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THE PRECISION OF SYMBOLIC NUMERICAL REPRESENTATION IN VERBAL FORMAT HAS AN INDIRECT EFFECT ON MATH PERFORMANCE IN FIRST GRADE

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Numerical information can be represented in three formats: two symbolic (visual (digits) and verbal (number words)) and one nonsymbolic (analog) format. Studies have shown that the precision of symbolic numerical representation is associated with math performance. The precision of symbolic representation is mostly discussed as the precision of representation in a visual format, whereas the precision of representation in verbal format and its relation with math performance is less studied. The current study examines the precision of symbolic numerical representation in visual and verbal formats and the relationship between such precision and math performance when controlling for prior math performance, nonsymbolic numerical representation, phonological processing, reading skills and working memory. We used data from 367 Russian first graders (mean age, 7.6 years; 53% girls). To assess the precision of symbolic numerical representation, magnitude comparison tasks with digits and number words were used. It was found that the precision of symbolic representation in verbal format did not have a direct effect on math performance, but has an indirect effect via visual format of symbolic representation, even when controlling for prior math performance and other cognitive abilities.

JEL classification: Z, I20.

Keywords: math performance, symbolic numerical representation, number words, digits, first grade.

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Introduction

The perception and processing of numerical information is an important ability that is required for formal math education and in real life. Numerical information can be processed in nonsymbolic and symbolic formats. The ability to process numerical information in a symbolic format refers to the ability to manipulate numerosity information that is represented by Arabic or Roman digits (e.g., “4” or “IV”, respectively) or by number words (e.g., “four” or “twenty-seven”). It has been postulated that the ability to represent numerosity in symbolic formats is culture based and exists only in humans (Cantlon, 2012).

A variety of tests are used to measure the precision of numerical representation in different formats. One of the most common is the magnitude comparison test, in which an individual has to compare two numbers and select the largest (Laski & Siegler, 2007; Matejko & Ansari, 2016; Toll et al., 2015; Wong et al., 2018). For example, the accuracy and the speed of comparison of two digits reflects the precision of symbolic representation in a visual format, whereas the accuracy and the speed of comparison of two number words reflects the precision of numerical representation in a verbal format (Cohen Kadosh et al., 2008; Matejko & Ansari, 2016; Toll et al., 2015; Wong et al., 2018).

There is evidence that digits and number words are processed differently. First, digits are processed faster in many numerical tasks. For example, it was demonstrated that arithmetic facts with digits are retrieved faster in comparison with number words (Megías & Macizo, 2016) and the comparison of digits is processed faster than the comparison of number words (Dehaene & Akhavein, 1995). Faster processing of digits could be explained by reading speed and by the experience of processing digits among adults (Campbell & Epp, 2004). For example, it was shown that the adults with higher arithmetic fluency show significantly better results in a symbolic number comparison task in comparison to those with lower fluency (Castronovo & Göbel, 2012).

However, the advantages in processing digits compared to number words is dependent on the task. Particularly, it was shown that naming digits takes longer (Ischebeck, 2003) or no difference in the response time between digits and number words was observed (Campbell, 1994). The naming task requires transcoding a number to the phonological format, while number words have privileged access to that format (Campbell & Clark, 1992; Damian, 2004). For example, it was shown that number words are perceived as words, while digits are perceived as pictures, so their meaning comprehension requires additional time in a naming task (Fias et al., 2001). Number words can be named without semantic mediation, while naming digits requires an activation of abstract representation and its translation into phonological representation.

From a development perspective, it was demonstrated that children acquire number words first, and then the verbal format is used to introduce the digits (Butterworth, 2005; Le Corre et al., 2006; Le Corre & Carey, 2007; Purpura et al., 2013; Wynn, 1990, 1992). There is some evidence that number words are learned by first mapping onto the nonsymbolic abstract representation (also known as Approximate Number System, ANS) (Dehaene, 2009), and then digits are mapped onto the ANS via number words (Benoit et al., 2013). Hurst, Anderson and Cordes (2017) have shown that mapping between digits and analog representations was less accurate for 3- to 4-year-old children than mapping between number words and analog representations or between two symbolic representations. Thus, children's acquisition of digits is likely to be based on understanding number words.

The precision of both the symbolic and the nonsymbolic representation of numerosity has a positive association with math performance (e.g., Chen & Li, 2014; Reeve et al., 2012; Sasanguie et al., 2012; Vanbinst et al., 2016). There is plenty evidence that magnitude comparison skills when numerosity is presented as Arabic digits have a close association with math performance (e.g., Göbel, Watson, Lervåg, & Hulme, 2014). It has also been shown that the precision of mapping from nonsymbolic representation to a verbal format correlates with math performance (Libertus et al., 2016).

Despite numerous findings regarding the effect of the precision of symbolic magnitude representations on math performance, the extent to which the precision of symbolic representation in a verbal format is associated with math performance is understudied. The precision of symbolic representation in a verbal format is usually studied by using audio format of presentation whereas digits were presented visually. Moreover, the processing of written number words involved reading skills and phonological awareness, so the association between the precision of magnitude representation in a verbal format and math performance might be partly explained by the association between math and reading achievement. Hence, to estimate the effect of symbolic representation on math performance in a visual and a verbal format it is necessary to control for reading achievement, phonological awareness and nonsymbolic magnitude representation. However, few studies have analyzed these associations and controlled for reading, phonological processing and nonsymbolic magnitude representation simultaneously.

The current study aims to fill this gap, examining the relationship between math performance and the precision of symbolic representation in both visual and verbal formats. We estimate these relationships at the end of first grade, controlling for prior math performance and other well-established predictors of math performance, such as working memory (Peng et al., 2016), phonological awareness (Kuzmina et al., 2019; Lopes-Silva et al., 2014; Simmons & Singleton, 2008), reading skills (Jordon et al., 2002) and the precision of nonsymbolic magnitude representation (Chen & Li, 2014). Based on previous findings with number words in audio format, we expect that there is a positive association between the precision of symbolic representation in verbal format and math performance, or that the association might be indirect via digits due to the necessity to transcode the verbal format into the visual before all numerical operations.

Method

Participants

The data came from the START assessment for first graders, previously known as iPIPS (international Performance Indicators in Primary Schools) (Ivanova et al., 2018), which was originally developed in Britain (Tymms, 1999). The study was conducted during the 2018–2019 academic year. At the beginning of first grade (October 2018), the math and reading performance and phonological processing of 2,701 pupils were assessed. At the end of the academic year (April 2019), five schools from the sample were randomly selected. 398 first graders from randomly selected schools (18 classes) who participated in the study previously were tested to assess their math performance, symbolic and nonsymbolic numerical representation, mapping skills and working memory. Data from pupils who did not complete more than 90% of the cognitive tasks were excluded from the analysis. The final sample consisted of 367 first graders (53% girls). The mean age was 7.6 (range 6.43-8.32, SD = 0.36).

Procedure and Measures

All participants were tested in quiet settings within their school facilities by trained experimenters. All of the experimenters strictly used the same protocol with instructions for administering the test. Cognitive assessment was performed in a computer classroom in groups of 5–7 pupils. Each pupil sat in front of an individual monitor approximately 60 cm from the screen and performed the tasks independently. The assessment of cognitive performance lasted for 35–40 minutes.

The assessment of math, reading performance and phonological processing was performed in the following 1–2 days. Pupils did all the performance tests individually under the supervision of trained testers using computer-assisted software in quiet, separate classrooms. The assessment lasted 15–20 minutes. The computerized software-guided test administration employed an 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 in a section, the assessment of that section was stopped, and the child proceeded to the next section.

Cognitive Tests

Symbolic Magnitude Representation. To test the precision of the child's symbolic magnitude representation, a magnitude comparison task was used. Two numerals were presented simultaneously in visual (digit—digit) or verbal (number word—number word) formats. Participants were asked to select the larger number (right or left) by pressing the corresponding key on the keyboard. Numerals ranged from 1–9. There were 10 items per condition; in total, 20 tasks were executed. We controlled for the distance between numerals (small: 1–3 vs. large: 4–8) and the side of the greater quantity (right or left). The allotted time of representation was limited to 15 seconds for each stimulus, and answers beyond that time were scored as missing values. The tasks were separated by the fixation point screen. Items with digits and number words were presented randomly, but the order was the same for all children.

Accuracy, response time (RT), and the rate correct scores (RCS) were calculated separately for the digit and number word conditions (Vandierendonck, 2017). RCS were calculated as the number of correct answers divided by the sum of all RTs in the set of trials.

Nonsymbolic Magnitude Representation. The nonsymbolic comparison test was used to estimate the precision of the nonsymbolic representation. Participants were presented with arrays of yellow and blue figures (50% in an intermixed format and 50% in a paired separated format) and varying in size and number. The task required the participants to judge whether the array contained more yellow or blue figures and press the corresponding key. The stimuli were 96 static pictures with figure arrays varying between 9 and 19 figures of each color. In 50% of the trials, the stimuli were congruent in their cumulative area or convex hull. The presentation order was the same for all participants. The stimulus flashed on the screen for 400 milliseconds, and the maximum RT was 8 seconds. If no answer was given during this time, then the answer was recorded as incorrect, and a message appeared on the screen prompting the participant to press the spacebar to see the next trial. The proportion of correct answers was calculated to measure the precision of the nonsymbolic representation (Inglis & Gilmore, 2014).

Working Memory. The digit span backward task is a measure of working memory in children (St Clair-Thompson, 2010). For this task, the participants were presented with a series of single-digit numbers at a rate of one digit per second. The participant was asked to write the exact sequence in reverse order. The sequence began with a string of 3 digits and proceeded to progressively larger strings, with a maximum of 7 digits. In total, 9 items were presented. The longest sequence of 7 numerical digits was not remembered by anyone and, therefore, was excluded from the data. Accuracy in the test was calculated as the proportion of correct answers across 8 items.

Achievement Tests

Mathematical Performance. To assess math performance, the Russian version of the START instrument, which included 42 tasks, was used (Ivanova et al., 2018). The tasks assessed pupils' ability to count objects, perform simple object addition, and solve word and arithmetic problems.

Reading Performance. The reading performance scale was constructed based on four types of tasks: letter recognition, word decoding, reading decoding and comprehension. In total, 30 items were used.

Phonological Awareness. The phonological awareness scale was constructed based on tasks that included word rhyming and syllable deletion tasks (e.g., Demont & Gombert, 1996). In total, 15 items were used.

All of the performance tests were scaled with the dichotomous Rasch model (Rasch, 1960). The analysis of the scales was performed using the Winsteps software package (Linacre, 2011). All of the scales were unidimensional, with item fit to the model, and a sufficiently high test reliability (Cronbach's alpha) was obtained. The psychometric characteristics of all scales are presented in Table 1. For math, vertical scaling procedure was applied to examine the achievement level of students over two cycles.

Statistical Approach

Prior to analyzing the relationships between predictors and math performance, we analyzed the RT data of all tests. Answers with an RT lower than 0.005 seconds were coded as missing values (e.g., Harald Baayen & Milin, 2010). In total, 36 such cases were distributed randomly across the sample and the items were identified and recorded.

Next, to estimate the relationship between the precision of the symbolic numerical representation in a verbal format and math performance, we used hierarchical regression analysis and subsequently included different predictors in regression models for math performance at the end of first grade as the outcome. Model 1 included the RCS for the number word comparison task as the single predictor; in Model 2 other cognitive skills (phonological awareness, working memory, precision of nonsymbolic representation and reading performance) were included. The RCS for digit comparison were added (Model 3). At the last step, prior math performance was added as the predictor.

Finally, in order to estimate the indirect effect of number words on math performance we conducted a mediation analysis with digits as a mediator, while controlling for all the predictors.

To make the coefficients of different measures comparable, all predictor variables were transformed into Z-scores before being included in the regression analysis with the exception of transcoding variables as they had already been standardized.

Results

Descriptive Statistics

Tab. 1. Descriptive statistics and psychometric properties of performance tests

Variable	Mean	SD	95% CI	Person's estimate range	Cronbach's alpha	Person reliability
Mathematical performance, Time 1 (logits)	0.64	1.17	[0.52; 0.76]	-3.83-4.12	.90	.85
Mathematical performance, Time 2 (logits)	1.98	1.21	[1.85; 2.10]	-1.63-6.16	.88	.85
Reading performance, Time 1 (logits)	1.43	1.66	[1.26; 1.60]	-5.05-6.74	.98	.92
Phonological awareness, Time 1 (logits)	1.02	2.03	[0.81; 1.23]	-4.41-4.65	.90	.74

Descriptive statistics for the performance in cognitive tests are reported in Table 2. Pupils demonstrated the highest RCS in the digit—digit condition, while the lowest RCS were in the number word—number word condition.

Tab. 2. Descriptive statistics of cognitive tests

Variables	Mean	SD	95% CI	Range
Symbolic representation in visual format (digit – digit)				
RCS	0.56	0.17	[0.55; 0.58]	0.21-1.05
Accuracy	.95	.13	[.94; .96]	.10-1.00
RT	18.1	5.52	[17.55-18.65]	2.29-39.93
Symbolic representation in verbal format (number word – number word)				
RSC	0.34	0.11	[0.33; 0.35]	0.08-0.83
Accuracy	.95	.13	[.93; .96]	.30-1.00
RT	31.24	11.89	[30.06; 32.43]	6.18-101.46
Cognitive predictors				
Nonsymbolic representation (proportion of correct answers)	.55	.18	[0.54-0.57]	.00-.85
Working memory (proportion of correct answers)	.16	.15	[0.15; 0.18]	.00-.88

Correlation Analysis

We estimated correlations between symbolic representation in two formats and other cognitive tests (Table 3).

Tab. 3. Pearson correlations among performance tests and cognitive tests

	1.	2.	3.	4.	5.
1. Symbolic representation in a visual format (digit – digit, RCS)					
2. Symbolic representation in a verbal format (number word – number word, RCS)	.52***				
3. Nonsymbolic representation	.21***	.17***			
4. Working memory	.08	.13*	.01		
5. Reading performance, Time 1	.08	.40***	.08	.20***	
6. Phonological awareness, Time 1	.09	.18***	-.08	.29***	.54***

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

The correlation analysis revealed a moderate association between the magnitude comparison tests in the visual and the verbal format. Inversely to magnitude comparison in the digit—digit condition, a comparison in the verbal format is positively associated both with reading performance and phonological awareness.

Nonsymbolic magnitude representation is positively related to performance in the symbolic magnitude comparison test in all conditions. Working memory had a small and positive correlation only with the symbolic comparison in the number word—number word condition, and with reading performance and phonological awareness.

Relations between Symbolic Representation in a Verbal Format and Math Performance

To estimate the association between symbolic representation in a verbal format and math performance, a hierarchical regression analysis was performed (Table 4).

Tab. 4. Results of hierarchical regression analysis for math performance at the end of first grade as an outcome and symbolic representation in a verbal format

Predictors	Model 1	Model 2	Model 3	Model 4
	B (s.e.)	*B* (s.e.)	*B* (s.e.)	*B* (s.e.)
Symbolic representation in a verbal format (number word – number word)	0.38*** (0.06)	0.17** (0.06)	0.05 (0.07)	0.03 (0.06)
Nonsymbolic representation		0.09 (0.06)	0.06 (0.06)	-0.01 (0.05)
Working memory		0.18** (0.06)	0.18** (0.06)	0.08 (0.05)
Phonological awareness, Time 1		0.43*** (0.07)	0.42*** (0.07)	0.11 (0.06)
Reading performance, Time 1		0.10 (0.07)	0.14* (0.07)	-0.02 (0.06)
Symbolic representation in a visual format (digit – digit)			0.21** (0.06)	0.11* (0.06)
Mathematics performance, Time 1				0.69*** (0.07)
(Intercept)	1.98*** (0.06)	1.98*** (0.06)	1.98*** (0.06)	1.98*** (0.05)
F	39.68*** (1, 365)	29.62*** (5, 361)	27.12*** (6, 360)	46.16*** (7, 359)
R^2	.10	.29	.31	.47
R^2 changes		.19***	.02**	.16***
Observations	367	367	367	367

*** $p< .001$, **$p< .01$, *$p<.05$

The analysis revealed that the precision of symbolic representation in a verbal format had a significant effect on math performance adjusted for working memory, nonsymbolic representation, phonological awareness and reading performance. After symbolic representation in a visual format was added, the effect of verbal symbolic representation became non-significant.

Based on these results, we suggest that symbolic representation in a visual format might mediate the effect of verbal symbolic numerical representation. To test this hypothesis, we ran a mediation analysis. In the first step, the effect of the predictor (symbolic representation in a verbal format) on the mediator (symbolic representation in a visual format) was estimated. The analysis demonstrated that the predictor had a significant effect on the mediator when controlling for other variables (B = 0.56, s.e. 0.05, p<.001). Next, the effects of the mediator and predictor were estimated. The results revealed that symbolic representation in a visual format had a significant effect on math performance (B = 0.21, s.e. 0.07, p< .01). Direct and indirect effects and 95% CIs were calculated by bootstrapping (Table 5).

Tab. 5. Direct, indirect and total effects of symbolic representation in a verbal format on math performance

Mediator	Direct effect	Indirect effect	Total effect	Proportion of effect mediated
Symbolic representation in visual format	0.05 [-0.09; 0.20]	0.12 [0.04; 0.22]	0.17 [0.06; 0.28]	0.69

In summary, the effect of symbolic representation in a verbal format on math performance was partly mediated by symbolic representation in a visual format. The effect of magnitude representation in a visual format was significant even after prior math performance was added as a predictor.

Discussion

This study investigated the relationship between the precision of symbolic numerical representation in a verbal format (number words) and math performance adjusted for prior math performance, nonsymbolic numerical representation, working memory, phonological awareness and reading performance at the end of first grade. To test the precision of symbolic representation, we used a magnitude comparison test involving digits and number words with a sample of first graders. Previous studies have shown that the processing of number words is influenced by language (Ganayim & Ibrahim, 2014; Imbo et al., 2014; Lukas et al., 2014), and our study is the first to investigate the precision of symbolic format representation in a sample of Russian-speaking children.

Previous studies reported that symbolic numerical representation was significantly associated with math performance, although this conclusion was mostly based on the estimation of symbolic representation in a visual format (digits). Our results revealed that the precision of symbolic representation in a verbal format had a significant link with math performance, but this association became non-significant after symbolic representation in a visual format was added to the model. Mediation analysis demonstrated that the visual format of symbolic representation mediated the effect of the verbal format and that the verbal format did not have a direct effect on math performance.

The indirect effect of number words via digits may support the hypothesis that the verbal and visual formats of representations play different roles in solving different math tasks**.** It has been shown that digits are processed faster than number words and that these differences manifest in magnitude comparison and arithmetic tasks and in word problem solving (e.g., Cohen Kadosh, Henik, & Rubinsten, 2008; Megías & Macizo, 2016). These findings are consistent with the Triple-Code Model which assumes the existence of a preferred format for every numerical procedure (Dehaene, 1992). For example, the preferred format for a naming task is the verbal format, so the displayed digits have to be translated into the verbal format first. Thus, the processing of number words in a written format might be less involved during magnitude comparison.

On the other hand, the absence of a direct effect of number words on math performance might be related to developmental processes. There is plenty of evidence that the acquisition of number words occurs earlier than the acquisition of digits (Benoit et al., 2013; Le Corre et al., 2006; Le Corre & Carey, 2007; Wynn, 1990, 1992). It has been shown that children's understanding of digits is based on their understanding of number words (Hurst et al., 2017), and from a developmental perspective, children's ability to manipulate digits is predicted by their ability to understand number words (Knudsen et al., 2015). It is possible that at the end of first grade pupils have sufficient experience in manipulating digits and that verbal symbolic representation starts to play a supporting function.

However, magnitude processing in a verbal format has an indirect effect on math performance, which can indicate the involvement of language processing and math problem solving (Simmons & Singleton, 2008; Zhang et al., 2014; Zhang & Lin, 2015). In particular, it has been demonstrated that children routinely transform Arabic digits into number words to solve arithmetic problems (Geary et al., 1996). The Triple-Code model postulated that to solve arithmetic problems presented visually, an individual may recruit verbal and analog representations of numerosity (e.g., Dehaene, 2001). It has been demonstrated that number words, unlike digits, gain access to analog code via phonological code and that speech sound processes are used to solve math problems (Damian, 2004). Specifically, to solve a problem, children may first transform some operators into a speech-based code.

It is possible that the processing of number words is restricted by the audio format and that the importance of such processing is reflected in the involvement of phonological processing in problem solving (e.g. Prado et al., 2011; Simon et al., 2002). According to the McCloskey model (Abstract Code Model), there is a difference between the processing of spoken and written number words. While spoken number words involve comprehension and production with phonological processing mechanisms, written number words are processed with graphemic processing mechanisms (McCloskey et al., 1985). For example, it has been shown in neurological studies that transcoding written number words into digits is more difficult than transcoding spoken number words into digits (Cipolotti & Butterworth, 1995; Messina et al., 2009). The non-significance of the association between math performance and the precision of comparing written number words in the current study might reflect the low involvement of graphemic processing in math problem solving; this issue should be addressed in future studies.

It should be noted that most studies on the association between math performance and the precision of symbolic representation have used number recognition and dictation tasks in an audio format or magnitude comparison tasks with spoken number words, which might involve a greater amount of phonological processing (e.g., Göbel et al., 2014; Imbo et al., 2014; Moura et al., 2015). We investigated the precision of symbolic representation using written number words, and the results obtained might be explained by the different format of the tasks. Longitudinal studies need to be carried out to explore the developmental changes in acquiring digits and, more broadly, the transition from number words to digits, and their role throughout formal education.

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