be predicted by phonological awareness and visuo-spatial short-term memory, concurrently and longitudinally. This hypothesis was supported by the concurrent results; in contrast, the longitudinal results did not support this hypothesis since phonological awareness and phonological working memory predicted performance on the timed arithmetic task. Overall, the second hypothesis was supported concurrently in Grade One; however, the hypothesis was not supported longitudinally.

The third hypothesis was that the untimed arithmetic task would be predicted by visuo-spatial short-term memory and phonological working memory, concurrently and longitudinally. The results revealed that phonological working memory was not a significant predictor of untimed arithmetic performance, neither concurrently or longitudinally. While, visuospatial short-term memory and phonological awareness were significant predictors, both concurrently and longitudinally. Overall, the third hypothesis was partially supported with visuo-spatial short-term memory being a significant predictor both concurrently and longitudinally for performance on the untimed arithmetic task. However, against the third hypothesis, phonological working memory was not a significant predictor, while phonological awareness was a significant predictor of performance on the untimed arithmetic task, both concurrently and longitudinally.

In consideration of the previous research, the results from the present study are in mixed agreement with the past research concerning the predictors of different aspects of arithmetic. For instance, Berg (2008) investigated the predictive value of visuo-spatial short-term memory and phonological working memory on a general arithmetic test that incorporated no time pressures. The results demonstrated that both visuo-spatial short-term memory and phonological working memory were significant predictors; however, in the present study, phonological working memory did not reach significance for predicting performance on our untimed arithmetic task, while visuo-spatial short-term memory did at both time points. Additionally, Berg (2008) discussed how visuo-spatial memory may be a broader predictor of arithmetic achievement compared to phonological memory, which may be true based on the present results. Since, visuo-spatial short-term memory was a significant predictor for three out of the four arithmetic outcomes and phonological working memory was only significant for one outcome. Furthermore, the significance of visuo-spatial short-term memory on three out of the four outcomes in the present study was not surprising considering the study by LeFevre et al., (2010) that demonstrated visuo-spatial short-term memory (i.e., the spatial attention pathway) was a significant predictor for six out of the seven outcomes investigated.

A study by De Smedt et al., (2009) had a similar sample as the present study and examined the predictors of children's arithmetic performance on a general achievement test at the beginning of Grade One to the beginning of Grade Two. Interestingly, the study found that visuo-spatial short-term memory was a significant predictor for Grade One performance, while phonological working memory was not; however, Grade Two performance was predicted by phonological working memory, while visuo-spatial short-term memory was no longer a significant predictor. This shift is similar to the predictors of performance on the timed arithmetic task in the present study.

This shift in the predictive value for visuo-spatial short-term memory and phonological working memory has been demonstrated in previous research with visuo-spatial abilities decreasing and phonological abilities increasing involvement in solving arithmetic problems with age or grade (e.g., De Smedt et al., 2009, 2010; Hecht et al., 2001; Rasmussen & Bisanz, 2005). The rationale for this shift has been the development from utilizing concrete representations for performing arithmetic (e.g., finger counting) at a young age, which requires visuo-spatial abilities, to the increased reliance on verbally coded information during calculations. In other words, children learn to use verbal labels for numbers and utilize phonological working memory to store and manipulate this information (De Smedt et al., 2009). Furthermore, as previously mentioned in the review of past literature, this increasing reliance on phonological abilities (e.g., phonological working memory and phonological awareness) may be due to the development of arithmetic retrieval accuracy and facts in long-term memory (De Smedt et al., 2009, 2010; Dehaene et al., 2003; Geary, Hoard, & Hamson, 1999). Considering the tasks that were utilized in the present study, this rationale makes sense; however, visuo-spatial short-term memory has been demonstrated to be involved more-so in multi-digit arithmetic, or more difficult problems, which for the untimed arithmetic task (i.e., the Woodcock-Johnson Calculation subtest) children had to complete multi-digit arithmetic problems (Trbovich & LeFevre, 2003). This could explain why visuo-spatial short-term memory remained as a predictor for performance on the untimed arithmetic task in Grade Two, while phonological working memory became a significant predictor for performance on the timed arithmetic task at the same time point.

Interestingly, phonological awareness demonstrated to be a significant predictor for both performance on the timed and untimed arithmetic tasks in Grade One and Grade Two. This finding was unexpected, considering previous research (e.g., De Smedt et al., 2010). For instance, De Smedt et al., (2010) found that phonological awareness was predictive of arithmetic performance on their computerized timed tasks, which is in line with the findings of the present study. In contrast, phonological awareness was found by De Smedt et al., (2010) to not be a predictor of the Woodcock-Johnson Calculation subtest, which was included in the present study. Phonological awareness was not only a significant predictor of the Woodcock-Johnson Calculation subtest, but also the dominant predictor of performance on this untimed task. In contrast to De Smedt et al., (2010), and in line with the present study, LeFevre et al., (2010) found that phonological awareness (i.e., the linguistic pathway) was a significant predictor of all seven of their outcome tasks, which included the Woodcock-Johnson Calculation subtest. Similarly, regarding other arithmetic outcome tasks, phonological awareness has been demonstrated to be a robust predictor of performance (e.g., Leather & Henry, 1994; Passolunghi et al., 2015; Simmons et al., 2008; Sowinski et al., 2015; Szucs et al., 2014).

Previous research, such as De Smedt et al., (2010) has rationalized that phonological awareness, similar to phonological working memory, may play a role in arithmetic fact retrieval for single-digit arithmetic. However, the present study suggests that phonological awareness may also plays a role in procedural accuracy regarding multi-digit arithmetic problems, since it was a significant predictor of the Woodcock-Johnson Calculation subtest, which involves both single-digit and multi-digit arithmetic. Another explanation could be that the role of phonological awareness is grade or age dependent, similar to phonological working memory, since De Smedt et al., (2010) involved children in Grade 4 and Grade 5, while the present study

(Grade One and Grade Two) as well as the study by LeFevre et al., (Junior and Senior Kindergarten; 2010) included children near the beginning of their education. Potentially, based on the findings of the present study, phonological awareness may play a larger or more complex role in arithmetic than some previous research has discussed.

The findings from the present study are in mixed agreement with the previous research regarding the predictors of arithmetic performance. As previously mentioned, the shift in the predictive value of visuo-spatial short-term memory to phonological working memory for performance on the timed arithmetic task has been demonstrated in past research (e.g., De Smedt et al., 2009, 2010; Hecht et al., 2001; Rasmussen & Bisanz, 2005). However, our findings concerning phonological awareness are of interest since the findings are in line with some previous research such as LeFevre et al., (2010), while they are in contrast to De Smedt et al., (2010). Interestingly both of these previous studies incorporated the Woodcock-Johnson Calculation subtest as an outcome, similar to the present study. Regardless, in Grade One both the timed and untimed arithmetic tasks were predicted by visuo-spatial short-term memory and phonological awareness, which may demonstrate task difficulty. While, in Grade Two the tasks were differentially predicted with performance on the timed task predicted by both phonological predictors, potentially demonstrating an act of retrieval, and the untimed task still predicted by visuo-spatial short-term memory and phonological awareness which may demonstrate task difficulty, again. Overall, the present study did find that phonological awareness was a robust predictor of all of the outcomes under investigation. This finding suggests that phonological awareness should be considered to be included in future diagnostic tests to help determine if a child may have or has mathematical difficulties.

The present study does possess some important limitations that should be mentioned. First, the timed and untimed arithmetic tasks that were utilized differ on more than time pressures being incorporated or not. For instance, the computerized arithmetic fluency task (i.e., timed arithmetic) only includes single-digit addition, while the Woodcock-Johnson Calculation subtest (i.e., untimed arithmetic) includes addition, subtraction, division and multiplication, which includes single-digit and multi-digit problems. Therefore, there is a difference between the two tasks concerning difficulty. Another limitation of the present study is that the experimental control over the testing of the participants was not meant for the purposes of the present study, since participants were drawn from a pre-existing data set from Count Me In project. This meant that the present study was unable to include other cognitive predictors that have been determined to be significant predictors of arithmetic performance, such as the other components of the multicomponent model of working memory the visuo-spatial sketchpad and the central executive.

Future research on this topic should include outcome tasks that are similar, but differ on the incorporation of time pressures. Furthermore, the inclusion of additional robust predictors of arithmetic performance should be included, specifically the other components of working memory. These additional working memory predictors are potentially important to this research since math anxiety has been offered as a rationale for the difference in performance on timed and untimed arithmetic tasks (Ashcraft & Kirk, 2001; Tsui & Mazzocco, 2006). Additionally, math anxiety has been demonstrated in previous research to be related to working memory abilities (Ashcraft & Kirk, 2001; Ramirez, Gunderson, Levine, & Beilock, 2013). By future research investigating the components of working memory in predicting performance on timed and untimed arithmetic tasks, it could help determine whether math anxiety plays a role in the decrease in performance on timed arithmetic tasks, at least at a correlational level. Additionally, experimental research should investigate the role of phonological awareness in arithmetic to determine if there is a causal link between the two. If there is a causal link that would imply that interventions for mathematical difficulties should incorporate the improvement of phonological abilities to help performance.

In conclusion, the present study did not find a difference in the set of predictors between timed and untimed arithmetic performance in Grade One. However, in Grade Two it was found that there was a difference in the set of predictors between the performance on timed and untimed arithmetic, suggesting there may be a difference in the predictors between timed and untimed arithmetic performance, but future research needs to investigate this further. The present study was quite novel, since no previous research has explicitly investigated the cognitive predictors of timed and untimed arithmetic performance, and the potential difference in the set of predictors between the two tasks. As stated at the start, this is an important area to investigate since children, at a young age, are expected to perform both timed and untimed arithmetic and are evaluated on both. Additionally, by investigating this topic we can learn not only more about the complex relations between cognitive predictors and arithmetic, but also how to help identify and potentially intervene to assist children who have difficulties with arithmetic.

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