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THE DEFICIT OF PHONOLOGICAL PROCESSING ASSOCIATED WITH BOTH MATHS AND READING DIFFICULTIES RATHER THAN SEPARATE MATHS OR READING DIFFICULTIES[4]

In this study, we aimed to estimate the effect of phonological processing in the emergence of specific maths or combined maths and reading difficulties during the first year of schooling. We also estimated whether the high level of phonological processing could be a resource for coping with math difficulties. The study was conducted on a large sample of Russian first-graders (N=3296 pupils, mean age 7.3 years, 49% of them were girls). Pupils were tested twice, at the beginning and at the end of the first grade in their level of maths performance, reading performance, phonological processing, and number recognition skills. In each test, four groups of pupils were identified regarding their level of maths and reading performance: a group with mathematical difficulties only (MD), pupils with reading difficulties only (RD), pupils with both maths and reading difficulties (MDRD) and pupils without difficulties (TD). The probability to move into the MD group, the MDRD group and in the TD group was estimated for pupils regarding their group status at Time 1 and their level of phonological processing. Results revealed that at first grade, phonological processing did not correlate with specific maths difficulties, but associated with both maths and reading difficulties. At the same time, a high level of phonological processing may prevent typically developing pupils from moving into the MD group. Moreover, a high level of phonological processing increases the probability to move into the TD group for pupils who had specific maths difficulties at the start of schooling.

JEL Classification: Z.

Keywords: maths difficulties, phonological processing, maths and reading difficulties, elementary school.

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Acquisition of maths skills in elementary school is an important factor for future academic progress in different domains (Clements & Sarama, 2016). Moreover, difficulties in mathematics acquisition during primary school can be followed by further difficulties in other domains like reading (Gersten, Jordan, & Flojo, 2005), or problem-solving (Geary, Brown, & Samaranayake, 1991). Furthermore, maths difficulties may lead to the emergence of mathematical or learning anxiety, which prevents students enrolling on math-related courses and the choice of STEM education (Ramirez, Gunderson, Levine, & Beilock, 2013).

There exist different approaches to the identification of maths difficulties. Early studies identified several types of difficulties, regarding the severity of disabilities or their content. One of the most severe disorders in the acquisition of maths is dyscalculia. Dyscalculia reflects sustainable difficulties in the acquisition of mathematics knowledge, operations and concepts for individuals with normal intelligence and working memory (Butterworth, Varma, & Laurillard, 2011).

There are also students who do not have severe problems like dyscalculia, but they still have difficulties in mathematics acquisition. They have low mathematical performance due to the moderate deficit in maths knowledge or deficit of different maths skills. The majority of students with a low level of maths performance do not have dyscalculia, but rather such difficulties (Peard, 2010). There are different ways of identifying groups with maths difficulties. Some studies refer to different assessment instruments, assuming that the students in the lowest quartile (<25 percentile) have difficulties in mathematics acquisition or are predisposed to them (Peng, Congying, Beilei, & Sha, 2012).

It is a common practice to differentiate between children with only mathematics difficulties (MD), children with mathematics and reading difficulties (MDRD), and typically developing (TD) children (Peng et al., 2012). Researchers assumed that different mechanisms exist underlying difficulties both in maths and reading or in maths only (Ashkenazi, Black, Abrams, Hoeft, & Menon, 2013; Light & DeFries, 1995). Regarding the stability of difficulties over time, several groups can also be identified. Children who demonstrated persistent mathematics difficulties (MD-p) differ from children with transient mathematics difficulties (MD-t) and typically developing children (Vukovic & Siegel, 2010).

Much attention is paid to the cognitive predictors of the emergence of maths difficulties in children. Particularly, several domain-specific cognitive factors are identified. In particular, children with MD demonstrated deficit in different aspects of number sense such as magnitude comparison, number recognition or nonsymbolic arithmetic (Dyson, Jordan, & Glutting, 2013; Gersten et al., 2005; Kroesbergen, Van Luit, Van Lieshout, Van Loosbroek, & Van De Rijt, 2009), and calculation fluency was proved to be connected with MD, but not with MDRD (Jordan, Hanich, & Kaplan, 2003). It was also demonstrated that a deficit of spatial ability was revealed in children with MD (Maria Chiara Passolunghi & Mammarella, 2012).

Some researchers also identified nonspecific (or domain-general) cognitive factors. Usually, these factors are connected to both reading and mathematics, but some of these factors can have an independent influence on the emergence of mathematical difficulties. In particular, children with MD demonstrated a deficit of working memory and executive function (Andersson & Lyxell, 2007; Swanson & Beebe-Frankenberger, 2004; Toll, van der Ven, Kroesbergen, & van Luit, 2011).

Among domain-general factors phonological ability was also identified as a possible predictor both maths and reading achievement (Melby-Lervåg, Lyster, & Hulme, 2012; M. Chiara Passolunghi, Vercelloni, & Schadee, 2007). Phonological ability refers to the sensitivity for the sounds of language and to capacity to use these sounds to decode linguistic information and the ability to process and understand the sound structure of oral language (Torgesen & Wagner, 1987). Researchers have identified three main dimensions of phonological ability: phonological awareness, lexical access or rapid automatized naming (RAN) and phonological memory, which is the temporary memory storage of phonological information similar to the phonological loop in models of working memory (Baddeley, 1992, 2010).

The findings regarding the role of phonological abilities in the emergence of difficulties in the acquisition of math skills or in dyscalculia are rather controversial. Robinson, Menchetti, and Torgesen (2002) proposed that poor phonological processing can be a source of the deficit of fact retrieval in children with dyscalculia. Other studies have confirmed this suggestion and have demonstrated that children with dyscalculia suffer from poor phonological processing (Boets & De Smedt, 2010; Vukovic, Lesaux, & Siegel, 2010; Vukovic & Siegel, 2010). Vanbinst, Ghesquière and De Smedt (2015) demonstrated that children with dyscalculia, who exhibited persistent difficulties in arithmetic fact retrieval, performed significantly more poorly on all dimensions of phonological processing, and these differences were significant even when controlling for IQ, working memory (WM) capacity or reading achievement (Vanbinst, Ceulemans, Ghesquière, & De Smedt, 2015).

Some researchers supposed that phonological deficit is not the main cause of the emergence of specific maths difficulties but could be an additional risk factor for developmental maths difficulties (De Smedt, 2018; Landerl, Bevan, & Butterworth, 2004). Some studies also indicated that there is no connection between phonological processing and maths difficulties. In particular, studies have shown that children with both maths and reading difficulties usually demonstrated a deficit in phonological processing, while children with maths difficulties only often did not show phonological impairments (Geary, 1993; Moll, Snowling, Göbel, & Hulme, 2015; Rourke & Conway, 1997). In line with these results, phonological processing was found to be a unique predictor of reading difficulties but not specific mathematics difficulties (Bryant, MacLean, Bradley, & Crossland, 1990; M. Chiara Passolunghi et al., 2007). Maths difficulties might arise as a secondary deficit of reading difficulties (Gersten et al., 2005; Jordan et al., 2003). Thus, the role of the phonological deficit in the emergence of specific maths difficulties remained unclear.

Since there is evidence about the link between the deficit of phonological processing and maths difficulties, it is possible to assume that a high level of phonological processing can be a resource for improvement in maths performance and overcoming of maths difficulties. However, we could not find any studies on that. So, little is known about the role of phonological processing in persistence or reduction of maths difficulties in elementary school.

The current study has two main goals. We used the two-wave longitudinal study of the large sample of first-graders and identified four groups of children (MD, RD, MDRD, and TD) at the beginning of the first grade and traced their transition to a specific group at the end of the first grade. Firstly, we aimed to estimate the role of phonological processing in the emergence and persistence of specific maths difficulties or combined maths and reading difficulties from the start to the end of the first grade. The second goal is to evaluate if the high level of phonological processing can be a source of overcoming of MD at the end of the first grade. We also checked if the role of phonological processing varied for pupils depending on their group status at the start of the first grade. We also control for number identification as the important predictor of maths performance in order to accurately estimate the effect of phonological processing.

Method

Participants

The study was conducted in the Tatar Republic during the 2017-2018 academic year. The socioeconomic characteristics of the Tatar Republic are similar to the average in Russia (based on the 2015 census, Russian Federal Statistics Service).

The research was conducted in two stages – the first one took place at the beginning of the school year, in October 2017 (Time 1) on first-graders. The second stage took place at the end of the first year of schooling, in May 2018 (Time 2). The initial sample consisted of 3450 pupils, the resulting sample consisted of 3296 pupils (49% of them were girls). Sample size reduction was due to the transition of pupils at another school or illness in the day of testing. 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 pupils gave their informed consent before the survey. The Institutional Review Board at the Higher School of Economics approved the study, and the data were collected according to the guidelines and principles for human research subjects.

Procedure

The testing procedure was computer-based and was conducted on a one-on-one basis by a trained tester. The assessment lasted from 15 to 20 minutes and was localized at school in a separate quiet room. The software employed an adaptation algorithm which defines which items the students will receive during the test, based on their performance.

Each section in testing is organized so that it starts from the easy items, and the difficulty increases as the pupil moves along the test. When the child makes three consecutive or four cumulative errors in the section, the assessment proceeds to the next section.

Instruments and measures

The results were obtained by means of a baseline and follow-up assessments using the iPIPS (international Performance Indicators in Primary Schools) instrument. iPIPS was originally developed by the Centre for Education and Monitoring at Durham University in the UK (Tymms, 1999; Tymms, Merrell, & Wildy, 2015), and the Russian version was developed and validated from 2013 to 2015 (Ivanova, Kardanova, Merrell, Tymms, & Hawker, 2018).

The IRT technique was used for examining the achievement level of students, particularly, the anchor item equating, using the dichotomous Rasch model (Kolen & Brennan, 2004). The items were equated so that it was possible to measure student achievement on a continuous scale from Time 1 to Time 2.

Math performance

For the estimation of maths achievement, a total of 19 tasks were presented. These tasks included word problem-solving tasks and two-digit arithmetic tasks. The scale appeared to be unidimensional, with items highly correlated, and test reliability (Cronbach's alpha) varied from 0.8 to 0.9 for Time 1 and Time 2.

Phonological processing

We used two types of tasks to assess phonological processing: rhyming tasks and word/pseudoword repetition tasks. For a rhyming task, the child had to select a word that rhymed with a target word from three options. In total, five target words were presented. As incorporated in the software, each word was illustrated with a picture and pronounced by a professional narrator. In the word/pseudoword repetition task, the child was asked to repeat 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. The reliability was 0.7 at Time 1 and 0.9 at Time 2 assessment.

Number identification

The number-identification tasks included single-, two- and three-digit numbers. The child was asked to name numbers that were presented visually. A total of 9 one-, two- and three-digit numbers were presented. The scale appeared to be unidimensional, with items highly correlated, and test reliability (Cronbach's alpha) varied from 0.8 to 0.9 for Time 1 and Time 2.

Reading performance

The reading performance scale was constructed based on tasks that included letter recognition, word decoding, and reading comprehension. First, for letter recognition estimation, children were asked to name letters presented on the screen, 8 letters in total. Tasks for the estimation of word decoding skills included fluent printed word recognition and the reading of a simple short story that the child was asked to read aloud. The words were of high frequency. For words and the short story, each word that was recognized and read correctly was counted as a correct answer. In the story reading task, the child had to read a short story of 34 words divided into three parts accompanied by related pictures. If the child was able to read half of the words in each part correctly, the item was scored as correct.

The reading comprehension task included two more difficult texts where the child was required to read a passage and, at certain points, to select one word from a choice of three that fit the story best (in total, 36 choices were scored). The reliability of the reading scale was higher than 0.9 for both Time 1 and Time 2.

Statistical approach

Firstly, we identified four groups of pupils at the start of the first grade and the end of the first grade using the threshold of 25 percentile. Pupils who had only maths achievement lower than 25 percentile were identified as only MD group. Pupils who had only reading achievement lower than 25 percentile were identified as only RD group. Pupils who had both maths and reading achievement lower than 25 percentile were identified as MDRD group. Other pupils were identified as the TD group. We estimated what proportion of students within each group at the start of schooling moved to another group or stay in the same group (MD, RD, MDRD or TD) at the end of the school year. We compared the level of phonological processing between groups at the start and at the end of the school year using one-way ANOVA with Bonferroni multiple corrections.

Further, we estimate the effect of phonological processing on the probability to move in a different group at the end of the school year using multinominal regression. The dependent variable was the group status at Time 2 (MD, RD, MDRD, TD), MDRD was a reference group. The predictors were group status at Time 1 (TD was the reference), Phonological Processing at Time 1 (PP1), Number Recognition at Time 1 (NR1) and gender (0 = boys; 1 = girls). We conducted this analysis to understand if PP had an effect on the transition to MD group, MDRD group and TD group at Time 2 under control of group status at Time1, NR at Time 1 and gender.

We also estimate if the effect of PP1 varied for pupils with different group status at Time 1 and included an interaction between status at Time 1 and PP1. We calculated predicted probability to move into MD, MDRD and TD groups for students with different levels of PP1 and group status at Time 1.

Results

Descriptive statistics

Table 1.

Descriptive statistics for math, reading, phonological achievement and number recognition

Variables	Mean (in logits)	SD	Min	Max
Math performance at Time 1	-1.06	2.05	-8.01	6.61

Math performance at Time 2	0.80	1.93	-6.63	6.63
Reading performance at Time 1	-.02	2.61	-7.01	6.89
Reading performance at Time 2	2.45	2.12	-7.2	6.91
Phonological processing at Time 1	0.81	1.45	-5.24	4.36
Phonological processing at Time 2	1.96	1.78	-5.22	4.36
Number Recognition at Time 1	2.02	4.79	-9.08	8.34

Descriptive statistics demonstrated that all measures increased from Time 1 to Time 2, while all standard deviations reduced. These results indicate that our sample became more homogenous in terms of academic achievement.

Further, we traced the transition between different groups from Time 1 to Time 2.

Table 2.

Transitions between different groups from Time 1 to Time 2 (percent from a group at Time 1)

Group status	TD at Time 2		MD at Time 2		MDRD at Time 2		RD at Time 2		Overall	
	N	%	N	%	N	%	N	%	N	%
TD 1	1560	76%	162	8%	96	5%	228	11%	2,046	62%
MD at Time 1	175	43%	125	30%	57	14%	53	13%	410	12%
MDRD at Time 1	101	22%	92	20%	203	44%	65	14%	461	14%
RD at Time 1	168	44%	48	13%	70	18%	93	25%	379	12%
Overall	2,004	61%	427	13%	426	13%	439	13%	3296	100%

Note:

TD – typical development (without any difficulties); MD – only maths difficulties; MDRD – maths and reading difficulties; RD – only reading difficulties

The results revealed that the majority of TD children remained at this group at Time 2. A considerable number of children with separate MD or RD at Time 1 moved to TD group at Time2 (43%) whereas only 22% of children with both MD and RD moved to the TD group. At the same time, 11% of children without any difficulties at Time 1 moved to a group with RD and 8% moved into the group with MD.

Comparison of the level of phonological processing within each group demonstrated that at Time 1 and Time 2 children from the TD group had a significantly higher level of phonological processing (Table 3).

Table 3.

Level of phonological processing in different groups at Time 1 and Time 2

Groups	TD	MD	MDRD	RD	F
	Mean [95% CI]	Mean [95% CI]	Mean [95% CI]	Mean [95% CI]	
Time 1	1.18 [1.12; 1.24]	0.35 [0.22; 0.48]	-0.05 [-0.17; 0.08]	0.33 [0.20; 0.47]	140.01***
Time 2	2.55 [2.49; 2.62]	1.62 [1.47; 1.77]	0.41 [0.26; 0.55]	1.07 [0.92; 1.22]	282.21***

***p<.001

Post-hoc comparisons, using Bonferroni correction, revealed that there were no difference between MD and RD group in the level of phonological processing, whereas the MDRD group had the significantly lower level of phonological processing in comparison with the MD and RD groups (mean difference = -0.40, 95% CI -0.64; -0.15). However, at Time 2 children from the MD group had a significantly higher level of phonological processing in comparison to the RD (mean difference = 0.56; 95% CI 0.27; 0.84) and MDRD groups (mean difference was 1.22; 95% CI 0.93; 1.50).

Next, we estimated if the phonological processing had the effect on transitions in the TD, MD or RD groups at Time 2 under control of group status at Time 1, number recognition and gender (Table 4).

Table 4.

Results of multinomial logistic regression analysis for status at Time 2 (MDRD is a reference group)

	Outcomes		
	TD Time 2	MD Time 2	RD Time 2
Constant	1.87*** (0.13)	0.07 (0.16)	0.38* (0.16)
PP1	0.19*** (0.05)	0.08 (0.06)	0.07 (0.06)
Gender	0.32* (0.13)	0.60*** (0.15)	0.07 (0.15)
NR1	0.20*** (0.02)	0.04* (0.02)	0.16*** (0.02)
MD1	-0.89*** (0.20)	0.38 (0.22)	-0.38 (0.24)
RD1	-1.15*** (0.19)	-0.67** (0.24)	-0.08 (0.21)
MDRD1	-2.03*** (0.19)	-1.00***(0.21)	-0.96*** (0.22)
Log likelihood		-3192.10	
Pseudo R-square		.15	

Note: *p<.05, **p<.01, ***p<.001

The results of multinomial regression analysis revealed that phonological processing has a positive effect on the probability to have no difficulties in maths and reading. In comparison with MDRD, phonological processing did not distinguish pupils with different types of difficulties at Time 2. In comparison with boys, girls have a higher probability to have no difficulties or have MD only. There is no gender difference with having only RD difficulties in comparison with the probability of having both MDRD.

To make the picture of changes more clear, we calculated the predicted probability to move into the group with MD only, with RD only, with both MD and RD and in TD group at Time 2 for pupils with different types of difficulties at Time 1 (Table 5).

Table 5.

The predicted probability to move into the group with only maths difficulties or in the group without difficulties at Time 2 with 95% CI

	MD at Time 1	RD at Time 1	MDRD at Time 1	TD at Time 1
Mean predicted probability to move into MD group at Time 2	.24 [.20; .28]	.11 [.08; .14]	.15 [.11; .18]	.11 [.09; .12]
Mean predicted probability to move into RD group at Time 2	.13 [.10; 17]	.24 [.19; .28]	.19 [.14; .23]	.12 [.10; .13]
Mean predicted probability to move into MDRD group at Time 2	.11 [.08; .14]	.15 [.12; .18]	.26 [.22; .30]	.07 [.05; .09]
Mean predicted probability to move to TD group at Time 2	.51 [.47; .56]	.50 [.45; .55]	.41 [.36; .47]	.70 [.68; .72]

The results revealed that pupils with MDRD at Time 1 have the lowest probability to have no difficulties at Time 2, whereas pupils with MD or RD only have an equal probability to move into the TD group or into the MDRD group.

We also tested if the effect of phonological processing on the transition into the TD group or into groups with different types of difficulties varied for pupils depending on their group status at Time 1 (Table 6).

Table 6.

Results of multinomial logistic regression analysis for maths and/or reading difficulties at Time 2 (MDRD is a reference group)

	Outcomes		
	TD Time 2	MD Time 2	RD Time 2
Constant	1.91*** (0.14)	0.16 (0.17)	0.42* (0.17)
Phonological processing	0.13 (0.08)	-0.04 (0.10)	0.01 (0.09)
Gender	0.32* (0.13)	0.61*** (0.15)	0.07 (0.15)
Number recognition	0.20*** (0.02)	0.04* (0.02)	0.16*** (0.02)
MD Time 1	-0.93*** (0.21)	0.31 (0.23)	-0.43 (0.25)
RD Time 1	-1.09*** (0.20)	-0.67** (0.25)	-0.05 (0.23)
MDRD Time 1	-2.07*** (0.20)	-1.08*** (0.22)	-0.98*** (0.23)
MD1 * phonological processing	0.05 (0.16)	0.08 (0.17)	0.08 (0.19)
RD1 * phonological processing	-0.24 (0.14)	-0.17 (0.18)	-0.14 (0.16)
MDRD1 * phonological processing	0.29* (0.14)	0.45** (0.15)	0.13 (0.15)
Log likelihood		-3074.96	
Pseudo R-square		.15	

Note: *p<.05, **p<.01, ***p<.001

The results of multinomial regression with interaction effect demonstrated that the effect of phonological processing on transition into the MD group and into the TD group varied depending on the pupil's group status at Time 1. In particular, phonological processing had a positive effect on probability to move into the MD group for pupils with MDRD and had a negative effect for other pupils (Figure 1).

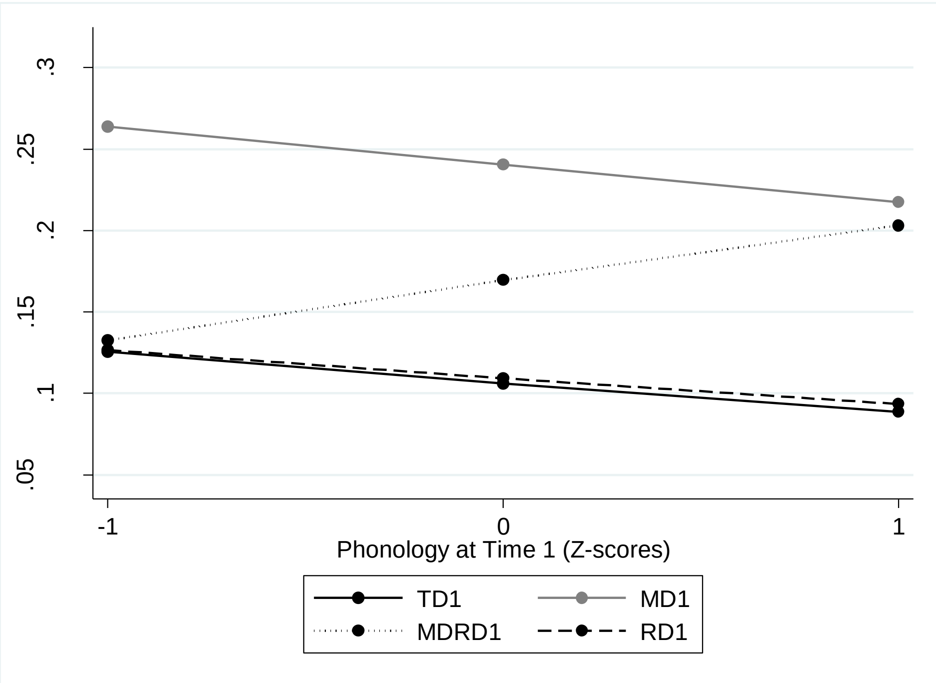

Figure 1. The effect of phonological processing at Time 1 on the probability to move into the group with maths difficulties only depending on group status at Time 1

We also calculated the predicted probability to move into the MD group for pupils with different levels of phonological processing and types of difficulties at Time 1 (Table 7).

Table 7.

Predicted probability of transition into the group with MD only with 95% CI depending on status and level of phonological processing at Time 1

	TD at Time 1	MD at Time 1	MDRD at Time 1	RD at Time 1
Low phonology (-1 s.d.)	.13 [.10; .15]	.26 [.21; .32]	.13 [.10; .17]	.13 [.09; .17]
Medium phonology	.11 [.09; .12]	.24 [.20; .28]	.17 [.13; 21]	.11 [.08; .14]
High phonology (+1 s.d.)	.09 [.07; .11]	.22 [.15; .29]	.20 [.13; 28]	.09 [.04; .14]

As these results demonstrated, at the low level of phonological processing, pupils with MD at Time 1 have a higher probability to remain in this group at Time 2, in comparison with other pupils. At the high level of phonological processing, pupils with MDRD at Time 1, and pupils with MD, have the same probability to be in the MD group at Time 2.

In order to compare transitions to the MD and to the MDRD groups, we also calculated the probability to move into the MDRD group for pupils with different group status and the level of phonological processing at Time 1 (Table 8).

Table 8.

Predicted probability of transition into MDRD group with 95% CI depending on status and level of phonological processing at Time 1

	TD at Time 1	MD at Time 1	MDRD at Time 1	RD at Time 1
Low phonology (-1 s.d.)	.08 [.06; .09]	.12 [.09; .15]	.27 [.23; .31]	.15 [.11; .18]
Medium phonology	.07 [.06; .09]	.11 [.08; .14]	.23 [.19; .27]	.16 [.12; .19]
High phonology (+1 s.d.)	.07 [.05; .08]	.10 [.06; .14]	.18 [.13; .23]	.17 [.12; .22]

As we can see from these results, phonological processing reduced the probability to stay in the MDRD group for pupils from the MDRD group at Time1. Independently from the level of phonological processing, pupils from the MD and RD groups did not significantly differ in their probability to move into the MDRD group at Time 2.

The effect of phonological processing on the probability to move into the TD group, also varied depending on status at Time 1. In particular, the effect of phonological processing was significant for pupils who had MD or MDRD, while the effect was not significant for pupils with RD only (Figure 2).

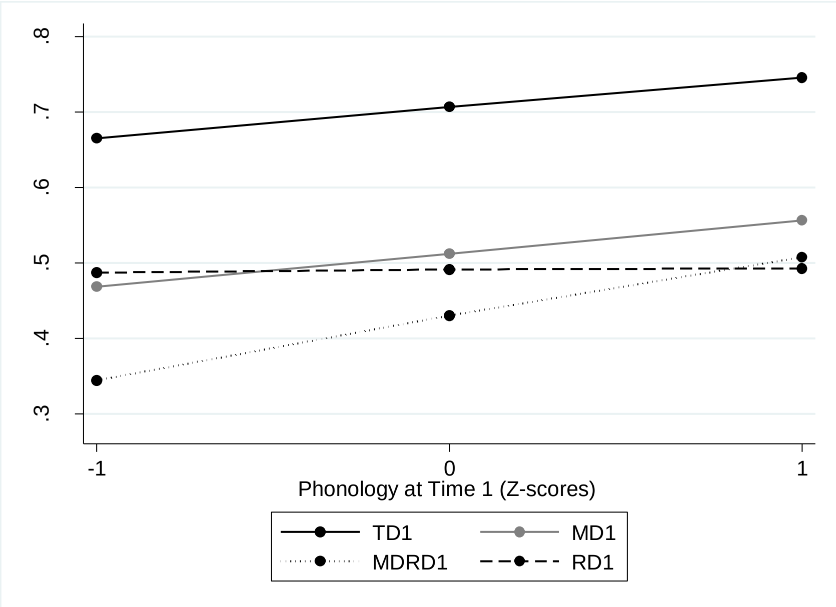

Figure 2. The effect of phonological processing at Time 1 on the probability to move into group with no difficulties depending on status at Time 1

We also calculated the predicted probability to move into the TD group for pupils with different levels of phonological processing and types of difficulties at Time 1 (Table 9).

Table 9.

Predicted probability of transition into the group without difficulties with 95% CI depending on status and level of phonological processing at Time 1

	TD at Time 1	MD at Time 1	MDRD at Time 1	RD at Time 1
Low phonology (-1 s.d.)	.67 [.63; .70]	.47 [.40; .53]	.34 [.28; .41]	.49 [.42; .55]
Medium phonology	.71 [.69; .73]	.51 [.46; .56]	.43 [.37; 49]	.49 [.44; .54]
High phonology (+1 s.d.)	.75 [.72; .77]	.56 [.47; .65]	.51 [.40; 62]	.49 [.40; .58]

These results revealed that at the low level of phonological processing at Time 1, differences in probability to move into the group without difficulties were significant, only between the MDRD group and the RD group. In comparison with MDRD, pupils from the RD group or the MD group had a higher probability to move into the TD group at Time 2. At the high level of phonological processing at Time 1, pupils from the MD group had small advantages in comparison with pupils from the RD group to move into the TD group. It is worth noting, that increasing the level of phonological processing related to a larger probability to move into the TD group for pupils with MD or MDRD but not for the RD group.

Discussion

Our study had two main goals. The first goal was to estimate the effect of phonological processing on the origin of specific maths difficulties or combined math and reading difficulties during the first grade. The second goal was to estimate the phonological processing effect on the probability of overcoming the existing maths difficulties. Despite the large body of studies regarding relations between phonological processing and maths achievement, we did not find, in previous studies, any evidence that phonological processing had any effect on coping with mathematics difficulties.

To fulfil these aims, we implemented a longitudinal design on a large sample of first-graders in Russia (N=3296) and identified four groups of pupils regarding their level of maths and reading achievement at the start and at the end of the first grade. Thus, the first group was the group with only maths difficulties (MD); the second was the group with only reading difficulties (RD); the third was the group with both maths and reading difficulties (MDRD) and typical development pupils without any difficulties were combined into the TD group. We traced the transition between groups from the start to the end of the first grade and estimated the probability of moving into different groups, for pupils with different levels of phonological processing and group status at Time 1.

We had several findings regarding these goals. First, our results revealed that at the beginning of the first year of schooling, the MD and RD groups do not significantly differ at the level of phonological processing while MDRD children had a significantly lower level. However, at the end of the first grade the MD and RD groups became different in the level of phonological processing. Among children with difficulties, at the end of the first grade, MDRD children had a lower level of phonological processing and MD children had a higher level of phonological processing in comparison with RD or MDRD children.

Thus, at the start of schooling, the deficit of phonological processing is rather related to difficulties, both in maths and reading, than in one separate domain. This finding may be supported by the results of the research, which showed that phonological awareness might be the factor associated with the conjunction of both math and reading difficulties and explained the overlap between maths and reading skills (Lopes-Silva et al., 2016; Peterson et al., 2017). In particular, Child and colleagues (2019) demonstrated that, at the second grade, phonological awareness accounted for the overlap between maths and reading, even when working memory and processing speed were controlled for.

There exists some hypothesis regarding neurobiological underpinning of the overlap between maths and reading difficulties. In particular, Ashkenazi and colleagues (2013) identified three possible pathways of maths and reading difficulties comorbidity. The additive model posits that MD and RD difficulties originate from unique for each domain impairment and comorbidity arises from the addition of two effects. The "verbally mediated" model postulated that comorbidity originates in the impairment to the phonological system associated with RD. The "domain-general" model implied that comorbidity originates from the impairment of domain-general cognitive function, such as working memory or attention.

Our results were in contradiction with the "verbally-mediated" model, although they confirmed that impairment of phonological processing was associated with arising both maths and reading difficulties. According to the "verbally-mediated" model, maths difficulties arise from the existing reading difficulties, which, in turn, arise from the deficit of phonological processing. In this case, children with reading difficulties at Time 1 should have a higher probability to move into the group with MDRD at Time2 in comparison with children with MD at Time 1. In our sample, the probability to move into the MDRD group was not significantly different for MD and RD children with any level of phonological processing. Therefore, poor phonological processing was the factor that connected with arising additional maths difficulties for children with RD and additional reading difficulties for children with MD.

According to our findings, the effect of phonological processing on the probability to have specific maths difficulties at the end of the first grade was positive for children with both maths and reading deficits at the start of schooling. This indicated that for children from the MDRD group, phonological processing could be the resource for the correction of reading difficulties. Previous studies revealed that phonological training might improve difficulties in reading (Männel, Schaadt, Illner, van der Meer, & Friederici, 2017). Additional analysis demonstrated that phonological processing did not enhance overcoming maths difficulties for children with MDRD.

On the other hand, phonological processing had a negative effect on the probability to have specific maths difficulties at Time 2 for children with separate maths and reading difficulties, or without difficulties. From this point of view, a high level of phonological processing could reduce the probability to have specific maths difficulties for children who did not have such maths difficulties previously. Probably, phonological processing may not be directly connected to the difficulties in mathematics, but it can be a resource which prevents children from other groups from the emergence of difficulties in mathematics.

Besides, a high level of phonological processing could be negatively related to the probability of having consistent maths difficulties. In a longitudinal study, Vukovic and Siegel (2010) found that persistent difficulties in mathematics, from the first to the fourth grade, were characterized, among others, by the deficit in phonological decoding. Phonology might not be the main factor of origin-specific maths difficulties but it can be connected to the persistence of these difficulties in time.

Regarding the second goal, our results revealed that phonological processing had a positive effect on the probability of moving into the group without difficulties, for children who had specific maths, or both maths and reading difficulties. Moreover, this effect was more salient for children with both maths and reading deficits. These results also confirmed the previous findings of the phonological processing, as a factor of overlapping between maths and reading skills. The poor phonological processing could impair both maths and reading skills and vice versa, while the high level of phonological processing could improve the achievement of pupils with MDRD.

In summary, the results obtained in this study may reflect the close connection between mathematics and reading. Probably, they are less differentiated in the primary school, while, by the end of the first grade of primary school, the difference between them starts to grow. We can assume that our results support this hypothesis, since the level of phonological processing was not different for MD and RD groups at Time 1, but became different at Time 2. Supposedly, the more a child develops, the more the phonological processing becomes specific for reading achievement rather than for mathematics.

Our study had some limitations. First, in the present study, we did not consider specific dimensions of phonological processing, such as phonological awareness or phonological memory separately. Instead, we included phonological processing in the analysis as a general construct. Meanwhile, it was demonstrated that phonological awareness had a larger effect on maths performance compared to other dimensions. It is possible that including specific dimensions into the model would change possible outcomes. Secondly, at Time 1, pupils were at the very beginning of formal education in maths and reading. So, the low level of maths performance might be related to a lack of experience in formal maths, rather than to difficulties in the acquisition of maths skills.

However, we can say that pupils with a low level of maths performance at the start of schooling have a higher probability to have further maths difficulties. In order to estimate the transition between the group with difficulties, it is necessary to trace the transition of pupils from different groups further, for example, at the second and the third grade. The ongoing longitudinal project iPIPS gives us this opportunity.

It is also worth noting, that the methodology for defining learning difficulties may differ between studies. We used the threshold of 25 percentile to identify such children. This approach is quite popular, but there are other ways to define difficulties. Some research use several tests to identify children with difficulties, either in mathematics or in general abilities, for example the subtest Arithmetic of the Wechsler Intelligence Scale for Children-Revised and a Standard Mathematics Performance Test (Ostad, 2015), or the Chinese Character Recognition Measure and Assessment Scale for Primary School Children (CRMA) and the Wide Range Achievement Test-4 Computation (WRAT–Computation) (Peng et al., 2012). Sometimes the 40th percentile is used to define the TD or MD group (Vukovic & Siegel, 2010). Differences between methodological approaches to defining MD may cause differences in the obtained results.

References

Andersson, U., & Lyxell, B. (2007). Working memory deficit in children with mathematical difficulties: A general or specific deficit? *Journal of Experimental Child Psychology*, *96*(3), 197–228. https://doi.org/10.1016/j.jecp.2006.10.001

Ashkenazi, S., Black, J. M., Abrams, D. A., Hoeft, F., & Menon, V. (2013). Neurobiological Underpinnings of Math and Reading Learning Disabilities. *Journal of Learning Disabilities*, *46*(6), 549–569. https://doi.org/10.1177/0022219413483174

Baddeley, A. D. (1992). Working Memory. *Science*, *255*(ii), 556–559.

Baddeley, A. D. (2010). Working memory. *Current Biology*, *20*(4), 136–140.

Boets, B., & De Smedt, B. (2010). Single-digit Arithmetic in Children with Dyslexia. *Dyslexia*, *16*, 183–191.

Bryant, P. E., MacLean, M., Bradley, L. L., & Crossland, J. (1990). Rhyme and Alliteration, Phoneme Detection, and Learning to Read. *Developmental Psychology*, *26*(3), 429–438. https://doi.org/10.1037/0012-1649.26.3.429

Butterworth, B., Varma, S., & Laurillard, D. (2011). Dyscalculia : From Brain to Education. *Science*, *332*, 1049–1053.

Clements, D. H., & Sarama, J. (2016). Math, Science, and Technology in the Early Grades. *Future of Children*, *26*(2), 75–94. https://doi.org/10.1353/foc.2016.0013

De Smedt, B. (2018). Language and Arithmetic: The Potential Role of Phonological Processing. In *Heterogeneity of Function in Numerical Cognition* (pp. 51–74). Elsevier Inc. https://doi.org/10.1016/B978-0-12-811529-9.00003-0

Dyson, N. I., Jordan, N. C., & Glutting, J. (2013). A Number Sense Intervention for Low-Income Kindergartners at Risk for Mathematics Difficulties. *Journal of Learning Disabilities*, *46*(2), 166–181. https://doi.org/10.1177/0022219411410233

Geary, D. C. (1993). Mathematical disabilities: Reflections on cognitive, neuropsychological, and genetic components. *Psychological Bulletin*, *114*(2), 345–362. https://doi.org/10.1016/j.lindif.2009.10.008

Geary, D. C., Brown, S. C., & Samaranayake, V. A. (1991). Cognitive Addition: A Short Longitudinal Study of Strategy Choice and Speed-of-Processing Differences in Normal and

Mathematically Disabled Children. *Developmental Psychology*, *27*(5), 787–797. https://doi.org/10.1037/0012-1649.27.5.787

Gersten, R., Jordan, N. C., & Flojo, J. R. (2005). Early identification and interventions for students with mathematics difficulties. *Journal of Learning Disabilities*, *38*(4), 293–304. https://doi.org/10.1177/00222194050380040301

Ivanova, A., Kardanova, E., Merrell, C., Tymms, P., & Hawker, D. (2018). Checking the possibility of equating a mathematics assessment between Russia, Scotland and England for children starting school. *Assessment in Education: Principles, Policy and Practice*, *25*(2), 141–159. https://doi.org/10.1080/0969594X.2016.1231110

Jordan, N. C., Hanich, L. B., & Kaplan, D. (2003). A Longitudinal Study of Mathematical Competencies in Children with Specific Mathematics Difficulties versus Children with Comorbid Mathematics and Reading Difficulties. *Child Development*, *74*(3), 834–850.

Kolen, M. J., & Brennan, R. L. (2004). *Test equating, scaling, and linking. Methods and practices*. https://doi.org/10.1007/978-1-4757-4310-4

Kroesbergen, E. H., Van Luit, J. E. H., Van Lieshout, E. C. D. M., Van Loosbroek, E., & Van De Rijt, B. A. M. (2009). Individual differences in early numeracy: The role of executive functions and subitizing. *Journal of Psychoeducational Assessment*, *27*(3), 226–236. https://doi.org/10.1177/0734282908330586

Landerl, K., Bevan, A., & Butterworth, B. (2004). Developmental dyscalculia and basic numerical capacities: A study of 8-9-year-old students. *Cognition*, *93*, 99–125. https://doi.org/10.1016/j.cognition.2003.11.004

Light, J. G., & DeFries, J. C. (1995). Comorbidity of Reading and Mathematics Disabilities. *Journal of Learning Disabilities*, *28*(2), 96–106. https://doi.org/10.1177/002221949502800204

Lopes-Silva, J. B., Moura, R., Júlio-Costa, A., Wood, G., Salles, J. F., & Haase, V. G. (2016). What Is Specific and What Is Shared Between Numbers and Words? *Frontiers in Psychology*, *7*(February), 1–9. https://doi.org/10.3389/fpsyg.2016.00022

Männel, C., Schaadt, G., Illner, F. K., van der Meer, E., & Friederici, A. D. (2017). Phonological abilities in literacy-impaired children: Brain potentials reveal deficient phoneme discrimination, but intact prosodic processing. *Developmental Cognitive Neuroscience*, *23*, 14–25. https://doi.org/10.1016/j.dcn.2016.11.007

Melby-Lervåg, M., Lyster, S. A. H., & Hulme, C. (2012). Phonological skills and their role in learning to read: A meta-analytic review. *Psychological Bulletin*, *138*(2), 322–352. https://doi.org/10.1037/a0026744

Moll, K., Snowling, M. J., Göbel, S. M., & Hulme, C. (2015). Early language and executive skills predict variations in number and arithmetic skills in children at family-risk of dyslexia and typically developing controls. *Learning and Instruction, 38*, 53–62.

Ostad, S. A. (2015). Private speech use in arithmetical calculation: relationship with phonological memory skills in children with and without mathematical difficulties. *Annals of Dyslexia*, *65*(2), 103–119.

Passolunghi, M. C., & Mammarella, I. C. (2012). Selective Spatial Working Memory Impairment in a Group of Children With Mathematics Learning Disabilities and Poor Problem-Solving Skills. *Journal of Learning Disabilities, 45*(4), 341–350. https://doi.org/10.1177/0022219411400746

Passolunghi, M. C., Vercelloni, B., & Schadee, H. (2007). The precursors of mathematics learning: Working memory, phonological ability and numerical competence. *Cognitive Development*, *22*(2), 165–184. https://doi.org/10.1016/j.cogdev.2006.09.001

Peard, R. (2010). Dyscalculia: What is its prevalence? Research evidence from case studies. *Procedia Social and Behavioral Sciences, 8,* 106–113. https://doi.org/10.1016/j.sbspro.2010.12.015

Peng, P., Congying, S., Beilei, L., & Sha, T. (2012). Phonological storage and executive function deficits in children with mathematics difficulties. *Journal of Experimental Child Psychology*, *112*(4), 452–466. https://doi.org/10.1016/j.jecp.2012.04.004

Peterson, R. L., Boada, R., McGrath, L. M., Willcutt, E. G., Olson, R. K., & Pennington, B. F. (2017). Cognitive Prediction of Reading, Math, and Attention: Shared and Unique Influences. *Journal of Learning Disabilities*, *50*(4), 408–421. https://doi.org/10.1177/0022219415618500

Ramirez, G., Gunderson, E. A., Levine, S. C., & Beilock, S. L. (2013). Math Anxiety, Working Memory, and Math Achievement in Early Elementary School. *Journal of Cognition and Development*, *14*(2), 187–202. https://doi.org/10.1080/15248372.2012.664593

Rourke, B. P., & Conway, J. A. (1997). Disabilities of Arithmetic and Mathematical Reasoning: Perspectives From Neurology and Neuropsychology. *Journal of Learning Disabilities, 30*(1), 34–46. https://doi.org/10.1177/002221949703000103

Swanson, H. L., & Beebe-Frankenberger, M. (2004). The relationship between working memory and mathematical problem solving in children at risk and not at risk for serious math difficulties. *Journal of Educational Psychology*, *96*(3), 471–491. https://doi.org/10.1037/0022-0663.96.3.471

Toll, S. W. M., van der Ven, S. H. G., Kroesbergen, E. H., & van Luit, J. E. H. (2011). Executive functions as predictors of math learning disabilities. *Journal of Learning Disabilities*, *44*(6), 521–532. https://doi.org/10.1177/0022219410387302

Torgesen, J. K., & Wagner, R. K. (1987). The nature of phonological processing and its causal role in the acquisition of reading skills. *Psychological Bulletin*, *101*(2), 192–212. https://doi.org/10.1037/0033-2909.101.2.192

Tymms, P. (1999). Baseline assessment, value- added and the prediction of reading. *Journal of Research in Reading*, *22*(1), 27–36. https://doi.org/10.1111/1467-9817.00066

Tymms, P., Merrell, C., & Wildy, H. (2015). The progress of pupils in their first school year across classes and educational systems. *British Educational Research Journal*, *41*(3), 365–380. https://doi.org/10.1002/berj.3156

Vanbinst, K., Ceulemans, E., Ghesquière, P., & De Smedt, B. (2015). Profiles of children's arithmetic fact development: A model-based clustering approach. *Journal of Experimental Child Psychology*, *133*, 29–46. https://doi.org/10.1016/j.jecp.2015.01.003

Vukovic, R. K., Lesaux, N. K., & Siegel, L. S. (2010). The mathematics skills of children with reading difficulties. *Learning and Individual Differences*, *20*(6), 639–643. https://doi.org/10.1016/j.lindif.2010.08.004

Vukovic, R. K., & Siegel, L. S. (2010). Academic and Cognitive Characteristics of Persistent Mathematics Difficulty from First Through Fourth Grade. *Learning Disabilities Research & Practice*, *25*(1), 25–38. https://doi.org/10.1111/j.1540-5826.2009.00298.x

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