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Examining the Role of Phonological Memory in Math and Reading Development

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EXAMINING THE ROLE OF PHONOLOGICAL MEMORY
IN MATH AND READING DEVELOPMENT

BY

STEPHANIE TANG

A DISSERTATION SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY IN PSYCHOLOGY

UNIVERSITY OF RHODE ISLAND

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DOCTOR OF PHILOSOPHY DISSERTATION

OF

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ABSTRACT

Although much research has supported the role of phonological memory with reading and math achievement, there has been mixed results within each academic domain pertaining to when in development and with what subskills. Additionally, the major focus of most research has been on the causal influence of phonological memory on reading abilities without considering potential reciprocal relations. Therefore, the purpose of the present study was to: a) evaluate the contributions of phonological memory to reading and math skills development; and b) examine if reading influenced the development of phonological memory.

Secondary data was used from the Reading Development and Reading Disability: A Cross Linguistic, Longitudinal Study. The participants for this dissertation ranged from 6 to 11 years old at the first time of assessment and were tested again twelve and twenty-four months later ($n = 80$). At all three times, the participants were administered standardized measures of phonological memory, math fluency, math achievement (i.e., applied math problem solving), word identification, reading fluency, and reading comprehension. Participants also completed a standardized measure of intelligence at the beginning and end of the study.

Results revealed a tentative trend towards phonological memory predicting math achievement but not math fluency. As well, reading fluency at the beginning of the study consistently predicted change in phonological memory beyond IQ, age, word identification, reading comprehension, math fluency, and math achievement. Overall, these findings indicate that phonological memory has greater contributions to reading development. As well, there is preliminary support that reading acquisition influences

the development of phonological memory. The present results have implications for examining how phonological memory is related to specific math and reading skills and highlights a need to examine how reading acquisition may influence the development of phonological memory. Limitations of the study and suggestions for future research are discussed.

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PREFACE

This dissertation is in manuscript format.

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Examining the Role of Phonological Memory in Math and Reading Development

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INTRODUCTION

Statement of the Problem

As children begin formal schooling, they acquire and develop math and literacy skills that are important for their daily function in today's society. Unfortunately, an estimated 7% of children and adolescents have a mathematical learning disability (MLD) and an additional 10% demonstrate persistently low math achievement compared to their peers (Geary, 2011b). Similar prevalence rates have been estimated for reading disabilities (RD), with 5-12% of children demonstrating impairments in reading and/or spelling abilities (de Weerd, Desoete, & Roeyers, 2012). Further, MLD and RD are highly comorbid; population-based studies report that 17% to 64% of individuals with MLD also have RD (van Daal, van der Leij, & Adèr, 2012). Poorly developed reading and math skills have been associated with a wide array of negative long-term consequences such as fewer employment opportunities and higher rates of unemployment (Geary, 2011b). These issues highlight the importance of understanding cognitive factors related to the development of literacy and math skills.

Examination of the cognitive demands of these two academic domains have indicated that the temporary processing of phonological information is related to math and reading achievement (e.g., Alloway, 2009; de Smedt et al., 2009; Geary, 2011a), although for each area, there have been mixed results as to when in development and with what subskills phonological memory is associated. According to Baddeley's model, working memory (WM) refers to the temporary storage and manipulation of information and is divided into four subsystems (Baddeley, 2003b). One of these, the

phonological loop, is posited as a subsystem that temporarily stores verbal information (Baddeley, 2003b). (In this study, the terms 'phonological loop' and 'phonological memory' both will be used to refer to the temporary processing of verbal information. Further discussion of this is presented below in a section entitled Critical Review of the Literature).

The phonological loop has been implicated in early math development in terms of helping children acquire fundamental math skills such as verbal counting strategies and learning number words (e.g., Östergren & Träff, 2013; Preßler, Krajewski, & Hasselhorn, 2013). For example, phonological memory has been hypothesized to be important for encoding and maintaining verbal representations for counting, acquiring basic arithmetic facts, determining problem information, and generating partial solutions to math problems (Butterworth, 2005; Hecht, Torgesen, Wagner, & Rashotte, 2001; Holmes & Adams, 2006). As children's math skills mature, language demands in math tasks increase and the cognitive load on phonological memory might be expected to increase as well (Butterworth, 2005; Geary, 2000). Accordingly, results from de Smedt and colleagues' (2009) study indicated that phonological memory at the beginning of first grade did not predict math achievement four months later, but was linked with math performance in the second grade. Yet results from other studies do not reveal an association with phonological memory for math in later grades (Geary, 2011a; Meyer, Salimpoor, Wu, Geary, & Menon, 2010). Instead, other components of WM predict later math achievement, leading to an alternative perspective that the phonological loop may only be important for facilitating early math learning (e.g., Geary, 2011a; Meyer et al., 2010). However, a common limitation of predictive

research is that many studies may not have been sufficiently long to evaluate developmental changes in the contribution of phonological memory to math achievement. The mixed findings also may result from different operationalizations of math achievement as outcome measures; research indicates that different math skills (e.g., computation versus problem solving) may be related to different components of WM (Meyer et al., 2010; Simmons, Willis, & Adams, 2012). In addition, a number of studies have controlled for reading ability when examining how phonological memory influences math achievement. Although this has merit, the influence of reading aptitude on growth in math achievement has been documented (e.g., Hecht et al., 2001; Purpura, Hume, Sims, & Lonigan, 2011). Also, as noted, there is a high comorbidity rate between MLD and RD, potentially the result of over-lapping cognitive demands (Gathercole, Alloway, Willis, & Adams, 2006; Siegel & Ryan, 1989). As such, the potential contribution of phonological memory to math ability over time may have been overshadowed by the inclusion of reading achievement as a covariate (i.e., over-controlled analyses).

Further, there is a general consensus that the phonological loop is important for reading, for example, storing words and phrases while these and other aspects of text are processed (Alloway et al., 2005; Gathercole & Baddeley, 1993; Siegel, 1994). However, much of the research has focused on the causal role of phonological memory in reading development (e.g., Alloway, 2009; Nevo & Breznitz, 2011) without considering the potential reverse influence of whether reading acquisition might affect phonological memory processes. Thus, reading skills may influence the observed developmental increase in the capacity of short-term recall, hypothetically

because of improvements in subvocal rehearsal that may result from experience reading phonological elements in written words (Gathercole & Baddeley, 1993; Hulme, Thomson, Muir, & Lawrence, 1984). In light of this, it remains important to assess whether there are unidirectional or reciprocal relations between the development of phonological memory and reading skills. Therefore, to address the issues pertaining to the associations between phonological memory with math and reading development, this study examined the relations with a cohort of young children followed over a two-year period of time.

Critical Review of the Literature

Brief Overview of Phonological Memory

Although much research has highlighted the importance of phonological memory for reading and math achievement, there continues to be debate about its nature, as well as operational confusion with short-term memory (STM). One of the most influential models presented by Baddeley and Hitch suggests that WM is a limited capacity, multicomponent system composed of independent systems that interact with each other but have different functions (Alloway, Gathercole, Willis, & Adams, 2004; Baddeley, 2003b; Baddeley, 2012; de Smedt et al., 2009). In particular, the higher-order central executive is proposed to be responsible for regulating complex cognitive processes and three subsystems. These subsystems include a visuospatial sketchpad that temporarily holds visual and spatial information, the phonological loop that processes verbal information, and an episodic buffer that has been posited to integrate multimodal information. The phonological loop, the area of present focus, involves a phonological store to briefly hold verbal memory traces and an articulatory

rehearsal process that helps maintain the memory traces (Baddeley, 2003b). Tasks that assess verbal WM includes a combination of storage and manipulation such as backward digit span (recalling digits in reverse order) and reading span (verifying the logical accuracy of a series of sentences while remembering one word from each sentence; Demoulin & Kolinsky, 2015). In contrast, STM has been conceptualized as passive temporary storage of information. Theoretically, it should be assessed with tasks that require immediate recall of items such as forward digit span and nonword repetition (Demoulin & Kolinsky, 2015). However, distinctions between verbal WM and STM tasks are still under debate and their operationalization has been less clear in research studies (see Conway et al. (2005) and Hutton and Towse (2001) for detailed discussions of the kinds of tasks that should be used to assess verbal WM versus STM, and Snowling, Chiat, & Hulme (1991) for a critique of pseudoword repetition as a measure of the phonological loop). As such, in this study the terms 'phonological loop' and 'phonological memory' both will be used in a broad sense to refer to the temporary processing of verbal information.

The Role of Phonological Memory in Math Development

Many studies have documented that the phonological loop is associated with math achievement (e.g., Alloway et al., 2005; de Weerd et al., 2012; Gathercole et al., 2006). Specifically, deficits on measures tapping the phonological loop have been found to be correlated with low math achievement and with the occurrence of a mathematical learning disability (Andersson & Lyxell, 2007; Gathercole et al., 2006). Other results indicate that phonological memory plays a role in early math skills acquisition via reading abilities, such as for learning numerals, the number-word

sequence, and acquiring automaticity with basic math facts and computation (e.g., Jordan, Kaplan, & Hanich, 2002; Preßler et al., 2013; Purpura et al., 2011; Vukovic & Lesaux, 2013). Although basic mathematical competencies (e.g., number recognition) have been observed independent of language, reading acquisition can further develop these competencies (for example, by fostering an understanding of number and relational words and facilitating the retrieval and maintenance of numerical and quantitative representations in memory while completing math) (Geary, 2000; Jordan et al., 2002; Purpura et al., 2011; Vukovic & Lesaux, 2013). Related to this, as children develop more automatic reading abilities, they rely less on visuospatial strategies (e.g., finger counting) when they do math activities and more on verbal strategies (e.g., verbal counting), potentially placing more demands on phonological memory (Gersten, Jordan, & Flojo, 2005; Holmes & Adams, 2006). Additionally, research suggests that phonological memory accounts for variance in more advanced math skills (e.g., problem solving) when the math tasks have greater language demands (Raghubar, Barnes, & Hecht, 2010). These developmental and curricular changes may be associated with an increased role of phonological memory in math performance (e.g., de Smedt et al., 2009).

Conversely, other research indicates that phonological memory is not a unique predictor of math achievement over time (e.g., Geary, 2011a; Meyer et al., 2010). Instead, these studies suggest that phonological memory supports the initial acquisition of basic math skills, as noted above, but as those become more automatic and efficient over time, the demands on phonological memory diminish and it

becomes less relevant for more advanced math competencies (Krajewski & Schneider, 2009; Meyer et al., 2010).

The mixed findings may be attributed partially to the various conceptualizations and measures of math achievement used across studies that result in differing demands on verbal WM (Meyer et al., 2010; Simmons et al., 2012). In addition, given the increasing language demands in math tasks, the high degree of covariance between reading and math achievement, and the correspondingly high comorbidity between reading and math disabilities, the results may have obscured whether phonological memory relates to the growth of math skills. Finally, factors stemming from instruction or socioeconomic status may create confounding effects in a study's sample, such as factors stemming from instruction or socioeconomic status.

The Role of Phonological Memory in Reading Development

Many studies have suggested that the phonological loop is more strongly associated with reading than math achievement (Alloway et al., 2005; Gathercole & Pickering, 2000; Geary, 2011a; Shankweiler et al., 1995). In particular, phonological memory may be especially important for initial acquisition of alphabetic code skills and vocabulary development with the consequence that poor phonological memory may hinder the development of reading success (Alloway & Alloway, 2010; Baddeley, 2003a; Gathercole & Baddeley, 1993; Nevo & Breznitz, 2011). In support of this, Alloway and Alloway (2010) examined whether IQ and phonological memory of preschool children predicted their literacy (and math achievement) in first grade. The results revealed that phonological memory uniquely influenced later literacy achievement beyond IQ. Similarly, Avons, Wragg, Cupples, and Lovegrove (1998)

studied how different measures of phonological memory related to vocabulary development in preschool children. Their findings indicated that phonological memory contributed to later vocabulary acquisition while initial vocabulary did not predict later phonological memory. These studies suggest that the phonological loop is especially important in the early school years for reading acquisition.

However, other research has not supported the role of phonological memory in reading development and suggests that abilities such as phonological skills and vocabulary knowledge are better predictors (Bowey, 2001; Melby-Lervåg et al., 2012; Melby-Lervåg, Lyster, & Hulme, 2012; Metsala, 1999; Nation & Hulme, 2011). In relation to this, there is a general consensus that vocabulary strongly affects pseudoword repetition, a commonly used measure of phonological memory (e.g., Metsala, 1999). According to this linguistic hypothesis, vocabulary knowledge strengthens associations between linguistic subunits (some of which may be present in pseudowords) and their representations in memory that then can affect ease of pseudoword recall. In support of this, Gathercole, Willis, Emslie, and Baddeley (1991) found that pseudoword recall was more accurate as the similarity of pseudowords with real words increased. Further support comes from pseudoword repetition priming studies that examine how repetition priming influences pseudoword recall. For example, Rueckl and Olds (1993) found that presentations of orthographically similar pseudoword primes and learning definitions for pseudowords improved pseudoword recall. They argued that the primes and definitions created and strengthened orthographic-semantic associations that aided pseudoword recall. As such, the

influence of phonological memory on reading development may reflect (or incorporate to some degree) various other processes and latent factors.

Various operationalizations of reading achievement have been used as outcome measures in research on the role of phonological memory in reading that may have influenced the outcomes. Reading requires the coordination of numerous skills and cognitive processes, such as word reading and reading comprehension, that may place differing demands on phonological memory (Georgiou, Parrila, & Papadopoulos, 2008; Nation, 2005; Nation & Snowling, 1997; Nevo & Breznitz, 2011; Savage, Lavers, & Pillay, 2007; Vellutino, Tunmer, Jaccard, & Chen, 2007). For instance, results from Oakhill, Cain, and Bryant's (2003) study indicated that seven- to eight-year old children's phonological memory was related a year later to reading comprehension, but not to reading accuracy. Accordingly, it would be informative to examine how phonological memory contributes to the growth of major reading components, such as decoding, fluency, and reading comprehension.

Effects of Reading Acquisition on Phonological Memory

In addition to these issues, another consideration is that despite a general consensus regarding the importance of the phonological loop in reading, most studies have focused on the causal role of phonological memory without considering the potential of an influence in the reverse direction. Studies with adults who are illiterate suggest that literacy acquisition affects phonological memory independent of formal schooling (Ardila et al., 2010; Kosmidis, Zafiri, & Politimou, 2011). For example, Kosmidis and colleagues (2011) examined phonological memory for four groups of adults that differed in their level of schooling and reading ability: 1) individuals who

were illiterate and had received no formal schooling (illiterate); 2) those who had attended school but were illiterate (functionally illiterate); 3) those who had not attended school but were literate (self-educated literate); and 4) those who had attended school and were literate (educated literate). Although the participants had similar socio-cultural backgrounds and were from the same rural community, the findings indicated that self-educated literates had better phonological memory than illiterates, and that the illiterate and functionally illiterate groups had comparable phonological memory performance. Although research examining the effects of literacy acquisition on phonological memory in younger children is sparse, emerging results are comparable to studies with adult illiterates. For example, Matute and colleagues (2012) examined a broad range of cognitive abilities (e.g., phonological memory and metalinguistic awareness) in illiterate and literate children ages 6 to 13 years old. All participants had similar socioeconomic and cultural backgrounds and the illiterate children were matched according to sex and age with a literate peer. The results showed that the literate children displayed better phonological memory (i.e., word learning and free story-recall) and metalinguistic awareness (e.g., phonemic blending, phoneme counting, and word counting) than the matched illiterate group. Because these findings are compatible with the view that acquisition of literacy can improve phonological memory, it again would be informative to explore how specific reading skills (e.g., decoding, reading fluency, and reading comprehension) might correspond with the functioning of phonological memory. Given that these reading skills develop over time, examining the associations between reading subskills and phonological memory at different time points may be informative.

One explanation of how reading acquisition might impact memory is that reading experience may enhance subvocal rehearsal, allowing more items to be maintained in memory (Gathercole, Pickering, Ambridge, & Wearing, 2004; Hulme et al., 1984; Roodenrys, Hulme, & Brown, 1993). Learning how to read also involves acquiring the knowledge that spoken words can be decomposed into smaller phonological units (i.e., phonemes). Thus, another interpretation of the effects of learning to read on phonological memory is that focusing on the phoneme structure of words may facilitate the efficiency of phonological memory by prompting utilization of finer-grained phonological representations for spoken utterances (Huettig & Mishra, 2014). Supporting this hypothesis, Melby-Lervåg and Hulme (2010) found that seven-year-old children who received phoneme awareness training subsequently had better memory of word strings compared to children who had received rhyme training (i.e., targeting larger phonological units). Similarly, adults who are illiterate because of a lack of educational opportunities have been documented to have difficulty repeating pseudowords but not high-frequency real words; some researchers have suggested that this reflects their use of strategies that are good for processing semantic, but not fine-grained phonemic, information, maintaining that phonological processing is enhanced by literacy acquisition (Ardila et al., 2010; Baddeley, 2003a; Petersson, Reis, Askelöf, Castro-Caldas, & Ingvar, 2000). In addition to improving rehearsal strategies and phonological processing, another potential mechanism of how reading acquisition may affect phonological memory is that reading involves connecting speech sounds with orthographic codes that can improve the quality, strength, and recall of mental representations in the verbal lexicon (Baddeley, 2003a;

Clark & Wagner, 2003; Dehaene, Cohen, Morais, & Kolinsky, 2015; Koda, 1989; Perfetti, 2007). As such, the influence of reading acquisition on phonological memory warrants further examination.

Purpose of the Study

Mixed findings persist regarding the role of phonological memory in two areas of academic development, math and reading. Two of the ongoing questions relate to the direction(s) of influence (i.e., whether early phonological memory predicts later reading achievement and/or is affected by the development of reading and math skills), and whether the association between phonological memory and math performance stems from the reading demands entailed in many of the more advanced kinds of math problems. To address these issues, this study examined patterns of growth in reading and math in a three-year, longitudinal study, evaluating associations with phonological memory and possible variance accounted for in math performance by reading skill. Permission was obtained to use select data from a longitudinal database (K. Pugh, personal communication, April 21, 2015). The data were obtained from English-speaking students who were assessed on several behavioral measures across three time points that were 12 months apart, with age at Time 1 ranging from six to eleven years old (see Table 17 in Appendix A).

The following hypotheses are postulated:

Hypothesis 1: Phonological memory is associated with later math achievement. In particular, it is expected that phonological memory is weakly related to basic math skills (i.e., computation), but has a greater influence as language demands in math tasks increase (i.e., with math problems embedded in text in word problems).

Hypothesis 2: Phonological memory influences the rate of change in reading achievement (i.e., in decoding, reading fluency, and reading comprehension).

However, it is expected that there is a greater contribution of phonological memory to higher-order reading skills such as comprehension that emerges as text becomes more complex beyond the earliest grades.

Hypothesis 3: Proposing a reciprocal relationship as well, development of reading skills is expected to increase the capacity of phonological memory. Thus, acquisition of reading skills is hypothesized to facilitate the functioning of the phonological loop.

METHODOLOGY

Participants

Permission was obtained to use data from a larger project, “Reading Development and Reading Disability: A Cross Linguistic, Longitudinal Study” (K. Pugh, personal communication, April 21, 2015). The data from an English-speaking cohort in the study was used for this dissertation. The participants were beginning to early readers tested at three time points spaced twelve months apart (see Table 17 in Appendix A). Specifically, the current sample included 80 participants who had been tested at all three time points. At Time 1, the participants ranged in age from 6 to 11 years old and were assessed again twelve and twenty-four months later. The gender distribution of the sample was relatively equal, with 57.5% of participants identified as male and 42.5% identified as female. More information regarding the demographic characteristics of the current sample can be found in Table 1.

Table 1
Participant Demographics at Time 1

Characteristic	<i>n</i>	Percent (%)
Sex		
Female	46	57.50
Male	34	42.50
Age (years)		
6	12	15.00
7	31	38.75
8	15	18.75
9	11	13.75
10	9	11.25
11	2	2.50
Race/Ethnicity		
Caucasian	67	83.75
African American	4	5.00
Hispanic	1	1.25
Asian	1	1.25
Pacific Islander	0	0.00
More than one race	6	7.50
Unknown race	1	1.25
Grade		
Kindergarten	2	2.50
1	18	22.50
2	23	28.75
3	15	18.75
4	10	12.50
5	2	2.50
6	1	1.25
Homeschool	4	5.00
Unknown	5	6.25

Materials

Phonological memory measure. The Memory for Digits and Nonword Repetition subtests from the Comprehensive Test of Phonological Processing (CTOPP) were used as a composite measure of phonological memory (Wagner, Torgesen, & Rashotte, 1999). The CTOPP is appropriate for students ages 5 to 24 years old and was normed on a representative US population according to the 1997 census. It has strong validity and reliability with reported inter-rater reliability of .95

to .99 for all age ranges (Wagner et al., 1999). The Memory for Digits measures the ability to recall short series of numbers of increasing length. This task has 21 items and participants received 1 point for each item recalled accurately. Specifically, the first three items involved recalling 2 numbers. The series of numbers recalled increased by one for each subsequent set of three items. There was no basal and participants stopped after they missed 3 items in a row. The Nonword Repetition task has 18 items and requires participants to repeat pseudowords presented one at a time. Each student started at item one, received 1 point for each correct answer, and stopped after missing 3 test items in a row. The raw scores from these two subtests were combined to produce a total raw score as a measure of phonological memory (Mitchell, 2001). As such, the composite measure of phonological memory was composed of 39 items.

Math measures.

Math fluency. The Math Fluency subtest from the Woodcock-Johnson III Tests of Achievement battery (WJ III) was used as a measure of automaticity with math facts. The WJ III is appropriate for people ages 2 to 90 years and was normed on a large sample representative of the U.S. population in 2000. The Math Fluency task is an individually-administered test that entails writing solutions to visually presented simple single-digit addition, subtraction, and multiplication problems within three minutes. Each student began with Item 1 and there were 160 questions. The total number of correct responses computed within three minutes was used as an index of math fluency. The Math Fluency subtest has strong validity and reliability (median reliability coefficient = 0.90; McGrew & Woodcock, 2001).

Math achievement. The Applied Problems subtest from the WJ III was used as a measure of math achievement. The WJ III is appropriate for people ages 2 to 90 years and was normed on a large sample representative of the U.S. population in 2000. The Applied Problems subtest is an untimed, individually-administered test that evaluates the ability to analyze and solve math problems. Students are verbally given math problems with accompanying visual stimuli and have to respond with an oral answer. There are 63 items on the Applied Problems task and one point is given for each correct answer. The students' grade determined the starting item. Basal was established with the six lowest correct answers and ceiling was reached with the six highest incorrect answers. This subtest has strong validity and reliability (median reliability coefficient = 0.93; McGrew & Woodcock, 2001). For each student, the total number of correct responses (including all items before the basal) was used as the pupil's math achievement score.

Reading measures.

Word Identification. The Letter-Word Identification subtest from the WJ III was used as a measure of word recognition ability. This untimed task requires students to verbally identify printed letters and words. There are 76 items in this subtest and each student's grade determined the starting item. Basal was established with the six lowest correct answers and participants stopped when they stated six incorrect answers in a row. The Letter-Word Identification subtest has strong validity and reliability (median reliability coefficient = 0.94; McGrew & Woodcock, 2001). For each student, a raw score based on the child's total number of correct responses was used.

Reading fluency. The Test of Word Reading Efficiency (TOWRE) was used as a measure of word reading fluency. The TOWRE is a reliable and valid measure that is individually administered and appropriate for individuals age 6 to 24 years old (Torgesen, Wagner, & Rashotte, 1999). There are two subtests: on one the student has to read aloud as many printed real words as possible out of 104 words within a 45 second period of time, on the other the student has to read as many printed pseudowords as possible out of 63 items in 45 seconds. The items become progressively more complex as the list continues. For each student, the total number of items read correctly on the two subtests was used as a measure of word reading fluency.

Reading comprehension. The Passage Comprehension subtest from the WJ III was used as a measure of reading comprehension. Passage Comprehension is an untimed, individually-administered test in which students have to identify and verbally provide missing words that fit within a written passage. There are 47 items and the students' grade determined the starting item. Basal was established with the six lowest correct answers and the task was discontinued after six consecutive incorrect answers. This subtest has good validity and reliability (median reliability coefficient = 0.88; McGrew & Woodcock, 2001). For each student, the total number of correct responses was used as the student's reading comprehension score.

Intelligence measure. The Wechsler Abbreviated Scale of Intelligence (WASI) was administered at Times 1 and 3 to assess general, verbal, and nonverbal intelligence in the English cohort. The WASI is appropriate for people ages 6 to 89 years, 11 months and is composed of four subtests (Vocabulary, Similarities, Block

Design, and Matrix Reasoning) that each have established reliability and validity (Canivez, Konold, Collins, & Wilson, 2009; Pierson, Kilmer, Rothlisberg, & McIntosh, 2012). On each subtest, the starting item is determined by the students' age. The Block Design subtest is a timed task that involves manipulating blocks to replicate a visually presented pattern. Depending on the item, the time limit varied from 30 to 120 seconds. Extra points were awarded for completing an item quickly. As such, for participants aged six to eight years old, there were 11 items for a total of 57 possible points while there were 13 possible items for a total of 71 points for participants aged nine and older. The Block Design subtest was discontinued after two incorrect model replications. On the Vocabulary task, each student had to orally describe verbally presented words. Depending on the detail of the answer, students received one to two points for each correct response. The total number of items and possible points also depended on age. Specifically, participants aged six years old could complete a total of 22 items out of 41 points, seven to eleven years old could complete a total of 25 items out of 47 points, and twelve to fourteen years old could complete a total of 28 items out of 53 points. The task was discontinued after three consecutive incorrect responses. The Matrix Reasoning subtest involved viewing an incomplete puzzle and selecting a response to complete it. Students earned one point for each correct response. There were 24 items for participants aged six to eight years old and 30 items for participants nine years and older. The Matrix Reasoning task was discontinued after three incorrect responses. Lastly, the Similarities subtest involved describing how two verbally presented objects or concepts were similar. One to two points were awarded depending on the quality of the correct response. The task was discontinued

after three consecutive incorrect answers. For participants aged six to eight, there were 22 items for a total of 41 points and for participants aged nine and older there were 24 items for a total of 45 points. For each student, the total number of correct responses on these subtests were converted to *T* scores and then summed. A standardized score based on age and the sum of *T* scores was used as a measure of the student's IQ.

Procedure

As mentioned above, permission was obtained to use data from the Reading Development and Reading Disability: A Cross Linguistic, Longitudinal Study (K. Pugh, personal communication, April 21, 2015). There was no testing of participants since this dissertation involved the use of secondary data. The current study was reviewed and approved by the Institutional Review Board at the University of Rhode Island. The participants for this study ranged from 6 to 11 years old at the first time of assessment (i.e., Time 1) and were tested again twelve and twenty-four months later (i.e., Times 2 and 3, respectively). At all three times, the participants were administered measures of phonological memory (CTOPP Memory for Digits and Nonword Repetition), math fluency (WJ III Math Fluency), math achievement (WJ III Applied Problems), word identification (WJ III Letter-Word Identification), reading fluency (TOWRE), and reading comprehension (WJ III Passage Comprehension). Participants also completed a measure of IQ (i.e., WASI) at the beginning and end of the study (see Table 17 in Appendix A). Test performance on all measures have been scored and entered into a database for all of the participants. Confidentiality was maintained with assignment of subject code ID numbers for data entry and use of

password protected computers. As well, all electronic data from this study were securely stored under lock and key and on password protected computers.

RESULTS

Preliminary Analysis

Prior to conducting regression analyses, performance on all variables was evaluated for normality by examining box plots, skewness, and kurtosis. Several outliers were identified but after consideration of the participants' scores on the other measures and the broad age and IQ ranges, these outliers were deemed possible occurrences and included in analyses. The descriptive statistics for the participants at each time point and over time are presented in Tables 2 and 3, respectively. For each of the regression models, the assumptions of linearity, normality, and homoscedasticity also were evaluated and met.

Table 2

A. Means and Standard Deviations for All Variables

Variable	Time Point					
	1		2		3	
	(n = 80)		(n = 80)		(n = 80)	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
IQ (standard score)	110.67	16.02	-	-	-	-
Phonological Memory	22.04	4.48	22.90	4.43	24.05	4.39
Math Fluency	35.86	19.36	48.56	20.01	60.74	22.31
Math Achievement	31.51	6.30	36.50	6.42	39.98	6.50
Word Identification	45.26	12.86	50.85	10.15	55.04	9.02
Reading Fluency	72.67	33.45	89.46	27.66	101.55	23.65
Reading Comprehension	24.36	7.77	29.51	6.15	31.99	4.70

B. Ranges for all variables

Variable	Min.	Max.	Min.	Max.	Min.	Max.
IQ (standard score)	73.00	144.00	-	-	-	-
Phonological Memory	12.00	32.00	11.00	34.00	15.00	35.00
Math Fluency	5.00	88.00	14.00	104.00	12.00	115.00
Math Achievement	20.00	48.00	26.00	54.00	28.00	58.00
Word Identification	17.00	69.00	30.00	71.00	34.00	72.00
Reading Fluency	5.00	127.00	33.00	139.00	54.00	148.00
Reading Comprehension	3.00	36.00	14.00	43.00	20.00	41.00

*Note. All variables are raw scores unless otherwise noted

Table 3
Descriptive Statistics for Change in Variables

Variable	From Time Points 1 to 3 (<i>n</i> = 80)			
	Min.	Max.	<i>M</i>	<i>SD</i>
Change in Phonological Memory	-2.50	5.00	1.01	1.80
Change in Math Fluency	-2.00	32.00	12.44	7.43
Change in Math Achievement	-1.50	9.50	4.23	2.20
Change in Word Identification	-0.50	12.50	4.89	3.11
Change in Reading Fluency	-5.00	36.50	14.44	8.75
Change in Reading Comprehension	-1.50	12.50	3.81	2.65

**Note.* All variables are raw scores. Negative scores indicate that performance scores decreased from Times 1 to 3.

Correlational Analyses

Tables 4A-C presents the correlations among IQ, phonological memory, math fluency, math achievement, word identification, reading fluency, and reading comprehension across the three time points for the participants. The results indicate that at Time 1, there were significant and positive correlations between all the measures (Table 4A). Moreover, these significant associations also were consistently found across Times 2 and 3 (Tables 4B and 4C, respectively). This suggests that phonological memory, IQ, math skills (i.e., math fluency and applied problem solving), and reading subskills (word identification, reading fluency, and reading comprehension) were associated with each other at the start of the study and across each time point (12 and 24 months later).

Correlations of IQ, phonological memory, and math and reading subskills with changes in these variables (except IQ) across the three time points also are presented in Tables 4A-C. There was a significant and negative correlation between change in phonological memory and Time 1 phonological memory ($r(80) = -.43, p < .05$). Thus, greater stability in phonological memory over time was related to stronger initial

phonological memory. On the other hand, there was a significant and positive correlation between change in phonological memory and Time 3 phonological memory ($r(80) = .39, p < .05$). As such, greater growth in phonological memory over time was associated with later, stronger phonological memory at Time 3, as one would anticipate.

In regard to changes in math skills over time (Tables 4A-C), there was a significant positive correlation between change in math fluency and Time 3 math fluency ($r(80) = .52, p < .05$), suggesting that greater growth in math fluency was associated with better math fluency ability at Time 3. Change on the math achievement task over time was significantly correlated with Time 1 math achievement ($r(80) = -.30, p < .05$) and Time 3 math achievement ($r(80) = .38, p < .05$). This indicates that growth in math problem solving ability was related to weaker math problem solving ability at Time 1 and stronger problem solving performance at Time 3.

From Times 1 to 3, change in word identification was significantly and negatively correlated with the following: Time 1 IQ; math skills (math fluency and math achievement) and reading subskills (word identification, reading fluency, and reading comprehension) at all three time points; and phonological memory at Times 2 and 3 (see Tables 4A-C). The correlations show that growth in word identification covary with weaker math and reading subskills at all three time points. Moreover, less change in word identification skill related to stronger phonological memory at Times 2 and 3. Less growth in word identification also was associated with higher IQ as measured at Time 1.

The results presented in Tables 4A-C indicate that there was a significant and negative correlation between change in reading fluency and phonological memory at Time 2 ($r(80) = -.26, p < .05$), suggesting that less growth in reading fluency corresponded to stronger phonological memory at Time 2. Change in reading fluency also was significantly and negatively correlated with Time 1 IQ and math and reading subskills at Times 1, 2, and 3. Hence, higher IQ was related to less growth in reading fluency while weaker reading and math subskills (i.e., math fluency, math problem solving, word identification, reading fluency, and reading comprehension) were associated with greater growth in reading fluency.

Change in reading comprehension was significantly and negatively correlated with the following: Time 1 IQ; Time 2 phonological memory; Times 1 and 2 math and reading subskills; Time 3 math subskills; and Time 3 word identification and reading fluency (see Tables 4A-C). This means that higher IQ and stronger Time 2 phonological memory was related to more stable reading comprehension ability (i.e., less change) over time. In contrast, growth in reading comprehension was associated with weaker math and reading subskills at Times 1 and 2. Likewise, reading comprehension growth was related to weaker Time 3 math subskills, word identification, and reading fluency.

The findings from Table 4D show a significant and positive correlation between changes in math fluency and reading fluency over time, showing that greater growth in the ability to quickly compute math facts covary with greater growth in the ability to quickly read aloud words ($r(80) = .32, p < .05$). Change in math achievement over time was significantly and positively correlated with change over time in word

identification ($r(80) = .35, p < .05$) and reading comprehension ($r(80) = .22, p < .05$).

This suggests that greater growth in math achievement was associated with greater change in word identification and reading comprehension abilities. In addition, there were significant and positive correlations between change in word identification and changes in reading fluency ($r(80) = .72, p < .05$) and reading comprehension over time ($r(80) = .62, p < .05$). Thus, greater growth in word identification was related to greater growth in reading fluency and reading comprehension skills. Lastly, change in reading fluency over time was significantly and positively correlated with change in reading comprehension ($r(80) = .61, p < .05$), indicating that better reading fluency was associated with greater reading comprehension skill over time.

Table 4

A. Correlation Matrix for All Variables Collected With Time Point 1

Measure	1a	2a	3a	4a	5a	6a	7a
<i>Time 1</i>							
1a. IQ	-						
2a. Phonological Memory	.50*	-					
3a. Math Fluency	.39*	.46*	-				
4a. Math Achievement	.64*	.60*	.80*	-			
5a. Word Identification	.60*	.41*	.64*	.65*	-		
6a. Reading Fluency	.61*	.36*	.64*	.65*	.96*	-	
7a. Reading Comprehension	.63*	.40*	.60*	.66*	.91*	.88*	-
<i>Time 2</i>							
2b. Phonological Memory	.49*	.67*	.34*	.51*	.47*	.44*	.43*
3b. Math Fluency	.32*	.42*	.84*	.65*	.48*	.51*	.43*
4b. Math Achievement	.66*	.61*	.73*	.82*	.59*	.57*	.62*
5b. Word Identification	.61*	.43*	.61*	.60*	.94*	.92*	.87*
6b. Reading Fluency	.55*	.33*	.65*	.63*	.89*	.92*	.81*
7b. Reading Comprehension	.59*	.33*	.49*	.55*	.81*	.80*	.89*
<i>Time 3</i>							
2c. Phonological Memory	.52*	.67*	.47*	.54*	.45*	.46*	.41*
3c. Math Fluency	.36*	.41*	.75*	.65*	.46*	.49*	.41*
4c. Math Achievement	.69*	.66*	.64*	.76*	.57*	.56*	.58*
5c. Word Identification	.60*	.47*	.53*	.55*	.90*	.88*	.84*
6c. Reading Fluency	.57*	.38*	.53*	.56*	.84*	.87*	.76*
7c. Reading Comprehension	.66*	.50*	.53*	.65*	.70*	.66*	.74*
<i>Change Over Times 1-3</i>							
8. Phonological Memory	.01	-.43*	.00	-.09	.04	.12	.00
9. Math Fluency	.03	.02	-.17	-.07	-.15	-.10	-.16
10. Math Achievement	.11	.12	-.21	-.30*	-.09	-.11	-.09
11. Word Identification	-.37*	-.16	-.56*	-.54*	-.77*	-.71*	-.66*
12. Reading Fluency	-.40*	-.17	-.50*	-.48*	-.71*	-.74*	-.66*
13. Reading Comprehension	-.34*	-.14	-.41*	-.39*	-.71*	-.70*	-.81*

* Correlation is significant at $p < .05$ level.

Table 4

B. Correlation Matrix for Variables Collected With Time Point 2

Measure	2b	3b	4b	5b	6b	7b
<i>Time 2</i>						
2b. Phonological Memory	-					
3b. Math Fluency	.24*	-				
4b. Math Achievement	.40*	.72*	-			
5b. Word Identification	.46*	.48*	.56*	-		
6b. Reading Fluency	.39*	.54*	.55*	.90*	-	
7b. Reading Comprehension	.31*	.35*	.57*	.84*	.78*	-
<i>Time 3</i>						
2c. Phonological Memory	.69*	.39*	.53*	.44*	.43*	.34*
3c. Math Fluency	.32*	.81*	.64*	.44*	.55*	.31*
4c. Math Achievement	.49*	.61*	.87*	.60*	.54*	.55*
5c. Word Identification	.48*	.40*	.54*	.93*	.87*	.79*
6c. Reading Fluency	.42*	.46*	.51*	.86*	.91*	.71*
7c. Reading Comprehension	.40*	.44*	.66*	.71*	.63*	.74*
<i>Change Over Times 1-3</i>						
8. Phonological Memory	.01	-.05	-.10	.01	.11	.00
9. Math Fluency	.04	.13	.01	-.13	-.03	-.17
10. Math Achievement	-.01	-.03	.12	.04	-.11	.03
11. Word Identification	-.27*	-.42*	-.45*	-.58*	-.58*	-.53*
12. Reading Fluency	-.26*	-.35*	-.40*	-.59*	-.52*	-.56*
13. Reading Comprehension	-.27*	-.24*	-.33*	-.64*	-.63*	-.65*

* Correlation is significant at $p < .05$ level.

Table 4

C. Correlation Matrix for Variables Collected With Time Point 3

Measure	2c	3c	4c	5c	6c	7c
<i>Time 3</i>						
2c. Phonological Memory	-					
3c. Math Fluency	.45*	-				
4c. Math Achievement	.60*	.57*	-			
5c. Word Identification	.49*	.40*	.61*	-		
6c. Reading Fluency	.50*	.53*	.52*	.86*	-	
7c. Reading Comprehension	.49*	.41*	.70*	.73*	.64*	-
<i>Change Over Times 1-3</i>						
8. Phonological Memory	.39*	.04	-.09	.01	.14	-.02
9. Math Fluency	.06	.52*	.02	-.09	.10	-.08
10. Math Achievement	.12	-.09	.38*	.11	-.03	.10
11. Word Identification	-.22*	-.37*	-.28*	-.40*	-.48*	-.38*
12. Reading Fluency	-.20	-.22*	-.36*	-.51*	-.31*	-.40*
13. Reading Comprehension	-.16	-.24*	-.22*	-.59*	-.54*	-.20

Table 4

D. Correlation Matrix for Variables' Change Over Time

Measure	8	9	10	11	12
<i>Change Over Times 1-3</i>					
8. Phonological Memory	-				
9. Math Fluency	.05	-			
10. Math Achievement	-.01	.14	-		
11. Word Identification	-.07	.18	.35*	-	
12. Reading Fluency	-.03	.32*	.16	.72*	-
13. Reading Comprehension	-.02	.16	.22*	.62*	.61*

* Correlation is significant at $p < .05$ level.

Contribution of Phonological Memory to Math Development

Two sets of hierarchical regressions were used to test the first hypothesis that phonological memory is related to changes in math achievement. Specifically, one set of hierarchical regressions was conducted to examine the contribution of early phonological memory to basic math computation skill. For this analysis, the dependent variable was change in math fluency. To control for the influence of age and general intelligence, Time 1 IQ and age were entered in stage one of the regression and Time 1 phonological memory was entered at stage two. Findings revealed that the overall model was not significant, $F(3,76) = 2.26$, $p > .05$, $R^2 = .08$ (see Table 5). In particular, Time 1 IQ and phonological memory did not significantly contribute to change in math fluency ($p > .05$) while Time 1 age explained a significant amount of unique variance in the change in math fluency ($\beta = -.30$, $p < .05$).

Table 5

Summary of Hierarchical Regression Analysis for Time 1 Variables Predicting Change in Math Fluency (N = 80)

	Independent variable(s)	<i>t</i>	β	F	Df	<i>p</i>	R ²	adj.R ²
Stage 1				3.01	2,77	0.06	0.07	0.05
	IQ	0.34	.04					
	Age	-2.44*	-.27					
Stage 2				2.26	3,76	0.09	0.08	0.05
	IQ	-0.16	-.02					
	Age	-2.59*	-.30					
	Phonological Memory	0.87	.12					

* $p < .05$. ** $p < .01$

A second set of hierarchical regression were conducted to assess if early phonological memory contributes to more advanced math skills with greater reading demands. The dependent variable was change in math achievement and the independent variables were Time 1 IQ, age, and phonological memory. The former two independent variables were entered into the first stage of the regression as covariates while Time 1 phonological memory was entered into the second stage. The regression results indicated that when all three independent variables were entered, the model accounted for a significant amount of variation in growth in math achievement, $F(3,76) = 5.57, p < .01, R^2 = .18$ (see Table 6). Closer examination indicated that Time 1 age was a specific predictor of growth in math achievement ($\beta = -.43, p < .01$). Although Time 1 memory was not significantly related to math achievement growth over time, the result were approaching significance ($\beta = .25, p = .06$). Thus, these two sets of hierarchical regressions do not confirm the first hypothesis as Time 1 IQ and phonological memory did not significantly contribute to the growth of math fluency nor math achievement over time.

Table 6
Summary of Hierarchical Regression Analysis for Time 1 Variables Predicting Change in Math Achievement (N = 80)

	Independent variable(s)	<i>t</i>	β	F	Df	<i>p</i>	R ²	adj.R ²
Stage 1				6.23	2,77	<.01**	0.14	0.12
	IQ	1.15	.12					
	Age	-3.37**	-.36					
Stage 2				5.57	3,76	<.01**	0.18	0.15
	IQ	0.00	.00					
	Age	-3.88**	-.43					
	Phonological Memory	1.95	.25					

* $p < .05$. ** $p < .01$

Contribution of Phonological Memory and Reading Abilities to Math

Development

Two additional hierarchical regressions were conducted as exploratory analyses to examine how phonological memory contributes to math development after consideration of reading ability. In both regressions, the independent variables were Time 1 IQ, age, phonological memory, and word identification. Since there was high collinearity between word identification, reading fluency, and reading comprehension, the latter two reading skills were not entered in the regression models ($p > .80$; see Table 4 for Pearson correlations). Word identification was chosen as the representative reading measure because more advanced reading skills such as reading fluency and comprehension incorporate additional component skills (e.g., see Fuchs, Fuchs, Hosp, & Jenkins (2001) and Oakhill et al. (2003) for detailed discussions of the cognitive skills assessed by word reading, reading fluency, and reading comprehension tasks).

For the first regression, the dependent variable was the change in math fluency. To control for the effects of IQ and age, these variables were entered into the first stage of the regression model. Word identification was then entered into the second

stage, and phonological memory into the third. The findings showed that the final incorporation of Time 1 IQ, age, word identification, and phonological memory did not explain a significant amount of unique variance in math fluency growth, $F(4,75) = 1.95, p > .05, R^2 = .09$ (see Table 7). Of note, Time 1 age was a significant predictor in stage 1 ($\beta = -.27, p < .05$) although it was no longer significant once all the variables were incorporated into the model. These results do not support the hypothesis that Time 1 phonological memory contributes beyond word identification skills to growth in math achievement.

Table 7
Summary of Hierarchical Regression Analysis for Time 1 Variables Predicting Change in Math Fluency After Consideration of Reading Ability (N = 80)

	Independent variable(s)	<i>t</i>	β	F	Df	<i>p</i>	R^2	adj. R^2
Stage 1				3.01	2,77	0.06	0.07	0.05
	IQ	0.34	.04					
	Age	-2.44*	-.27					
Stage 2				2.34	3,76	0.08	0.08	0.05
	IQ	0.89	.13					
	Age	-1.79	-.22					
	Word ID	-0.99	-.15					
Stage 3				1.95	4,75	0.11	0.09	0.05
	IQ	0.44	.07					
	Age	-1.97	-.25					
	Word ID	-1.01	-.15					
	Phonological Memory	0.90	.12					

* $p < .05$. ** $p < .01$

In the second set of hierarchical regressions, the dependent variable was change in math achievement. Similar to the previous regression model, Time 1 IQ and age were entered into the first stage of the regression as covariates, then word identification, and lastly, phonological memory. The regression results presented in Table 8 indicate that growth in math achievement was significantly related [$F(4,75) = 4.22, p < .01, R^2 = .18$] to Time 1 age ($\beta = -.40, p < .01$) and approaching significant

association with Time 1 phonological memory ($\beta = .25, p = .06$). These findings do not support the hypothesis that phonological memory contributes to change in math achievement when reading ability (i.e. word identification), IQ, and age are considered.

Table 8
Summary of Hierarchical Regression Analysis for Time 1 Variables Predicting Change in Math Achievement After Consideration of Reading Ability (N = 80)

	Independent variable(s)	<i>t</i>	β	F	Df	<i>p</i>	R ²	adj.R ²
Stage 1				6.23	2,77	<.01**	0.14	0.12
	IQ	1.15	.12					
	Age	-3.37**	-.36					
Stage 2				4.20	3,76	<.01**	0.14	0.11
	IQ	1.21	.17					
	Age	-2.83**	-.33					
	Word ID	-0.51	-.08					
Stage 3				4.22	4,75	<.01**	0.18	0.14
	IQ	0.32	.05					
	Age	-3.32**	-.40					
	Word ID	-0.56	-.08					
	Phonological Memory	1.95	.25					

* $p < .05$. ** $p < .01$

Contribution of Phonological Memory to Reading Development

Hierarchical regressions were conducted to evaluate the second hypothesis that phonological memory contributes to changes in reading development, specifically word identification, reading fluency, and reading comprehension. The first set of regressions assessed the contribution of phonological memory to the basic ability to identify words. As such, the dependent variable was change in word identification and the independent variables were Time 1 IQ, age, and phonological memory. To control for the influence of age and general intelligence, Time 1 IQ and age were entered in stage one of the regression and Time 1 phonological memory was entered at stage two.

Findings revealed that the overall model was significant, $F(3,76) = 11.34, p < .01, R^2 = .31$ (see Table 9). Specifically, IQ ($\beta = -.45, p < .01$) and age ($\beta = -.44, p < .01$) at Time 1 significantly contributed to change in word identification performance. Therefore, the hypothesis that phonological memory contributes to change in word identification ability over time beyond IQ and age was not supported.

Of note, reversing the order of entry (i.e., phonological memory at Stage 1 and IQ and age at Stage 2) also indicated that phonological memory was not a significant predictor of change in word identification ability over time. However, there were significant correlations between phonological memory at each time point with change in word identification. These significant correlations imply that there may be shared variance between phonological memory with IQ and age.

Table 9
Summary of Hierarchical Regression Analysis for Time 1 Variables Predicting Change in Word Identification (N = 80)

	Independent variable(s)	<i>t</i>	β	F	Df	<i>p</i>	R^2	adj. R^2
Stage 1				15.26	2,77	<.01**	0.28	0.27
	IQ	-3.72**	-.36					
	Age	-3.97**	-.38					
Stage 2				11.34	3,76	<.01**	0.31	0.28
	IQ	-4.08**	-.45					
	Age	-4.34**	-.44					
	Phonological Memory	1.67	.19					

* $p < .05$. ** $p < .01$

Another set of hierarchical regressions was conducted to evaluate the notion that phonological memory contributes to the change in reading fluency over time. As such, the dependent variable was change in reading fluency and the independent variables were Time 1 IQ, age, and phonological memory. To control for the influence of age and general intelligence, Time 1 IQ and age were entered in stage one of the

regression and Time 1 phonological memory was entered at stage two. Findings revealed that the overall model was significant, $F(3,76) = 12.34$, $p < .01$, $R^2 = .33$ (see Table 10). Specifically, change in reading fluency over time was significantly predicted by Time 1 IQ ($\beta = -.49$, $p < .01$) and age ($\beta = -.43$, $p < .01$). These results do not support the hypothesis that phonological memory contributes to change in reading fluency ability over time.

Table 10
Summary of Hierarchical Regression Analysis for Time 1 Variables Predicting Change in Reading Fluency (N = 80)

	Independent variable(s)	<i>t</i>	β	F	Df	<i>P</i>	R^2	adj. R^2
Stage 1				16.40	2,77	<.01**	0.30	0.28
	IQ	-4.04**	-.39					
	Age	-3.93**	-.37					
Stage 2				12.34	3,76	<.01**	0.33	0.30
	IQ	-4.45**	-.49					
	Age	-4.35**	-.43					
	Phonological Memory	1.81	.21					

* $p < .05$. ** $p < .01$

A third set of hierarchical regressions was conducted to examine the hypothesis that phonological memory contributes to the development of reading comprehension over time. In this analysis, the dependent variable was the change in reading comprehension while the independent variables were Time 1 IQ, age, and phonological memory. In the first stage of the regression, Time 1 IQ and age were entered as covariates while phonological memory was entered into the second stage. The results suggest that the overall model significantly predicted change in reading comprehension, $F(3,76) = 8.34$, $p < .01$, $R^2 = .25$ (see Table 11). Specifically, it was found that Time 1 IQ ($\beta = -.42$, $p < .01$) and age ($\beta = -.38$, $p < .01$) significantly predicted change in reading comprehension over time. In sum, findings from these

three sets of hierarchical regressions do not support the second hypothesis that phonological memory influences rate of change in reading ability (i.e., word identification, reading fluency, and reading comprehension).

Table 11
Summary of Hierarchical Regression Analysis for Time 1 Variables Predicting Change in Reading Comprehension (N = 80)

	Independent variable(s)	<i>t</i>	β	F	Df	<i>P</i>	R^2	adj. R^2
Stage 1				11.20	2,77	<.01**	0.23	0.21
	IQ	-3.28**	-.33					
	Age	-3.31**	-.33					
Stage 2				8.34	3,76	<.01**	0.25	0.22
	IQ	-3.61**	-.42					
	Age	-3.64**	-.38					
	Phonological Memory	1.50	.18					

* $p < .05$. ** $p < .01$

Contribution of Reading and Math to the Development of Phonological Memory

Hierarchical regressions were conducted to examine how basic reading and math skills may influence the growth of phonological memory (Hypothesis 3). In particular, five sets of hierarchical regressions were conducted. As an overview, the regressions evaluated whether change in phonological memory was influenced by: 1. basic skills (i.e., math fluency, word identification, and reading fluency); 2. higher-order skills (i.e., math achievement and reading comprehension); 3. various reading subskills (word identification, reading fluency, and reading comprehension); 4. various math skills (math fluency and math achievement); 5. all Time 1 predictors.

In the first set of hierarchical regressions, the dependent variable was change in phonological memory and the independent variables were Time 1 IQ, age, math fluency, word identification, and reading fluency. The results of the regressions indicated that the five predictors significantly predicted change in phonological

memory, $F(5,74) = 3.45$, $p < .01$, $R^2 = .19$ (see Table 12). In particular, it was found that Time 1 age significantly predicted change in phonological memory ($\beta = -.41$, $p < .01$), as did Time 1 reading fluency ($\beta = .80$, $p < .05$). Although these results provide tentative support that basic reading skills influence the growth of phonological memory, it should be interpreted with caution since there is high collinearity between Time 1 word identification and reading fluency performances.

Table 12

Summary of Hierarchical Regression Analysis for Time 1 Basic Reading and Math Skills Predicting Change in Phonological Memory (N = 80)

	Independent variable(s)	<i>t</i>	β	F	Df	<i>p</i>	R^2	adj. R^2
Stage 1				3.85	2,77	0.03*	0.09	0.07
	IQ	0.22	.02					
	Age	-2.77**	-.30					
Stage 2				3.77	3,76	0.01*	0.13	0.10
	IQ	-0.62	-.07					
	Age	-3.36**	-.43					
	Math Fluency	1.84	.26					
Stage 3				3.11	4,75	0.02*	0.14	0.10
	IQ	-1.07	-.15					
	Age	-3.49**	-.46					
	Math Fluency	1.22	.19					
	Word ID	1.05	.17					
Stage 4				3.45	5,74	<.01**	0.19	0.13
	IQ	-1.24	-.17					
	Age	-3.11**	-.41					
	Math Fluency	0.89	.14					
	Word ID	-1.45	-.57					
	Reading Fluency	2.07*	.80					

* $p < .05$. ** $p < .01$

Additional hierarchical regressions were conducted to evaluate whether higher-order math and reading skills may influence the growth of phonological memory. For this analysis, the dependent variable was change in phonological memory while the independent variables were Time 1 IQ, age, math achievement, and reading comprehension. To control for the influence of intelligence and age, these variables

were entered into the first stage of the regression. The results show that even though the overall model significantly predicted change in phonological memory over time [$F(4,75) = 2.66, p < .05, R^2 = .12$], only Time 1 age was a significant predictor ($\beta = -.45, p < .01$; see Table 13). These findings suggest that higher-order math and reading skills do not contribute to the growth of phonological memory over time.

Table 13
Summary of Hierarchical Regression Analysis for Time 1 Higher-Order Reading and Math Skills Predicting Change in Phonological Memory (N = 80)

Independent variable(s)		<i>t</i>	β	F	Df	<i>p</i>	R^2	adj. R^2
Stage 1				3.85	2,77	0.03*	0.09	0.07
Stage 2	IQ	0.22	.02					
	Age	-2.77**	-.30					
				2.74	3,76	0.05	0.10	0.06
Stage 3	IQ	-0.39	-.06					
	Age	-2.60*	-.37					
	Math Achievement	0.75	.14					
				2.66	4,75	0.04*	0.12	0.08
Stage 3	IQ	-1.07	-.19					
	Age	-2.99**	-.45					
	Math Achievement	0.53	.10					
	Reading Comprehension	1.51	.25					

* $p < .05$. ** $p < .01$

To evaluate how various reading subskills predict change in phonological memory over time, hierarchical regressions were conducted with the dependent variable as change in phonological memory and the independent variables as Time 1 word identification, reading fluency, and reading comprehension. In addition, Time 1 IQ and age were entered into the first stage of the regression as covariates. The results in Table 14 show that the final model with all three reading subskills significantly predicted change in phonological memory, $F(5,74) = 3.26, p < .05, R^2 = .18$. In particular, it was found that Time 1 age ($\beta = -.36, p < .01$) and reading fluency ($\beta = .85, p < .05$) significantly predicted change in phonological memory. Although these

findings tentatively support Hypothesis 3 that basic reading skills influence the growth of phonological memory, these results should be interpreted with caution since there is high collinearity between the Time 1 reading measures.

Table 14
*Summary of Hierarchical Regression Analysis for Time 1 Reading Subskills
Predicting Change in Phonological Memory (N = 80)*

	Independent variable(s)	<i>t</i>	β	F	Df	<i>p</i>	R^2	adj. R^2
Stage 1				3.85	2,77	0.03*	0.09	0.07
	IQ	0.22	.02					
	Age	-2.77**	-.30					
Stage 2				3.63	3,76	0.02*	0.13	0.09
	IQ	-0.92	-.13					
	Age	-3.27**	-.39					
	Word ID	1.72	.26					
Stage 3				4.13	4,75	<.01**	0.18	0.14
	IQ	-1.15	-.16					
	Age	-3.04**	-.35					
	Word ID	-1.43	-.56					
	Reading Fluency	2.25*	.85					
Stage 4				3.26	5,74	0.01*	0.18	0.13
	IQ	-1.13	-.16					
	Age	-2.87**	-.36					
	Word ID	-1.36	-.58					
	Reading Fluency	2.21*	.85					
	Reading Comprehension	0.14	.04					

* $p < .05$. ** $p < .01$

Another set of hierarchical regressions were conducted to assess how various math skills predict change in phonological memory. As such, the independent variables were Time 1 IQ, age, math fluency, and math achievement while the dependent variable was change in phonological memory. The results of the regression indicate that the overall final model was statistically significant, $F(4,75) = 2.89$, $p < .05$, $R^2 = .13$, even though only Time 1 age was a significant predictor by itself ($\beta = -$

.40, $p < .01$). These results suggest that math skills do not influence the growth of phonological memory (Table 15).

Table 15
Summary of Hierarchical Regression Analysis for Time 1 Math Skills Predicting Change in Phonological Memory (N = 80)

	Independent variable(s)	<i>t</i>	β	F	Df	<i>p</i>	R ²	adj.R ²
Stage 1				3.85	2,77	0.03*	0.09	0.07
	IQ	0.22	.02					
	Age	-2.77**	-.30					
Stage 2				3.77	3,76	0.01*	0.13	0.10
	IQ	-0.62	-.07					
	Age	-3.36**	-.43					
	Math Fluency	1.84	.26					
Stage 3				2.89	4,75	0.03*	0.13	0.09
	IQ	-0.09	-.01					
	Age	-2.83**	-.40					
	Math Fluency	1.76	.33					
	Math Achievement	-0.58	-.14					

* $p < .05$. ** $p < .01$

Lastly, a set of hierarchical regressions were conducted to evaluate how all Time 1 predictors contributed to the growth of phonological memory over time. As such, the dependent variable was change in phonological memory while the independent variables were Time 1 IQ, age, math fluency, math achievement, word identification, reading fluency, and reading comprehension. To control for the influence of age and IQ, these variables were entered first into the regression. The results presented in Table 14 indicate that overall, the model with all seven predictors significantly predicted change in phonological memory over time, $F(7,72) = 2.52$, $p < .05$, $R^2 = .20$ (see Table 16). Specifically, Time 1 age ($\beta = -.37$, $p < .05$) and reading fluency ($\beta = .82$, $p < .05$) significantly contributed to the change in phonological memory. However, these results should be interpreted with caution since there is high collinearity between all three Time 1 reading measures. For exploratory purposes, the

order of entry for the math and reading variables were changed so that basic math and reading skills (i.e. math fluency and word identification) were entered before more advanced skills (i.e., math achievement, reading fluency, and reading comprehension).

However, the order of entry did not change the final regression results.

Table 16
Summary of Hierarchical Regression Analysis for Time 1 Basic and Higher-Order Reading and Math Skills Predicting Change in Phonological Memory (N = 80)

	Independent variable(s)	<i>t</i>	β	F	Df	<i>p</i>	R ²	adj.R ²
Stage 1				3.85	2,77	0.03*	0.09	0.07
	IQ	0.22	.02					
	Age	-2.77**	-.30					
Stage 2				3.77	3,76	0.01*	0.13	0.10
	IQ	-0.62	-.07					
	Age	-3.36**	-.43					
	Math Fluency	1.84	.26					
Stage 3				2.89	4,75	0.03*	0.13	0.09
	IQ	-0.09	-.01					
	Age	-2.83**	-.40					
	Math Fluency	1.76	.33					
	Math Achievement	-0.58	-.14					
Stage 4				2.51	5,74	0.04*	0.15	0.09
	IQ	-0.53	-.09					
	Age	-2.97**	-.43					
	Math Fluency	1.26	.25					
	Math Achievement	-0.51	-.12					
	Word ID	1.01	.17					
Stage 5				2.96	6,73	0.01*	0.20	0.13
	IQ	-0.51	-.09					
	Age	-2.49*	-.36					
	Math Fluency	1.18	.23					
	Math Achievement	-0.78	-.18					
	Word ID	-1.54	-.61					
	Reading Fluency	2.14*	.83					
Stage 6				2.52	7,72	0.02*	0.20	0.12
	IQ	-0.56	-.10					
	Age	-2.41*	-.37					
	Math Fluency	1.19	.24					
	Math Achievement	-0.77	-.18					
	Word ID	-1.51	-.66					
	Reading Fluency	2.08*	.82					
	Reading Comprehension	0.28	.08					

* $p < .05$. ** $p < .01$

DISCUSSION

Much research has supported the role of phonological memory for reading and math achievement (e.g., Alloway, 2009; Geary, 2011a; Seigneuric & Ehrlich, 2005). However, less attention has been directed toward comparing how phonological memory affects the change of various skills within both reading and math domains. Additionally, little research has studied how reading acquisition may influence the development of phonological memory. To address these concerns, the present study explored the effects of phonological memory on change over time for an array of reading and math skills (math fluency, math achievement, word identification, reading fluency, and reading comprehension). In consideration of emerging research suggesting that reading acquisition may affect the development of phonological memory, the influence of various reading and math abilities on the development of phonological memory also was examined. Specifically, it was hypothesized that phonological memory would have greater influence on the rate of change in math abilities that draw on higher language demands (such as applied problem solving). Second, it was predicted that phonological memory affects the rate of change of various reading abilities, especially for higher-order reading skills such as comprehension that are used to process more complex text. In terms of examining the effects of academic skills on the development of phonological memory, it was hypothesized that the development of reading, in particular basic skills such as reading fluency, facilitates the capacity of phonological memory. Much of the research supporting the importance of phonological memory for reading achievement has recruited early young readers or extreme groups (e.g., individuals with reading and/or

math disabilities) as participants. This study contributes to the literature by examining a broad group of children after school entry that differs in various aspects: reading and math ability, age, IQ, and geographic location of where they grew up.

Effects of Phonological Memory on Changes in Math Development

The present study found that phonological memory did not contribute to the rate of change in math fluency and achievement after IQ, age, and word identification (a measure of basic reading skill) were considered. However, it should be noted that an effect of phonological memory on change in math achievement was approaching significance. Thus, the first hypothesis was not supported although there was a trend suggesting that phonological memory may be more important for math when there are greater language demands. One possible explanation for this may be because of the large age range of participants. Research suggests that phonological memory and math skills have different developmental trajectories so the influence of phonological memory on math development may vary over time (e.g., Gathercole et al., 2004; Halberda & Feigenson, 2008; Jordan, Kaplan, Oláh, & Locuniak, 2006; Raghubar et al., 2010; Siegler & Booth, 2004). For example, de Smedt and colleagues (2009) found that the phonological loop was a predictor of second but not first grade math achievement. Further, phonological memory and math skills do not develop in isolation and may converge with other skills and cognitive processes as children receive more formal schooling (Alloway et al., 2004; Baddeley, 2003a). As such, the large variability in age may have helped diminish any influence of phonological memory on math fluency and achievement.

Another potential reason for the lack of effect of phonological memory on the rate of change in math fluency and math achievement may be that other cognitive abilities are more important for the development of these math skills. Although this study attempted to address this by considering the additional effects of reading ability (specifically word identification), much research has indicated that other factors such as executive functions and visuospatial memory are more important for math development (Bull, Espy, & Wiebe, 2008; Gathercole, Brown & Pickering, 2003; Geary, 2011a; Geary, Hoard, Nugent, & Bailey, 2012). As further support, correlational results from this study indicate that phonological memory at all three time points were not associated with changes in math fluency and achievement. Thus, the contribution of other cognitive abilities to math development may be stronger and confound the influence of phonological memory. Overall, the findings do not support the first hypothesis but tentatively suggest a trend towards phonological memory having greater influence on math achievement than math fluency (the former having greater demands on language) and warrants further examination.

Effects of Phonological Memory on Changes in Reading Development

The data in this study also permit an evaluation of how phonological memory contributes to changes in reading abilities, specifically word identification, reading fluency, and reading comprehension. There were consistent findings that after considering IQ and age, phonological memory did not significantly contribute to change in the three reading abilities over time. As such, the second hypothesis that phonological memory contributes to rate of change in reading abilities (especially higher-order reading comprehension) was not supported. Instead, the findings from

this study complement research highlighting that other abilities instead of phonological memory (such as phonological awareness and vocabulary) may be important for the development of subsequent reading abilities (Bowey, 2001; Gathercole & Baddeley, 1993; Melby-Lervåg et al., 2012; Nation & Hulme, 2011; Savage et al., 2007; Torppa, Lyytinen, Erskine, Eklund, & Lyytinen, 2010; Wagner et al., 1997).

Another possible explanation for these results is that the operationalizations of word identification, reading fluency, and reading comprehension were too broad. Studies have shown that these reading constructs involve many different cognitive skills and processes, some of which may be more important than phonological memory in contributing to reading outcomes (Cain, Oakhill, & Bryant, 2004; Nation, 2005; Oakhill et al., 2003; Vellutino et al., 2007). For example, some components involved in reading comprehension include phonological skills, vocabulary, inference and integration skills, knowledge about text structure, and comprehension monitoring (metacognitive ability to detect text inconsistencies; see Nation (2005) for a detailed discussion of processes involved in reading comprehension). Cain and colleagues (2004) examined how reading comprehension was influenced by phonological memory, verbal ability, and components of reading comprehension (specifically story structure knowledge, inference ability, and comprehension monitoring) in children aged seven years old over three years. They found that in each year, phonological memory significantly contributed to reading comprehension even after the contributions of several covariates (word reading accuracy, vocabulary, and verbal ability) were considered. In addition, inference and comprehension monitoring

abilities significantly predicted reading comprehension even after the contributions of covariates and phonological memory were considered. However, story structure knowledge only made significant additional contributions to reading comprehension at Time 3, when the participants were 10 years old. As such, the contribution of phonological memory to reading achievement in this study may have been overshadowed by the contributions of component processes involved in word identification, reading fluency, and reading comprehension.

The lack of significant findings also may be influenced by the development of the participants' phonological memory. In this study, although average phonological memory increased over time, examination of individual differences in how phonological memory changed over time by cohort revealed more complex patterns. Specifically, the rate of change in median phonological memory scores generally increased from 6 to 8 years old, was constant for 9 year olds, and then decreased from 10 to 11 years old (Tables 18A-F in Appendix B; median scores were compared due to unequal number of participants in each age group). This suggests that 8-year-old participants demonstrated greater growth in their phonological memory from Time Points 1 to 3 compared to 6-year-old participants. On the other hand, 11-year-olds displayed the greatest decrease in phonological memory over Time Points 1 to 3. As such, phonological memory may develop differently at each age or reading development. This implies that longitudinal data for a specific cohort – instead of looking across cohorts – would help diminish the effects of individual differences for different ages and would facilitate examination of changes associated with development. In addition, examination of correlations show that phonological memory

measured at Time 1 was not associated with rate of change in word identification, reading fluency, and reading comprehension. Interestingly, phonological memory measured a year later (i.e., Time 2) was significantly associated with changes in all three reading abilities but at Time 3 was only associated with change in word identification. This may reflect difficulties with combining data across ages and stages of reading development. Overall, these results suggest that the development of phonological memory is complex and depends on age and which reading ability is used as the outcome measure.

Influences of Math and Reading Skills on Changes in Phonological Memory

Although much research has examined the influence of phonological memory on academic skills development, there has been less focus on the effects of reading acquisition on the development of phonological memory. Results from the few available studies that have investigated this suggest that reading acquisition can affect enhance phonological memory (Kosmidis et al., 2011; Matute et al., 2012). However, this was only examined by comparing illiterate and literate individuals. The present study was the first to investigate the effects of reading and math skills on the rate of change in phonological memory for children who have already received formal schooling. Studying the influence of math skills on the development of phonological memory also served as a contrast domain to reading. Specifically, in this study math fluency, word identification, and reading fluency were measures of basic math and reading skills while math achievement and reading comprehension represented higher-order skills. Five hierarchical regressions were conducted to examine how various predictors affected change in phonological memory beyond the influence of IQ and

age: 1. basic math and reading skills; 2. higher-order math and reading skills; 3. all three reading skills; 4. both math skills; 5. all math and reading predictors. Together, the regression results provide strong support for an effect of reading acquisition on phonological memory.

The findings on how basic reading and math skills may influence change in phonological memory show that age and reading fluency at the start of the study predicted change in phonological memory over three years. Specifically, more stable phonological memory over time was predicted by older participants' age and by faster reading fluency at the beginning of the study after considering IQ, math fluency, and word identification. Examining the effects of higher-order reading and math skills (i.e., reading comprehension and math achievement, respectively) on change in phonological memory revealed that age was the only significant predictor, with older participants demonstrating more stable phonological memory over time. The findings from the current study also indicate that when the contributions of the three reading skills (word identification reading fluency, and reading comprehension) to change in phonological memory were evaluated, age and reading fluency at Time 1 made significant contributions after considering IQ and the other reading skills. In particular, older participants and faster reading fluency at Time 1 predicted less change in phonological memory over time. To serve as a contrast comparison, the influence of various math skills on change in phonological memory was examined. As expected, neither math fluency or math achievement made significant contributions after IQ and age were considered. Further, when the contributions of IQ, age, and the math and reading skills to change in phonological memory was assessed together, only reading

fluency and age were significant predictors. The current findings should be interpreted with caution, however, as correlations suggested collinearity between the reading subskills.

In sum, these findings support the third hypothesis that the development of reading, in particular basic reading skills, predicts increases in the capacity of phonological memory. Specifically, slower reading fluency was associated with greater change in phonological memory, suggesting that basic reading skills may more strongly influence changes in phonological memory instead of higher-order reading skills. In support of this, researchers have posited that faster reading fluency involves rapid and efficient low-level phonological processing that allows more cognitive resources in verbal memory to be available for higher level processing (Fuchs et al., 2001). Conversely, inefficient reading fluency places more demands on phonological memory and other processes involved in reading. As children develop from beginning to skilled readers, reading experience may enhance subvocal rehearsal strategies, allowing more items to be maintained in phonological memory (Gathercole et al., 2004; Hulme et al., 1984; Roodenrys et al., 1993). Another potential mechanism of how reading acquisition might have an impact on memory is that it may initiate utilizing finer-grained phonological representations for spoken words that may facilitate the efficiency of phonological memory (Ardila et al., 2010; Baddeley, 2003a; Huettig & Mishra, 2014; Melby-Lervåg & Hulme, 2010; Petersson et al., 2000). Another explanation of how reading fluency may influence phonological memory development is that as reading fluency increases, children are better able to connect orthographic representations with phonological representations that improve the

quality, strength, and recall of mental representations in phonological memory (Baddeley, 2003a; Clark & Wagner, 2003; Dehaene et al., 2015; Koda, 1989; Perfetti, 2007). The different contributions of math and reading skills to change in phonological memory also complement much research supporting stronger relations between phonological memory with reading compared to with math (Geary, 2011a; Raghobar et al., 2010).

Limitations

The current study has several limitations that should be considered, the first of which pertains to the characteristics of the sample. Specifically, the sample size was small and there was large variability in the participants' age, level of education, and where they were geographically located (i.e., from Massachusetts to New Jersey). This could have biased the findings because the children who participated might have differed from those who did not participate in this study. For example, the differences in quality of schools and socioeconomic communities in which the participants resided could have affected changes in their cognitive and academic abilities (e.g., amount of resources available to support early cognitive development). Additionally, research suggests that phonological memory and math and reading skills may have different developmental trajectories and that the influence of phonological memory on these academic skills varies over time (e.g., Gathercole et al., 2004; Jordan et al., 2006; Seigneuric & Ehrlich, 2005; Siegel, 1994; Siegler & Booth, 2004). The large variability in age and the small number of participants in each age group is likely to have decreased sensitivity to changes in these abilities (see Appendix B for changes in phonological memory and math and reading skills for the students at each beginning

age). In turn, this could influence findings on the reciprocal relations between various math and reading skills with phonological memory. A future study with a larger sample size and a more homogeneous sample of participants could overcome these limitations. As well, a short-term longitudinal design that allows comparison of groups at overlapping age or grade points or a longer longitudinal study would be useful in providing a better understanding of the relations between phonological memory and math and reading development.

It also would have been preferred if data collection began prior to or at the beginning of school entry. Research has suggested that the early years of formal instruction has a large role on the development of phonological memory and basic math and reading skills that then influences later academic performance (Gathercole et al., 2004; Halberda & Feigenson, 2008; Jordan et al., 2006; Nevo & Breznitz, 2011). Neurocognitive studies also show that formal instruction induces changes in brain areas that are correlated with reading skills (e.g., Dehaene et al., 2015; Petersson et al., 2000; Petersson, Reis, & Ingvar, 2001). As such, assessment of phonological memory and academic skills with a younger sample of participants would allow for a better understanding of how formal education influences the relations between phonological memory and math and reading skills over time.

Another limitation pertains to the measure used to assess phonological memory. The Memory for Digits and Nonword Repetition subtests were combined to produce a composite phonological memory score. However, research has suggested that the two tasks may differ in the extent to which they tap components such as vocabulary knowledge and knowledge of the phonological structure of language

(Gathercole, 1995; Gathercole, Willis, Baddeley, & Emslie, 1994; Snowling et al., 1991). As mentioned, studies have found that performance on nonword repetition tasks can be influenced by various factors such as wordlikeness and pseudoword length (Gathercole, 1995; Gathercole et al., 1991; Rueckl & Olds, 1993). Further, some studies that have measured phonological memory with different tasks (e.g., distinguishing between Memory for Digits and Nonword repetition) have found varying results on the relations between phonological memory and reading abilities (e.g., Gathercole et al., 1994; Leather & Henry, 1994; Müller & Brady, 2001; Oakhill et al., 2003). To address this limitation, a future study could examine the relations between math and reading skills with phonological memory measured by the Memory for Digits and Nonword Repetition subtests separately.

Finally, several statistical limitations should be considered. In this study outcome measures were calculated by determining the linear change over time (i.e., slope). However, some research suggests that the development of cognitive and academic abilities may not fit a linear growth trajectory (Gathercole et al., 2004; Jordan et al., 2006; Shrager & Siegler, 1998; Siegler & Booth, 2004). Further, because the calculation of slope is sensitive to the number of available data points, an alternative could be to conduct hierarchical regressions using Time 3 outcomes instead of change over time. Additionally, there were high correlations among the reading subskills that could have inflated the hierarchical regression results. A more rigorous approach would have been to use factor analysis to elucidate latent reading factors and growth curve modeling which could accommodate more flexible growth trajectories.

Implications and Future Directions

The findings from this study show a tentative trend towards Time 1 phonological memory predicting Time 1 math achievement (but not math fluency) after the contributions of IQ and age were considered. Since math achievement was measured with a task that had more language demands than math fluency, this suggests that phonological memory may be involved in math when the task places greater demands on reading. The significance of this in relation to the influences of other types of memory can be elucidated with more research comparing the effects of the central executive and visuospatial sketchpad on change in reading and math skills.

Further, this study examined the reciprocal influence of reading and math skills on phonological memory. The results show that Time 1 reading fluency, a relatively basic reading skill, consistently predicted change in phonological memory beyond IQ, age, word identification, reading comprehension, math fluency, and math achievement. This suggests that after formal schooling has begun there are effects of reading acquisition on phonological memory. As mentioned, collection of data before school entry with a larger sample of participants would provide a better evaluation of how math and reading acquisition influences the development of phonological memory over time. As well, a future study could examine the influence of reading and math skills on Time 3 outcomes instead of change over time (i.e., slope).

In conclusion, the present study provided preliminary support that phonological memory has greater influence on the rate of change in math abilities that have greater language demands. Contrary to expectations, there was no evidence for phonological memory influencing the rate of change of various reading abilities. The

study also showed that reading (but not math) acquisition influences the development of phonological memory. These findings indicate the value of investigating how phonological memory is associated with various reading and math skills, and the potential influence of reading on phonological memory over time.

APPENDICES

Appendix A: Timing of Assessments

Table 17
Measures Administered at Each Time Point

Time	<i>N</i>	Administered Measure
6-11 years old	80	IQ Phonological memory Math fluency Math achievement Word identification Reading fluency Reading comprehension
Year 1 later	80	Phonological memory Math fluency Math achievement Word identification Reading fluency Reading comprehension
Year 2 later	80	IQ Phonological memory Math fluency Math achievement Word identification Reading fluency Reading comprehension

Appendix B: Change in Median Raw Scores By Age

Table 18

A. Phonological Memory Median Raw Scores By Age Group

Age Group (Years)	Time 1	Time 2	Time 3	Rate of Change
6	19.5	21.5	21.5	1.0
7	22.0	24.0	23.0	0.5
8	23.0	23.0	26.0	1.5
9	23.0	21.0	23.0	0.0
10	24.0	24.0	23.0	-0.5
11	25.5	28.0	22.0	-1.8

Table 18

B. Math Fluency Median Raw Scores By Age Group

Age Group (Years)	Time 1	Time 2	Time 3	Rate of Change
6	17.0	32.5	52.0	17.5
7	33.0	40.0	57.0	12.0
8	36.0	54.0	58.0	11.0
9	36.0	55.0	59.0	11.5
10	50.0	61.0	72.0	11.0
11	49.0	65.5	68.5	9.8

Table 18

C. Math Achievement Median Raw Scores By Age Group

Age Group (Years)	Time 1	Time 2	Time 3	Rate of Change
6	27.5	32.0	35.0	3.8
7	30.0	36.0	40.0	5.0
8	32.0	40.0	43.0	5.5
9	33.0	39.0	40.0	3.5
10	36.0	38.0	41.0	2.5
11	40.0	45.5	46.5	3.3

Table 18

D. Word Identification Median Raw Scores By Age Group

Age Group (Years)	Time 1	Time 2	Time 3	Rate of Change
6	40.0	49.0	54.5	7.3
7	39.0	47.0	53.0	7.0
8	49.0	58.0	60.0	5.5
9	50.0	54.0	56.0	3.0
10	53.0	55.0	63.0	5.0
11	53.0	57.0	60.5	3.8

Table 18

E. Reading Fluency Median Raw Scores By Age Group

Age Group (Years)	Time 1	Time 2	Time 3	Rate of Change
6	71.5	81.5	100.0	14.3
7	59.0	84.0	100.0	20.5
8	93.0	98.0	106.0	6.5
9	96.0	110.0	119.0	11.5
10	89.0	100.0	109.0	10.0
11	93.0	103.0	106.5	6.8

Table 18

F. Reading Comprehension Median Raw Scores By Age Group

Age Group (Years)	Time 1	Time 2	Time 3	Rate of Change
6	22.0	28.0	29.5	3.8
7	20.0	30.0	31.0	5.5
8	30.0	33.0	34.0	2.0
9	30.0	32.0	33.0	1.5
10	30.0	33.0	33.0	1.5
11	33.5	36.0	38.0	2.3

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