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DIRECT AND INDIRECT EFFECTS OF PHONOLOGICAL ABILITY AND VOCABULARY KNOWLEDGE ON MATH PERFORMANCE IN ELEMENTARY SCHOOL*

The main aim of this study was to estimate direct and indirect effects of phonological ability and vocabulary knowledge on subsequent mathematics and reading performance. To achieve our goals we used two-wave longitudinal data from the international Performance Indicators in Primary Schools (iPIPS) data set, which was produced in Russia in 2015-2016. We used rhyming skills and ability to repeat words/pseudowords as indicators of phonological ability, and identified three types of mathematical skills (digit identification, number manipulations and formal math). The results of our analysis confirmed the predictive role of preschool phonological ability as a domain-general precursor of later achievements. Phonological ability had a positive direct and indirect effects on the subsequent reading and math performance. Moreover, the direct effect was higher than the indirect effect. Reading fluency mediated the effect of phonological ability and did not mediate the effect of vocabulary knowledge. Vocabulary knowledge had insignificant direct effect on math achievement and positive indirect effect via phonological ability.

Keywords: iPIPS; phonological abilities; vocabulary knowledge; mathematics; reading comprehension, elementary school

JEL Classification: Z

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Introduction

Phonological abilities refer to the sensitivity people possess for the sounds of their language and to their capacity to use these sounds to decode linguistic information (Mann & Ditunno, 1990; Wagner & Torgesen, 1987). There were identified several types of skills which related to phonological abilities: phonological short-term memory (STM) , rate of access to phonological name codes from long-term memory (LTM), phonological awareness (access to the sound structure of oral language) and rhyming skills (e.g. Hecht, Torgesen, Wagner, and Rashotte, 2001; Bryant, Maclean, Bradley, and Crossland, 1990; Gathercole, Willis, Emslie & Baddeley, 1991; Bryant, et al., 1989; Gathercole et al., 1999).

It was demonstrated that reading progress can be predicted by a level of phonological abilities, while difficulties in reading correlated with low levels of phonological abilities (e.g. Bryant, Maclean, Bradley, and Crossland, 1990; Gathercole, Alloway, Willis, & Adams, 2006; Leather & Henry, 1994; Muter, Hulme, Snowling, & Stevenson, 2004; Kirby, Parrila & Pfeiffer, 2003).

Another important source of reading development is vocabulary knowledge that refers to understanding the meaning of individual words (e.g. Muter, et al., 2004). There is evidence that vocabulary knowledge along with phonological abilities and grammatical skills can predict later reading comprehension (e.g. Muter, Hulme, Snowling, & Stevenson, 2004; Verhoeven , van Leeuwe & Vermeer, 2011; Torgeson, Wagner, Rashotte, Burgess, & Hecht, 1997; Verhoeven & van Leeuwe, 2008). Several studies emphasized close relationships between some indicators of phonological abilities (such as rhyming skills or phonological short-term memory (STM)) with vocabulary knowledge. Particularly, some studies demonstrated that phonological STM plays a causal role in vocabulary growth (e.g. Gathercole, Willis, Emslie, & Baddeley, 1991), others suggested that vocabulary knowledge predicted phonological STM (e.g. Roberts, 2005; Metsala, 1999).

The predictive role of phonological abilities for math development is less studied. Some studies confirmed the significant relations between phonological abilities and math achievements (e.g. Leather and Henry, 1994; Hecht, Torgesen, Wagner, & Rashotte, 2001). Discussing the predictive role of phonological abilities on math skills, researchers suggested several explanations for this relationship. Firstly, correlations between phonological abilities and mathematics may be explained by involvement of speech sound processes used to solve math problems (e.g. Bull & Johnston, 1997; Rourke & Conway, 1997). In order to solve a problem, children may firstly transform some operators into a speech-based code. For example, transformation of Arabic digits into number words is routinely used by children to solve arithmetic problems (Geary, Bow-Thomas, Liu, Siegler, 1996).

Secondly, when solving a math problem children may retrieve the answer from their long-term memory that demands the involvement of phonological processing (e.g. Geary et al., 1999). Consistent with this prediction, numerous studies have reported a significant association between phonological memory and individual differences in mathematical computation skills in children (e.g., Bull & Johnston, 1997; Geary, Brown, & Samaranayake, 1991). Particularly, it was shown that the rate of access to phonological information in long-term memory is related to individual differences in math computation skills (e.g., Bull & Johnston, 1997; Geary, 1993; Hitch & McAuley, 1991). It was also demonstrated that children with math disabilities had relatively poorer phonological memory abilities while mathematically gifted children tended to have high phonological memory abilities (e.g., Dark & Benbow, 1991; Siegel & Ryan, 1989). It was suggested that phonological processing deficits could impair some aspects of mathematical abilities that rely on the manipulation of verbal code such as counting speed and number fact recall (Simmons & Singleton, 2007). Probably, the same working memory resources are involved both in math computational tasks and phonological processing.

Besides the effect of phonological memory, other types of phonological abilities were considered as possible predictors of math acquisition. Bryant, MacLean, Bradley, and Crossland (1990) reported significant correlations between performance on various phonological awareness tasks and later individual differences in math computation skills (Bryant, MacLean, Bradley, and Crossland (1990). Hecht, Torgesen, Wagner, and Rashotte (2001) in longitudinal studies demonstrated that individual differences in phonological awareness along with phonological memory and rate of access explained the growth in general computation skills from the second to fifth grades even when general verbal ability and prior computation skills were controlled (Hecht, Torgesen, Wagner, & Rashotte, 2001). It was also found that the impact of phonological awareness on math achievements in elementary school was mediated by early quantity–number competencies. Phonological awareness predicted basic numerical competencies (i.e., quantity discrimination or knowledge about number-word sequences) but had no effect on higher numerical competencies (Krajewski, Schneider, 2009**).**

Although theoretical underpinning of relations between phonological abilities and math performance existed, some studies failed to find significant correlations between phonological abilities and math (e.g. Jong and van der Leij, 1999; Passolunghi, Vercelloni, Schadee, 2007). In line with these results, phonological abilities were found to be unique predictors of reading performance but not mathematics (Bradley & Bryant, 1983; Bryant et al., 1990; Passolunghi , Vercelloni &Schadee, 2007). Some studies showed that math difficulties may be related to a basic deficit in learning to count rather than to the generalized weakness in phonological storage mechanisms (Hitch & McAuley, 1991; Siegel & Ryan, 1989). Children with both math and reading difficulties usually demonstrated a deficit in phonological processing ability, while children with only math difficulties often did not show phonological impairments (e.g., Geary, 1993; Rourke & Conway, 1997). Potentially, memory deficits associated with arithmetical difficulties may be secondary to the more basic deficit in learning to count (Krajewski, Schneider, 2009**).**

On the one hand, relations between phonological abilities and mathematics may be mediated by reading abilities. It is a well-established fact that individual differences in reading and math skills are correlated (e.g. Ackerman & Dykman, 1995; Rasanen & Ahonen, 1995; Share, Moffit, & Silva, 1988). Moreover, sometimes children with language deficits demonstrated a low level of math competencies (e.g. Koponen, Mononen, Räsänen & Ahonen, 2006). A level of reading achievements was positively related to the subsequent acquisition of mathematical content (Shin et al., 2013). Jordan, Hanich, and Kaplan (2002) found that children who started school with specific reading difficulties were at risk for developing secondary or associated mathematics difficulties (Jordan, Kaplan& Hanich, 2002). In contrast, mathematics abilities did not have a significant influence on reading growth. In line with this model, phonological processing may have indirect effect on math performance via reading abilities. Children may have math difficulties as a result of poor reading skills that in turn might arise as a result of phonological deficits.

On the other hand, some authors suggested that correlations between math and reading skills could be explained by domain-general cognitive processes which underlay both math and reading skills. Particularly, individual differences in reading and math computation skills should be correlated to the extent that both academic domains are influenced by the same core phonological processing ability or abilities (Ackerman & Dykman, 1995; Geary, 1993; Rourke & Conway, 1997). From this point of view, phonological abilities influence both academic domains rather than reading itself effected on math performance (or vice versa) (Geary, 1993; Rourke & Conway, 1997). This model implies that phonological processing might have direct effect on math skills even taking into account reading skills.

The overarching goal of the current study is to compare two models of relations between phonological abilities, vocabulary knowledge and mathematics. The first model implies that phonological abilities and vocabulary knoeledge have only indirect effect on mathematics via reading skills. The second model implies that phonological abilities have direct effect on mathematics and influence both reading and mathematics. To achieve our goals we estimated direct and specific indirect (via reading performance) effects of phonological abilities and vocabulary knowledge at the beginning of schooling on some components of math performance at the end of the first grade. In order to identify direct and specific indirect effects of phonological ability and vocabulary knowledge on math performance a set of structural equation models were tested.

Method

Participants

This study was conducted in the central part of Russia, in Tatarstan Republic. The data for the current study was collected during the 2015-2016 academic year. The participants were recruited from schools using two-stage stratified cluster random sampling. The first stratification criterion was school location, defined by the administrative jurisdictions (there was a total of 14 districts, both rural and urban). The second criterion was school type; within each district, some schools were classified as regular and others as specialized schools (i.e., schools with additional instruction in one or more academic subjects, such as math, science or foreign language). The number of classes participating in the assessment depended on school size.

The first stage of the assessment was conducted in October 2015, whereas the second stage was conducted in May 2016. The initial sample assessed in October 2015 included 5265 children. However, during the second stage of the assessment in May 2016, some children had transferred to other schools or were sick. Thus, the resulting sample consisted of 5095 first-graders (50% were girls) from 151 schools (255 classrooms). The mean age was 7.3 years at the beginning of the school year and 7.8 years at the end.

The data were collected anonymously. The parents of the respondents gave their informed consent before the start of the survey.

Instruments and measures

All measures were obtained during On-entry Baseline and Follow-up assessments through the Russian versions of the iPIPS (international Performance Indicators in Primary Schools) instrument. iPIPS is based on the Performance Indicators in Primary Schools monitoring system (PIPS) that was developed in the Centre for Education and Monitoring at Durham University in the UK (Tymms, 1999; Tymms et al., 2015). The development of the Russian version of the iPIPS assessment was conducted from 2013 to 2015 (Kardanova et al., 2014; Ivanova, Nisskaya, 2015).

Children were assessed on the one-on-one basis by trained testers using computer-assisted software. The assessment, which lasted approximately 15 to 20 minutes, occurred in school, in a separate quiet room. Each child sat with a tester in front of a computer. The computerized software-guided test administration employed a dynamic adaptation algorithm, that is, a sequence of items with stopping rules.

Because the items within each section were arranged in order of increasing difficulty, children started with easy items and moved on to progressively more difficult ones. When a child made three consecutive or four cumulative errors throughout the section, the assessment of that section stopped and the child proceeded to the next section. The tester entered the child's answers into the software during each assessment.

This instrument assessed vocabulary knowledge, phonological ability, reading performance, and e mathematics performance at the beginning and at the end of the first year of schooling. We used two types of tasks to assess phonological ability: rhyme tasks and word/pseudoword repetition. We also identified two types of reading performance (reading fluency and reading comprehension) and three types of early math performance (digit identification, number manipulations, formal math).

In order to assess vocabulary knowledge, sixteen sets of images were presented to children. Each set contained five images: one correct and four distractors. Distractors were related to the correct answer either semantically (for example, animals, plants) or visually. Children had to listen to a word (e.g. hoof, microscope, pelican, scroll, sphere, aerosol) and identify the right picture within a set. The number of correct answers was used as the indicator of vocabulary knowledge.

We used two types of tasks to assess phonological abilities: rhyming tasks and word/pseudoword repetition tasks. For a rhyming task a child had to select a word rhyming with a target word from three options. In total, five target words were presented. In the task of word/pseudoword repetition, children repeated a word or pseudoword (for example, "frigliyaga" (pseudoword) and "stop" (word)), immediately after hearing it pronounced by the assessment software. There were five items for word repetition and three items for pseudoword repetition.

Tasks for estimation of reading fluency included fluent printed word recognition and reading simple sentences that a child was asked to read aloud. The words were of high frequency and common to most reading schemes. Each word, which was recognized and read correctly, was counted as a correct answer. The maximum scores for these items were 43.

Tasks for estimation of reading comprehension included two stories which required a child to read the passage and at certain points select one word from the choice of three that best fits that position in the sentence. The maximum scores for this task were 36. We included into analysis the measure of reading comprehension at the end of school year only.

We identified three types of mathematics performance: two simple skills (digit identification and number manipulation) were measured at Time 1 and Time 2 and more complex math skills (formal math) were measured at Time 2. In a digit identification set of items a child was asked to name numbers which were demonstrated visually. Eighteen one-, two-, three-, four- and more-digit numbers could be presented in total. Number manipulation skills were assessed by six items. A child was asked how many more or less a number is than a target. A target number was presented on the screen together with a set of dots (for example, the child saw five dots on the screen and was asked, "What number is three more than five?"). Eighteen items were presented to measure formal math skills in which children had to solve different math problems. Some items included addition and subtraction problems presented without symbols. Some items included formal arithmetic and word problems.

Statistical analysis

We ran a set of models to assess how phonological ability and vocabulary knowledge at the start of the first year of schooling (Time 1) predicted formal math and reading comprehension at the end of the first year of schooling (Time 2). Phonological ability was estimated as a latent construct which was manifested by rhyming skills and repeating words/pseudowords. Firstly, we tested model where phonological ability had no direct effect and have only indirect effect (via reading fluency) on math performance at Time 2 and where only reading fluency at Time 1 and previous math skills predicted later math performance (Model 1). On this model phonological ability and vocabulary knowledge predicted later reading performance only. This model is presented in the Figure 1, correlations between variables at Time 1 and at Time 2 are estimated at the model but are not shown.

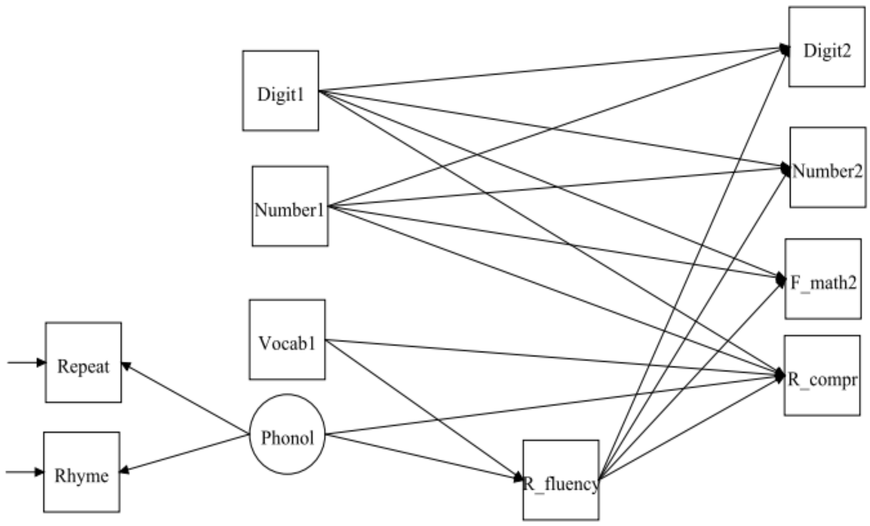

Figure 1. Path diagram for Model 1 (correlations arrows are missed)

Next, we tested models where phonological ability and vocabulary knowledge had direct effects on math performance and reading performance at Time 2 along with digit identification, number manipulation and reading fluency at the start of schooling (Model 2).

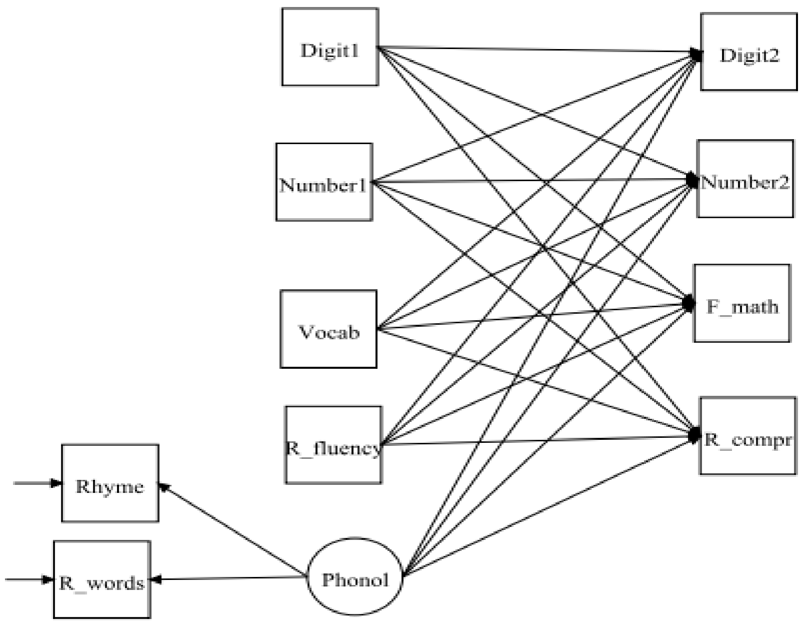

Figure 2. Path diagram for Model 2 (correlations arrows are missed)

Then we tested the model where phonological ability and vocabulary knowledge have both direct and the indirect effects on different types of math performance to compare direct and indirect effects (Model 3).

All variables were standardized before including into the analysis. The analysis was done using Mplus7 statistical package (Muthen & Muthen, 1998-2012).

Results

Descriptive statistics for our measures at the beginning and at the end of the school year are presented in the Table 1.

Table 1. Descriptive statistics

	Predictors (Time 1)			Outcomes (Time 2)		
	Mean	SD	Range	Mean	SD	Range
Rhymes	3.06	1.62	0 - 5			
Repeating words/pseudowords	5.13	1.95	0 - 8			
Vocabulary knowledge	7.71	3.70	0 - 16			
Reading fluency	27.99	15.78	0 - 43			
Digit identification	6.18	3.81	0 - 18	9.42	4.18	0 - 18
Number manipulation	1.76	1.74	0 - 6	3.57	1.83	0 - 6
Reading comprehension				22.07	11.25	0 - 36
Formal math				12.25	4.22	0 - 18

As we can see, digit identification and number manipulation skills increased during the first year of schooling.

In order to estimate the relations between phonological ability, vocabulary knowledge and math and reading achievements three models were tested. Fit indices for these models are presented in the Table 2.

Table 2. Goodness-of-fit indices

GOF	Model 1	Model 2	Model 3
AIC	123967.7	123852.5	123852.5
BIC (sample-size	124142.3	124047.3	124047.3

adjusted)			
χ^2	179.4	52.26	52.26
df	13	7	7
RMSEA	.050	.036	.036
90% C.I. RMSEA	.044 - .057	.027 - .045	.027 - .045
CFI	.99	.99	.99
SRMR	.024	.01	.01

As we can see from the Table 2, all models had good fit indices although Model 1 where phonological ability had no direct effect on subsequent math performance had worse fit indices than the other models.

Firstly, we tested the model where phonological ability had no direct effect on math performance and had only indirect effect via reading fluency. As we noted earlier, this model fitted data worse than the other models. Path coefficients for this model are presented in the Table 3.

Table 3. Path coefficients (Model 1)

Outcomes	Predictors	Unstandartized coefficients		Standartized coefficients	p	R^2
		B	SE	β		
Formal math2	Digit identification 1	.23	.01	.25	.00	.27
	Number manipulation 1	.20	.01	.22	.00	
	Reading fluency1	.16	.01	.17	.00	
Digit identification2	Digit identification 1	.58	.01	.60	.00	.52
	Number manipulation 1	.12	.01	.12	.00	
	Reading fluency1	.08	.01	.08	.00	
Number manipulation2	Digit identification 1	.18	.02	.19	.00	.20
	Number manipulation 1	.23	.01	.24	.00	
	Reading fluency1	.13	.01	.13	.00	
Reading comprehension 2	Digit identification 1	.01	.02	.01	.72	.30
	Number manipulation 1	.03	.02	.03	.25	
	Phonological ability1	.86	.12	.46	.00	
	Vocabulary knowledge1	-.09	.03	-.09	.00	
	Reading fluency1	.15	.03	.16	.00	
Reading fluency 1	Phonological ability1	1.39	.09	.72	.00	.42
	Vocabulary knowledge1	-.15	.03	-.15	.00	

In this model reading fluency had a significant effect on each of math outcomes. The highest effect was found for formal math (B= .16, s.e. = .01, β = .17, p<.01). For digit knowledge and number manipulation the effect was lower (B= .08, s.e. = .01, β = .08, p<.01 and B= .13, s.e. = .01, β = .13, p<.01, respectively).

Phonological ability had a positive effect on reading fluency at Time 1 (B= 1.39, s.e. = .01, β = .72, p<.01) and reading comprehension at Time 2 (B= .16, s.e. = .01, β = .17, p<.01). Under control of phonological ability vocabulary knowledge had a negative direct effect on reading fluency and reading comprehension (B= -.15, s.e. = .03, β = -.15, p<.01 and B= -.09, s.e. = .03, β = -.09, p<.01, respectively).

Results of Model 1 demonstrated that number manipulation and digit identification at the beginning of the first year had a significant effect on formal math at the end of school year. Digit identification had a greater effect than number manipulation. Interestingly, digit identification was more stable across time than number manipulation as the autoregressive coefficient for digit identification was higher than for number manipulation (.58 and .23, respectively).

Next, we tested model where phonological ability and vocabulary knowledge had a direct effect on later math performance. Regression coefficients from Model 2 are presented in the Table 4.

Table 4. Path coefficients (Model 2)

Outcomes	Predictors	Unstandartized coefficients		Standartized coefficients	p	R^2
		B	SE	β		
Formal math2	Digit identification 1	.21	.02	.22	.00	.30
	Number manipulation 1	.10	.02	.11	.00	
	Phonological ability1	.47	.09	.26	.00	
	Vocabulary knowledge1	.03	.02	.03	.13	
	Reading fluency1	.05	.02	.05	.043	
Digit identification2	Digit identification 1	.57	.01	.59	.00	.52
	Number manipulation 1	.08	.02	.08	.00	
	Phonological ability1	.18	.07	.10	.011	
	Vocabulary knowledge1	.02	.02	.02	.21	

	Reading fluency1	.035	.02	.04	.055	
Number manipulation2	Digit identification 1	.17	.02	.17	.00	.22
	Number manipulation 1	.17	.02	.17	.00	
	Phonological ability1	.33	.09	.17	.00	
	Vocabulary knowledge1	.01	.02	.01	.66	
	Reading fluency1	.05	.02	.05	.054	
Reading comprehension 2	Digit identification 1	.00	.02	.00	.85	.34
	Number manipulation 1	-.01	.03	-.01	.73	
	Phonological ability1	1.05	.14	.55	.00	
	Vocabulary knowledge1	-.08	.03	-.08	.00	
	Reading fluency1	.11	.03	.11	.00	

The results of Model 2 demonstrated that even after controlling for reading fluency at Time 1, phonological ability had a significant impact on subsequent math performance. The highest effect was found for formal math (B= .47, s.e. = .09, β = .26, p<.01). For digit knowledge and number manipulation the effect was lower (B= .18, s.e. = .07, β = .10, p<.01 and B= .33, s.e. = .09, β = .17, p<.01, respectively). Among all the measures of math performance only formal math was predicted by reading fluency at Time 1 (B= .05, s.e. = .02, β = .05, p<.05). Vocabulary knowledge was not a significant predictor for any of the math outcomes.

None of the math skills at Time 1 predicted reading comprehension at Time 2. Reading comprehension was predicted by previous reading fluency (B= .11, s.e. = .03, β = .11, p<.01), and vocabulary knowledge (B=- .08, s.e. = .03, β =0 .08, p<.01). Contrary to intuition, vocabulary knowledge had a negative effect on subsequent reading comprehension under control of previous reading fluency and math performance.

At the next step, we tested the model where phonological ability and vocabulary knowledge had both direct and indirect effects (via reading fluency) on the subsequent math outcomes. The results of mediation analysis are presented in the Table 5.

Table 5. Standardized coefficients for total, direct and indirect effects of phonological ability and vocabulary knowledge on math outcomes (the mediator is reading fluency)

Outcomes	Predictors	Total effect		Direct effect		Indirect effect	
		B	p	B	p	B	p
Formal math2	Phonological ability1	.29 (.04)	.00	.26 (.05)	.00	.04 (.02)	.037
	Vocabulary knowledge1	.026 (.021)	.21	.033 (.022)	.13	-.008 (.003)	.03
Digit identification2	Phonological ability1	.12 (.03)	.00	.09 (.03)	.01	.026 (.013)	.051
	Vocabulary knowledge1	.016 (.015)	.31	.021 (.017)	.21	-.005 (.003)	.055
Number manipulation2	Phonological ability1	.21 (.04)	.00	.174 (.048)	.00	.034 (.018)	.049
	Vocabulary knowledge1	.003 (.02)	.89	.01 (.02)	.66	-.007 (.004)	.05
Reading comprehension 2	Phonological ability1	.63 (.05)	.00	.55 (.06)	.00	.08 (.02)	.00
	Vocabulary knowledge1	-.09 (.03)	.00	-.08 (.03)	.00	-.02 (.004)	.00

The results of mediation analysis demonstrated that vocabulary knowledge had no significant total effect on any of the math outcomes at Time 2 although there was a small negative direct effect on the formal math results.

Phonological ability had a significant positive direct and total effect on every math outcomes. Indirect effect was positive and significant for the formal math and number manipulation results and not significant for digit identification. Both indirect and direct effects were positive for phonological ability while for vocabulary knowledge direct and indirect effects were oppositely directed in case of mathematics outcomes.

Discussion

The main aim of our study was the estimation of direct and indirect effects of phonological ability and vocabulary knowledge at the beginning of schooling on math performance at the end of the first grade. We used three types of math outcomes: simple math skills (digit identification and number manipulation) and more complex math skills (formal math). Simple math skills were measured twice: at the beginning of school year (Time 1) and at the end of school year (Time 2). Thus, we could estimate the effect of phonological ability and vocabulary knowledge on the development of simple math skills and on the complex math skills while controlling for the previous level of simple math skills.

There were contradictory results in the previous studies regarding the effect of phonological abilities on math. Some studies demonstrated that phonological abilities had an effect on reading performance only and had no effect on math (Passolunghi, Vercelloni, Schadee, 2007). Other studies showed that phonological abilities had a significant effect on math skills even after verbal ability and previous math skills were controlled (Hecht, Torgesen, Wagner, & Rashotte, 2001). Taking into account the evidence that reading skills have an effect on subsequent math performance (e.g. Shin et al., 2013), we aimed to compare direct and indirect effects (via reading fluency) of phonological ability on math skills. We tested three models and compared model where phonological ability had a direct effect and model where phonological ability had indirect effect only. In addition we estimated total, direct and indirect effects of phonological ability and vocabulary knowledge on math skills.

Our analysis demonstrated that the model where phonological ability and vocabulary knowledge had the indirect effects only fitted data worse than the model with direct effects. Phonological ability had a significant direct effect on each subsequent math outcomes even when previous math skills and reading fluency were controlled. These results are in line with some previous studies (Hecht, Torgesen, Wagner, & Rashotte, 2001). The effect of phonological ability was higher for formal math than for digit identification and number manipulation. Probably, it is because the formal math tasks included word problems which involved speech sound processing and reading skills (e.g. Rourke & Conway, 1997). It is also possible that the strong effect of phonological ability on formal math might be explained by the assessment procedure. Taking the digit identification and number manipulation items children could see stimulus on screen while during the execution of word problems they could only listen to the problems. There were four word problems presented only through audio information. To solve these word tasks children had to clearly identify each word and maintain audio information in working memory that demands phonological processing abilities and working memory resources.

Our longitudinal study demonstrated that digit identification skill at Time 1 was the strongest predictor of digit identification at Time 2 that confirmed the stability of this type of math skills. In comparison with digit identification, another simple math skill – number manipulation – did not have a large autoregressive path. Digital identification and phonological ability had the same effect on number manipulation at Time 1 as the previous level of this skill.

Our results showed that under control of phonological ability, reading fluency was a significant predictor of formal math and reading comprehension and did not predict later digit identification and number manipulation skills. According to some studies, reading performance was a significant predictor of subsequent math skills, and children with reading difficulties were at risk of development secondary math difficulties (e.g. Jordan, Hanich, and Kaplan , 2002). We tested the model where reading fluency predicted math outcomes at Time 2 while phonological ability and vocabulary knowledge did not. In this model (Model 1) reading fluency had a significant effect on each math outcomes whereas this effect was not significant (except for formal math) in case phonological ability had the effect on math (Model 2). These results suggested that relationship between reading fluency and math skills may be explained by phonological ability that correlated with both domains.

The results of mediation analysis indicated that phonological ability had a direct effect on math skills and that reading fluency mediated the effect of phonological ability on formal math only. Direct effect was higher than indirect for both math and reading achievements at Time 2. In general, our results confirmed some previous studies that phonological ability was a domain-general precursor of academic achievement (Krajewski, Schneider, 2009).

Vocabulary knowledge had no direct effect on math skills and had a small indirect effect on formal math via reading fluency. Moreover, surprisingly, under control of reading fluency and phonological ability, vocabulary knowledge had a negative effect on subsequent reading comprehension and a negative indirect effect on formal math. We suggested that the negative effect of vocabulary knowledge was significant because of including phonological ability into the model. Some studies demonstrated that phonological skills might change during the development process as a result of increasing vocabulary knowledge (Charles-Luce & Luce, 1995; Walley, 1993). We hypothesized that vocabulary knowledge might have a positive indirect effect on reading comprehension and mathematics skills via phonological ability. To test this hypothesis we ran the additional model where phonological ability was a mediator in the relation between vocabulary knowledge and later math and reading achievements. The results of this model demonstrated that vocabulary knowledge had a positive total and indirect effect on math skills and reading comprehension whereas a direct effect was nonsignificant or negative (for reading comprehension). The results of this model are presented in the Table 6.

Table 6. Standardized coefficients for total, direct and indirect effects of vocabulary knowledge on reading and math outcomes (mediator is phonological ability)

Outcomes	Predictors	Total effect		Direct effect		Indirect effect	
		B	p	B	p	B	p
Formal math2	Vocabulary knowledge1	.18 (.02)	.00	.03 (.02)	.13	.15 (.03)	.00
Digit identification2	Vocabulary knowledge1	.08 (.01)	.00	.02 (.02)	.21	.05 (.02)	.011
Number manipulation2	Vocabulary knowledge1	.11 (.02)	.00	.01 (.02)	.66	.10 (.02)	.00
Reading comprehension	Vocabulary knowledge1	.23 (.02)	.00	-.08 (.03)	.00	.31 (.04)	.00

According to these results, vocabulary knowledge had a significant positive indirect effect on math skills via phonological ability and negative indirect effect via reading fluency. At the same time, phonological ability had a significant and positive both direct and indirect effects, in addition, phonological ability mediated the effect of vocabulary knowledge on math outcomes.

It is worth noting that we treated phonological ability as a latent construct which was measured by two types of phonological skills: rhyming and repeating words and pseudowords. There were some studies where rhyming skills and repeating words/pseudowords were supposed to be separate predictors of reading performance whereas phonological ability was measured by other types of tasks (e.g. Snowling, Chiat, & Hulme, 1991; Muter, Hulme, Snowling & Stevenson, 2004; Gupta, 2003). It is possible to consider rhyming skills and repeating words and pseudowords skills as separate constructs and compare their effects on math achievements in future studies.

Conclusion: In summary, results of our analysis confirmed the role of preschool phonological ability as a domain-general predictor of later achievements. Phonological ability had a positive direct and indirect effect (via reading fluency) on the subsequent reading and math performance. It is important that the direct effect was higher than the indirect effect. Vocabulary knowledge had a nonsignificant direct effect and positive indirect effect (via phonological ability).

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