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Linking Quantities and Symbols in Early Numeracy Learning

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Supplementary Materials: Materials [see Index of Supplementary Materials]

Abstract

What is the foundational knowledge that children rely on to provide meaning as they construct an exact symbolic number system? People and animals can quickly and accurately distinguish small exact quantities (i.e., 1 to 3). One possibility is that children's ability to map small quantities to spoken number words supports their developing exact number system. To test this hypothesis, it is important to have valid and reliable measures of the efficiency of quantity-number word mapping. In the present study, we explored the reliability and validity of a measure for assessing the efficiency of mapping between small quantities and number words – speeded naming of quantity. Study 1 (N = 128) with 5- and 6-year-old children and Study 2 (N = 182) with 3- and 4-year-old children show that the speeded naming of quantities is a simple and reliable measure that is correlated with individual differences in children's developing numeracy knowledge. This measure could provide a useful tool for testing comprehensive theories of how children develop their symbolic number representations.

Keywords

subitizing, children, preschoolers, early mathematics, numeracy, rapid naming of quantities, exact system of number

Humans acquire a complex symbolic system for representing number. The symbolic number system has a visual code (i.e., Arabic digits) that is shared universally among the majority of numerate cultures, and spoken and written codes (i.e., number words) that vary across languages. The symbolic number system allows the representation, manipulation, and communication of exact quantities. Children's learning of the symbolic number system is a central component of education: Knowledge of the symbolic number system forms the foundation of all STEM disciplines (i.e., Science, Technology, Engineering, and Mathematics) and is used extensively in everyday life. The question of how nonsymbolic quantity knowledge supports the development of the symbolic system is central to theories of numerical cognition (Butterworth, 2010; Feigenson et al., 2013; Hutchison et al., 2020; Le Corre & Carey, 2007; Leibovich & Ansari, 2016; Libertus, 2015; Libertus et al., 2013; Lyons & Ansari, 2015a, 2015b). In the present research, we develop the view that children's ability to link small exact quantities to spoken number words is a useful index of early individual differences in symbolic number knowledge (Gray & Reeve, 2014; Landerl et al., 2004; Willburger et al., 2008) and test a simple measure of exact quantity naming for young children.

Humans are sensitive to various features of objects that may also help to determine quantity, including spatial contour and continuous magnitude (Leibovich et al., 2017; Mix et al., 2016). Two distinct non-symbolic systems have been described that allow representation and manipulation of quantity (Feigenson et al., 2004). The *approximate* *magnitude system* (AMS[1]) operates over a wide range of quantities whereas the *exact magnitude system* (EMS) applies to small quantities of one, two, and three (and perhaps four). Núñez (2017) described these two systems as quantical rather than numerical, distinguishing them from the exact symbolic number system which humans acquire through cultural experience. Although neither magnitude system developed specifically to process number (Feigenson et al., 2004), they nevertheless may support the acquisition of symbolic number in humans.

Performance on tasks that tap the approximate magnitude system (e.g., which of two sets of dots has more?) is correlated with various mathematical outcomes (Leibovich et al., 2017; Lyons & Ansari, 2015a; Schneider et al., 2017). AMS performance is ratio dependent, as are decisions about dimensions such as loudness, length, brightness, and area, indicating that it is a general characteristic of systems that code for relative magnitude (Lyons & Ansari, 2015a). Some researchers have argued that the AMS provides the initial semantic information that is used in the development of symbolic number representations (Libertus, 2015; Libertus et al., 2013; J. Wang et al., 2016). However, other empirical and theoretical evidence challenges this assumption (De Smedt et al., 2013; Leibovich & Ansari, 2016; Merkley et al., 2017; Merkley & Ansari, 2016; Mix et al., 2016; Szűcs & Myers, 2017). Instead, consistent with the focus of the present research, arguments are made that the *exact* magnitude system is the quantical basis for the symbolic number system (Butterworth, 2010; Merkley et al., 2017).

In support of an early link between visual attentional processes and quantities, infants show evidence of representing exact quantities of 1, 2, and 3 (reviewed by Feigenson et al., 2004; cf. Mix et al., 2016), and children as young as 4 years of age show characteristic patterns, identifying quantities up to 3 (and sometimes 4) relatively quickly and accurately (Le Corre & Carey, 2007; LeFevre et al., 2010). Verbal identification of small exact quantities, called subitizing, involves direct mapping between a visual array and a number word that indicates how many items are present in the array (Mandler & Shebo, 1982; Trick & Pylyshyn, 1994). In contrast, counting requires a procedure of mapping the sequence of number words to a set of items, systematically and exhaustively. Counting is much slower and more error-prone than subitizing, and response times for counting increase linearly with the number of items, both for children (Karagiannakis & Noël, 2020; LeFevre et al., 2010) and adults (Mandler & Shebo, 1982). Note that the underlying cognitive mechanisms which support subitizing have been described either as relying on a visual-attentional system that can track a limited number of objects (Bremner et al., 2017; Trick & Pylyshyn, 1993, 1994) or as a system of parallel individuation in which objects can be retained in working memory and compared to the visible set (Feigenson et al., 2004; see Cheung & Le Corre, 2018; Le Corre & Carey, 2007 for discussion of this distinction).

In this paper, we propose that the exact magnitude system helps children to connect non-symbolic quantities to their developing representation of the symbolic number system (Leibovich & Ansari, 2016; Lyons & Ansari, 2015a; Reynvoet & Sasanguie, 2016). Humans' ability to quickly identify the quantity of small sets has been recognized and measured for a very long time (Beckwith & Restle, 1966). The possibility that this ability may support the development of the exact number system has always been viable (e.g., see Feigenson et al., 2004; Izard, Pica, Spelke, & Dehaene, 2008; Le Corre & Carey, 2007), but has not received extensive empirical or theoretical development (but see detailed discussions by Hutchison et al., 2020; Leibovich & Ansari, 2016; Reynvoet & Sasanguie, 2016).

Reynvoet and Sasanguie (2016) provide a direct comparison of the plausibility of the AMS versus the EMS as the core capacity that humans use to link quantities and symbols and that therefore has a causal link to mathematics (Mix et al., 2016). Learning to count involves multiple skills and a series of conceptual advances, with expertise developing slowly in children between the ages of two and six years. The ability to rapidly and accurately map quantities to number words using visual-spatial attention could support this process. The EMS may be central to early counting knowledge, helping children quickly connect a perceived quantity to a spoken number (Hurst et al., 2017; Jiménez Lira et al., 2017). Mix et al. (2016) suggested that learning the count words in relation to sets of objects directs children's attention to the property of number. They also suggest that "the entire system that includes object recognition, naming, spatial location, and number" (p. 20) together constitute the framework which supports children's number system development.

1) The approximate magnitude system has often been referred to as the approximate *number* system, abbreviated as ANS, however, we prefer to reserve the term 'number' for exact symbolic representations, on the view that the magnitude systems that are available to various animals do not code for exact number (Núñez, 2017).

Many longitudinal studies have shown that verbal counting (i.e., recitation of the counting string), measured in kindergarten, predicts children's acquisition of other numerical skills (e.g., Muldoon, Towse, Simms, Perra, & Menzies, 2013; Stock, Desoete, & Roeyers, 2009; Zhang et al., 2014; cf. Soto-Calvo, Simmons, Willis, & Adams, 2015). However, fewer researchers have tested the links between visual attention, enumeration of small quantities, and children's developing symbolic number skills (cf. Gray & Reeve, 2014, 2016; LeFevre et al., 2010; Reeve, Reynolds, Humberstone, & Butterworth, 2012). Children who can easily and quickly match digits to small quantities show better performance on symbolic comparison tasks (Hurst et al., 2017; Jiménez Lira et al., 2017; Mundy & Gilmore, 2009). This link is important, because symbolic number comparison has been suggested as a fundamental component of children's developing numerical skills (Vanbinst et al., 2016; White et al., 2011). Thus, the EMS which allows children to perceive small quantities is an excellent candidate for a core ability supporting their acquisition of symbolic number knowledge.

Evidence for Links Between the Exact Magnitude System and Numerical Development

Children With Developmental Disabilities

Some work with children who have specific cognitive disabilities supports the link between the EMS and early numeracy development. For example, children and adults with Williams syndrome, a chromosomal disorder related to spatial processing, show worse performance than typically-developing children on mathematical measures that implicate quantity representations or mapping between quantities and symbols (O'Hearn et al., 2011; O'Hearn & Landau, 2007; Opfer & Martens, 2012). Consistent with the possibility that these deficits can be linked to the EMS, O'Hearn et al. (2011) found that individuals with Williams syndrome were only able to track two moving objects, whereas typically achieving adults can track four and sometimes more. Similarly, children with spina bifida have difficulty with mathematics and have a reduced subitizing range (Attout et al., 2020), as do children with 22q11.2 microdeletion syndrome (Attout et al., 2017) and those with cerebral palsy (Arp & Fagard, 2005; Van Rooijen et al., 2015). In these studies, the deficits in numerical tasks that required magnitude processes were linked to these children's more general problems in processing visual-spatial information.

Children who have specific numerical deficits, for example, developmental dyscalculia, may also have difficulty with mapping symbols to the EMS. Ashkenazi, Mark-Zigdon, and Henik (2013) found that children with developmental dyscalculia showed larger slopes in the subitizing range than matched controls (see also Landerl, 2013; Landerl et al., 2004; Schleifer & Landerl, 2011). van der Sluis, de Jong, and van der Leij (2004) also reported that children with dyscalculia showed deficits in speeded naming of quantities. To determine the specificity of naming deficits, Willburger et al. (2008) compared speed naming of digits, objects, letters, and quantities of 8- to 10-year-old children with dyslexia, dyscalculia, or a double deficit (i.e., dyslexia and dyscalculia), to that of typically-developing children. They found that children with dyscalculia were only impaired on speeded naming of quantities (1 to 4) whereas children with dyslexia were impaired on naming of quantities, objects, letters, and digits, indicating that they had a general deficit in lexical access. These findings suggest that there is a specific connection between children's performance on speeded naming of quantities and number system knowledge. However, because these children were older and already had diagnosed impairments, the relevance for the development of early numeracy knowledge in typically-developing children is not clear.

Typically-Developing Children

Very few researchers have explored the relations between subitizing performance and mathematical tasks for typically-developing children. Researchers who have studied children's counting, for example, have often not distinguished between quantities in the subitizing (i.e., 1 to 3) versus counting range (i.e., 4 to 9; Karagiannakis & Noël, 2020; Reigosa-Crespo et al., 2012). LeFevre et al. (2010) found that subitizing latency was correlated with a nonsymbolic exact arithmetic task for 4- and 5-year-old children and, as part of a quantitative factor, predicted performance on magnitude comparison, number line, calculation, and numeration tasks two years later. For 7- and 8-year-children, a quantitative factor that included subitizing, counting, and symbolic number comparison was concurrently related to calculation, backwards counting, number system knowledge, and arithmetic fluency, after controlling for working memory, and linguistic skills (Sowinski et al., 2015). Gray and Reeve (2016) found that the efficiency of dot counting for quantities

1 to 5 was a good predictor of 3½- to 5-year-old children's mathematical ability profiles, but counting and subitizing were not distinguished in that research. Reeve et al. (2012), in a longitudinal study of children from ages 6 through 12, found that children with larger slopes and smaller subitizing ranges than their peers also performed worse on measures of mathematical skill at all ages tested. For 69% of the students, performance profiles were consistent in this six-year time span. Overall, these results suggest that the EMS may have an early and persistent relation to mathematical performance.

Hutchison et al. (2020) found support for the view that quantities in the subitizing range are critical to the development of children's magnitude comparison processes. Kindergarten children (i.e., aged 5 to 6 years) completed magnitude comparison with both nonsymbolic (dots) and symbolic (digits) trials twice during the year. Longitudinal analyses showed that, within the subitizing range (i.e., quantities of 1 to 4), children's dot comparison performance in fall predicted their digit comparison performance in spring, and digit comparison in fall also predicted dot comparison in spring, suggesting that the knowledge involved in the comparison task was strongly linked for these quantities. In contrast, for trials in the counting range (i.e., 6 to 9), digit comparison in fall predicted performance on dot comparison in spring, but the reverse relation was not significant. Their results suggest that quantities in the subitizing range are more closely linked to symbolic knowledge than quantities in the counting range.

Measurement of the Developing Exact Number System

One limitation of existing research on non-symbolic exact number skills has been the lack of a reliable and valid measure of the EMS that can be used in a variety of situations, specifically, with different age groups, with different populations of children, and in both cross-sectional and longitudinal projects. Research on the AMS has benefitted, in contrast, from the availability of online measures (e.g., PanaMath; http://panamath.org/) and of simple paper-and-pencil measures (e.g., Hutchison et al., 2020; Nosworthy et al., 2013). Accordingly, the main goal of the present research was to test a measure that taps the relation between the EMS and exact number knowledge, specifically focused on mapping small quantities to symbols, and that is easy to administer, widely accessible, and suitable for children of different ages and abilities.

Accordingly, we used a brief speeded naming task for small quantities, specifically 1, 2, and 3, termed speeded naming of quantities (i.e., SN-Quantity). We focused on quantities of 1, 2, and 3 because there is evidence that subitizing of 4 develops later (Karagiannakis & Noël, 2020; LeFevre et al., 2010). Control speeded naming tasks, each with three different items, were developed where participants named digits, letters, or colors. Versions of speeded naming with digits, letters, or colors have been referred to as "rapid automatized naming" or RAN and have been used extensively to explore individual differences in reading skill (Norton & Wolf, 2012). These traditional speeded naming tasks are correlated with measures of mathematical skill (Koponen et al., 2017; Y. Wang et al., 2020). We hypothesized that speeded naming of quantities will be related to mathematical measures independently of other speeded naming measures.

In two studies with adults, the SN-Quantity task predicted unique variance in a measure of calculation fluency, even after controlling for speeded naming of letters and factors such as location of educational experience (Asia vs. Canada), gender, math anxiety, and age (Sowinski, 2016). A measure of the AMS, in contrast, did not predict significant unique variance in calculation fluency. Furthermore, the relation between speeded quantity naming and fluency was significant even when controlling for symbolic number comparison. Thus, for adults, the SN-Quantity task is a simple, fast, and reliable measure of the link between the exact magnitude system and exact number knowledge. The goal of the present research was to evaluate this measure with young children.

Present Research

In Study 1, we hypothesized that speeded naming of quantities (SN-Quantities) would predict early mathematical skills for 5- and 6-year-old children, whereas speeded letter naming (SN-Letters) would predict early literacy skills. There is a large literature on the relation between speeded letter naming and early reading skill (Norton & Wolf, 2012) and some literature on the relation between speeded letter, digit, object or color naming, and arithmetic (Koponen et al., 2017; Y. Wang et al., 2020). Fewer researchers have tested the relations between subitizing and early number skill (Karagiannakis & Noël, 2020; LeFevre et al., 2010; Schleifer & Landerl, 2011; Willburger et al., 2008). In Study 1, we also controlled for cognitive abilities that are known to predict early numeracy (i.e., nonverbal reasoning, spatial span) and early literacy (i.e., vocabulary, phonological awareness). Differential relations between the two speeded naming measures and math and reading outcomes will establish the construct validity of the speeded naming of quantities measure with 5- and 6-year-olds. In Study 2, we used the SN-Quantities measure with even younger children, to determine the lower age limit at which this task is valid and reliable. We predicted that the SN-Quantities measure would be related to those measures which required symbolic number knowledge (e.g., number words or digits), that is, object counting, verbal counting, and a comprehensive measure that included a range of number skills.

Study 1

Two hypotheses were tested in Study 1: (a) speeded processing of non-symbolic quantities (dots) would predict early numeracy, but not early literacy performance, whereas (b) speeded processing of letters would predict early literacy, but not early numeracy performance (Willburger et al., 2008). These hypotheses focus on the construct validity of the SN-Quantities measure.

Method

Participants

Participants were 128 kindergarten children (70 boys; 58 girls) with a mean age of 5:10 years: months. They were recruited through contacts with child care centres and other early childhood learning facilities in a large Canadian city. At recruitment, parents provided information about home numeracy and literacy activities (see Skwarchuk et al., 2014). Because of the method of recruiting, the children came from a broad range of socio-economic circumstances. English was the only language spoken at home for all but three of the families. All children were tested mid-way through their first year of school-based instruction (i.e., kindergarten). Family income was estimated based on postal codes (which were provided by parents) and used to index socio-economic status. In Canada, postal codes have six alpha-numeric characters. The last three characters represent a postal delivery unit, which in cities, typically includes the houses on one side of a city block. Statistics Canada provides information about average income (in Canadian dollars) that is linked to these postal codes. For the present study, incomes associated with postal codes were obtained from the 2006 census, the closest one to 2009, which is the year in which data were collected. Thus, this index of socio-economic status reflects the neighbourhoods of the families. Income was approximately normally distributed, with a mean of $70,260 and a median of $67,912.

Materials

Table 1 shows the tasks used in both studies. In Study 1, children completed two speeded naming tasks, two nonverbal cognitive tasks, two verbal cognitive tasks, and three measures of performance (two measures of early numeracy and one measure of early literacy).

Speeded Naming Tasks — Children were shown two pages of stimuli for each of the SN-Quantities and SN-Letters tasks. The SN-Quantities task included dots in groups of 1, 2, or 3, each presented 8 times per page in four rows of six. Speeded naming of pictures, letters, colors, and digits have been used in many versions of these tasks (e.g., in the CTOPP; Wagner, Torgesen, & Rashotte, 1999). In the present research, we created letter and color versions of these measures that had three alternatives, rather than four, because we wanted to limit the subitizing range to 3 and to match the number of alternatives across all three measures. Thus, the SN-letters consisted of the letters M, C, and A, each presented 8 times per page in four rows of six. Order was pseudo-random, such that the same quantity or letter was not presented sequentially more than twice. The practice page for each measure included six items in one row. Children were asked to name the items on the practice page, starting at the left. If they made an error, it was corrected. Once the experimenter was satisfied that the child understood the task, the two experimental pages were administered. For the test pages, children were asked to name each item, starting at the top left-most item and proceeding row-by-row.

Table 1

Summary of Measures in Study 1 and Study 2

Category / Name of Task	Study
Speeded Naming	
SN-Quantities	1, 2
SN-Letters	1, 2[a]
SN-Colors	2[b]
Nonverbal Cognitive skills	
Spatial span	1, 2
Nonverbal reasoning	1
Verbal Cognitive skills	
Phonological awareness	1
Receptive vocabulary	1, 2
Performance Measures	
Literacy	
Word reading	1
Numeracy	
Nonsymbolic arithmetic	1, 2
KeyMath Numeration	1, 2
Object counting	2
Verbal (rote) counting	2

[a]Canadian children only at pre-test. [b]Turkish children at pre-test; all children at post-test.

Naming times were recorded with a stopwatch for each page and children's naming errors were recorded. These tasks can be accessed from https://osf.io/uz6s3/.

Cognitive Tasks — Cognitive tasks included both nonverbal and verbal measures.

Spatial Span. Children viewed nine green circles on a laptop computer screen. On each trial, a frog visited a sequence of the circles. They watched and then copied the frog's path with a pointer. The experimenter recorded the sequence. After a single demonstration trial with two locations, children were shown two trials each with sequence lengths of 2, 3, 4, 5, and 6 locations. However, the next longest sequence was not shown if the child did not successfully reproduce at least one sequence of a particular length. Performance was the number of sequences correctly reproduced (maximum 12). Split-half reliability was .74.

Nonverbal Reasoning. Children were given the nonverbal analogies subtest from the CIT (Cognitive [Intelligence] Tests: Nonverbal; Gardner, 1990). This test is not normed for children younger than six years and thus all children started on the first item and continued until they made 6 consecutive errors. Scores were total correct. Kuder-Richardson 20 reliability is reported in the test manual as .90.

Receptive Vocabulary. To control overall testing time, a modified version of the Peabody Picture Vocabulary Test (PPVT-III; Dunn & Dunn, 1997) was used. All children started on Item 61 (i.e., no basal was established) and continued to Item 120 or until they made eight or more errors in a set of 10. Number correct (assuming a base score of 60) was used as the index of performance. With this non-standard procedure, testing time was approximately 10 minutes.

Sound Matching. Phonological awareness was measured with the sound-matching subtest of the Comprehensive Test of Phonological Processing (CTOPP; Wagner et al., 1999). Children are shown three pictures and then asked to match a target word to the pictures with either the same beginning sound or the same ending sound. Testing stopped when children made errors on four of seven items. Reported internal consistency of this test is above .90.

Performance Measures — Children completed two early numeracy measures (numeration and nonsymbolic arithmetic) and one early literacy measure (word reading). The KeyMath numeration test (Connolly, 2000) has initial items involving counting, digit naming, and ordinal position, followed by items requiring identification and ordering of double-digit numbers. Children started on the first item and when they made more than three errors in a row, the task was terminated. Scores were total solved correctly. Split-half reliabilities are reported in the testing manual of .70 for this age group.

The nonsymbolic arithmetic task is a variant of the test used by Jordan et al. (1992) that was modified by LeFevre et al. (2010). Children are shown a set of animals, which is then hidden. Additional animals are added or subtracted and then the child is asked to show (with their own set of animals) how many are left in the hidden set. Two initial trials that involve matching visible sets are administered first (sets of 2 and 5, not scored), to ensure the children understand the task. Subsequently, children attempted four addition and four subtraction trials, including 1 + 2, 3 + 1, 2 + 3, 4 + 2, 3 − 1, 4 − 3, 5 − 2, and 6 − 4. Subtraction trials were not presented if children were unsuccessful on all four addition trials. Performance was total correct arithmetic trials (out of 8).

To measure word reading, children were given the Letter-Word Identification subtest of the Woodcock-Johnson Reading Mastery Test (Woodcock, 1998). The initial items on this task requires that children name letters and subsequently progresses to single words. The test is terminated after six consecutive errors or when the child declines to continue. All children started at the beginning of the test and thus reported scores are total correct.

Results

Descriptive Statistics

As shown in Table 2, across the four pages of the speeded naming measures (i.e., two with quantities, two with letters), naming times averaged about 20 s per page. Children made few errors, with medians of 0 on all four pages and ranges from 0 to 8 errors per page.[2] A few children had very slow naming times, such that there was a positive skew for times on each page. To equate the scores across tasks and take both speed and errors into account, efficiency scores were calculated for each page, correcting for errors (i.e., the number of items either named incorrectly or skipped). Thus, efficiency (items-per-second) = [(24 − errors)/time in seconds].

Performance was consistent across pages. The correlations for efficiency scores between Pages 1 and 2 were: $r(121) = .802$, $p < .001$, for quantity naming; and $r(122) = .907$, $p < .001$, for letter naming. The means were not significantly different for page 1 compared to page 2: $t(122) = 1.096$, $p = .275$, for quantity naming; and, $t(123) = -1.14$, $p = .256$, for letter naming. Thus, averaged efficiency scores across the two pages of each test were used in further analyses. Five children were missing one of two pages of one version of the tasks (i.e., three were missing one page from the quantity task and two were missing one page from the letter task) and in these cases, performance on the one available page was used. Because this is an efficiency index (i.e., items-per-second), higher scores indicate better performance and so correlations with other measures are expected to be positive. Means for efficiency scores are shown in Table 3.

The correlations among the nine variables are shown in Table 3, along with means and standard deviations for each measure. The control measures (age, income, gender) were not correlated with one another, but each was correlated with some of the other measures and so they were retained in further analyses. Older children had higher vocabulary, sound matching, and nonverbal reasoning scores than younger children, and they performed better on the numeration and nonsymbolic arithmetic tests. Parental income was related to vocabulary, sound matching, numeration, and non-symbolic arithmetic performance. Boys scored higher than girls on the nonverbal reasoning and numeration tasks whereas girls had higher sound-matching scores. The cognitive abilities were inter-correlated, and most were also correlated with the literacy and numeracy performance measures. Spatial span was not significantly correlated with word reading, vocabulary, or speeded naming of letters, however.

2) One child made 18 and 16 errors on the letter naming pages; this child's data were excluded from further analyses.

Table 2

Children's Performance on Speeded Naming Tasks in Study 1 and Study 2

	Time (s)					Naming Errors				
Page	***n***	***M***	***SD***	***Min***	***Max***	***n***	***M***	***SD***	***Min***	***Max***
Study 1: Quantity Naming										
1	126	22.8	6.6	12.2	52.5	123	0.16	0.56	0	4
2	127	23.1	7.8	8.6	76.4	124	0.34	0.99	0	8
Study 1: Letter Naming										
1	125	20.9	6.9	9.7	49.8	123	0.49	1.7	0	18
2	125	20.7	7.7	10.2	64.5	123	0.46	1.6	0	16
Study 2: Canadian Quantity Naming										
1	59	50.2	24.5	23	172	65	3.32	4.33	0	23
2	59	45.7	18.1	21	115	64	3.50	5.26	0	24
Study 2: Canadian Letter Naming										
1	57	39.7	15.9	18	79	66	3.39	4.95	0	24
2	55	38.6	16.2	19	112	62	2.84	4.96	0	24
Study 2: Turkish Quantity Naming										
1	78	60.6	26.5	29	168	86	2.93	4.18	0	19
2	76	55.1	21.6	27	129	84	2.89	4.58	0	22
Study 2: Turkish Colour Naming										
1	76	48.8	15.9	19	100	82	2.89	4.45	0	17
2	75	48.6	18.0	21	137	82	2.90	4.47	0	17

Table 3

Correlation Coefficients, Means, and Standard Deviations for All Variables in Study 1

Variable	1	2	3	4	5	6	7	8	9	10	11	12
1. Age (months)												
2. Income (Cdn$)	-.132											
3. Gender	-.111	.111										
4. Vocabulary	.206*	.401**	-.089									
5. Sound Match	.203*	.288**	.180*	.465**								
6. NV Reasoning	.266**	.010	-.177*	.186*	.273**							
7. Spatial Span	.123	-.013	.014	.050	.285**	.337**						
8. Letter Word	.136	.175	.030	.521**	.570**	.268**	.073					
9. Numeration	.221*	.199*	-.243**	.407**	.409**	.427**	.210*	.517**				
10. NS Arithmetic	.196*	.296**	-.084	.425**	.445**	.312**	.305**	.490**	.534**			
11. SN-Quantity	.142	.117	.006	.361**	.551**	.370**	.188*	.650**	.654**	.574**		
12. SN-Letters	.153	.049	.040	.331**	.552**	.335**	.157	.742**	.524**	.427**	.790**	
M	70.2	70260	[a]	92.27	11.22	4.30	3.85	17.99	6.20	6.49	1.11	1.25
SD	3.4	20715		12.16	5.44	2.37	1.74	6.54	1.90	3.07	0.28	0.39
N	126	124	126	128	124	128	128	128	124	127	125	124

Note. *N* = 117 for correlations; NS = non-symbolic; SN = speeded naming; NV = Nonverbal. Scoring: Age (months), Income (Canadian dollars), Gender 1 = boys; 2 = girls, Vocabulary, Sound Match, Nonverbal reasoning, Letter Word, Numeration, Nonsymbolic arithmetic (number correct), spatial span (number of correct sequences).

[a]70 boys; 58 girls.

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

Table 4

Multiple Regression Analysis of Letter-Word Reading in Study 1 (n = 118)

	Hierarchical		Final Model	
Predictors	**β (step)**	***p***	**β**	***p***
Block 1: Control variables				
Income	.128	.169	-.053	.413
Age	.164	.080	-.045	.470
Gender[a]	.033	.724	.015	.808
R^2 change	*.038*	*.214*		
Block 2: Domain-Specific				
Vocabulary	.384***	< .001	.274***	< .001
Sound Matching	.415***	< .001	.107	.166
R^2 change	*.357***	*< .001*		
Block 3				
Speeded Naming - Quantities	.426***	< .001	.026	.792
R^2 change	*.125****	*< .001*		
Block 4				
Speeded Naming - Letters	.582**	< .001	.582***	< .001
R^2 change	*.113****	*< .001*		

Note. Block 1: R^2 = .038, $F(3, 115)$ = 1.51, p = .214. Block 2: R^2 = .395, $F(5, 113)$ = 14.75, p < .001. Block 3: R^2 = .520, $F(6, 112)$ = 20.23, p < .001. Block 4: R^2 = .633, $F(7, 111)$ = 27.39, p < .001.

[a]Coded 1 = boys; 2 = girls.

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

The two speeded-naming tasks were correlated with most of the cognitive and academic measures. As expected, however, the two numerical measures were more highly correlated with speeded naming of quantities than with speeded naming of letters (for numeration, r = .654 vs. .524, z = 2.70, p = .007; for nonsymbolic arithmetic, r = .574 vs. .427, z = 2.84, p = .0045). In contrast, word reading was more highly correlated with speeded naming of letters than with speeded naming of quantity (r = .742 vs. .650, z = -2.20, p = .0279)[3]. The generally high level of inter-relations among the various predictors indicates that multiple regression is needed to test the hypotheses about the specificity of the links between the speeded naming tasks and the numeracy versus literacy outcomes.

Multiple Regression Analyses

Each of the three performance measures (i.e., numeration, nonsymbolic arithmetic, and word reading) was used as the dependent measure in a hierarchical linear regression. The three control measures (i.e., age, parental income, and gender) were included in the first block of predictors. Domain-general predictors that are relevant for each domain were added in the second block, followed by the speeded naming task that was not specific to that domain (i.e., quantities for reading; letters for numeracy tasks) in the third block. The domain-specific speeded naming task was added in the final block. As shown in Tables 4 and Table 5, parental income predicted children's performance on numeration and nonsymbolic arithmetic but was not a significant predictor of the reading measure in the final model. Gender was only a significant predictor of numeration (boys did better). Age was not a significant predictor presumably because it was correlated with the other measures and the range was constrained.

3) Comparisons between correlations were done using the online cocor calculator (Diedenhofen & Musch, 2015).

Table 5

Multiple Regression Analysis of Numeracy Measures in Study 1

	Numeration (n = 118)				Nonsymbolic Arithmetic (n = 117)			
Variable	**β (block)**	***p***	**β (final)**	***p***	**β (block)**	***p***	**β (final)**	***p***
Block 1: Control variables								
Income	.210*	.018	.147*	.028	.297**	.001	.250**	.001
Age	.221*	.013	.097	.163	.199*	.028	.097	.216
Gender[1]	-.253***	.004	-.250***	< .001	-.077	.390	-.081	.287
R^2 change	*.147****	*< .001*			*.117***	*.003*		
Block 2: Domain-General								
Spatial reasoning	.343***	< .001	.133	.087	.238**	.010	.064	.467
Spatial span	.111	.191	.071	.308	.235**	.008	.189*	.017
R^2 change	*.139***	*< .001*			*.135****	*< .001*		
Block 3: Speeded Naming – Letters	.428***	< .001	.036	.740	.324***	< .001	-.017	.890
R^2 change	*.158***	*< .001*			*.089****	*< .001*		
Block 4: Speeded Naming – Quantities	.523***	< .001	.523***	< .001	.461***	< .001	.461***	< .001
R^2 change	*.094****	*< .001*			*.073****	*< .001*		

Note. For Numeration: Block 1: R^2 = .147, F(3, 115) = 6.58, p < .001; Block 2: R^2 = .285, F(5, 113) = 9.03, p < .001; Block 3: R^2 = .443, F(6, 112) = 14.85, p < .001; Block 4: R^2 = .537, F(7, 111) = 18.36, p < .001. For nonsymbolic arithmetic: Block 1: R^2 = .117, F(3, 114) = 5.04, p <.003; Block 2: R^2 = .252, F(5, 112) = 7.55, p < .001; Block 3: R^2 = .341, F(6, 111) = 9.59, p < .001; Block 4: R^2 = .414, F(7, 110) = 11.10, p < .001.
[a]Coded 1 = boys; 2 = girls.
*p < .05. **p < .01. ***p < .001.

Variables included in the second block of the regressions were those that were expected to predict specific outcome measures. Thus, as shown in Table 4, vocabulary and sound matching were entered as predictors of word reading, accounting for significant variance. In the third block, speeded naming of quantities accounted for significant variance. However, when speeded naming of letters was added in Block 4, speeded naming of quantities no longer accounted for unique variance. Thus, as expected, speeded naming of letters was a significant predictor of early word reading skill in the final model (Norton & Wolf, 2012), whereas speeded naming of quantities was not.

Regression analyses for the two early numeracy measures are shown in Table 5. Spatial span was a significant predictor of nonsymbolic arithmetic, whereas nonverbal reasoning predicted numeration. Most importantly, in the final step for both numeration and nonsymbolic arithmetic, speeded naming of quantities predicted additional significant variance (9.4 and 7.3%, respectively) whereas speeded naming of letters did not.

Discussion

The results of Study 1 showed that the speeded naming of quantities task is a reliable and valid measure for 5- and 6-year-old children. Speeded naming of quantities predicted numeracy outcomes whereas speeded naming of letters predicted early reading. This dissociation between the two speeded naming tasks is especially impressive given the high correlation between them. Despite considerable shared measurement similarity, the core cognitive factors that influence speeded naming in each task appear to be distinct.

Study 2

In Study 2, we used the speeded naming of quantities task with 3- and 4-year-old children. The goals were to determine whether younger children would be able to complete the task, whether it was reliable with the younger age group, and to establish construct validity for the measure for younger children. All of the children in this study were participants in a large project that involved training of verbal counting skills. The results of the intervention were reported in two papers (Cankaya et al., 2014; Dunbar et al., 2017). Performance on the speeded naming tasks was not analyzed in those papers, however. The training study involved children in two countries, Canada and Turkey. The Turkish number naming system from 10 to 20 is simpler and more regular than that in English and thus the comparison across countries was of interest for the intervention.

Data for the early numeracy measures were completed at twice, first at the pre-test before a training session began, and second, at a post-test session six weeks later, after the intervention. Children met with an experimenter each week and counted as high as possible, then either (a) played one of two number games, (b) played a colour game, or (c) returned to the classroom. Performance on all the early numeracy measures improved over the six-week intervention, however, differential improvement in the number game conditions only occurred for verbal counting.

Method

Participants

A total of 182 children participated in the larger study, 94 (46 boys; 48 girls) in Canada and 88 (48 boys; 39 girls; one not specified) in Turkey. The Canadian children were recruited from four child care centres and ranged in age from 34 to 62 months (M = 45.3, SD = 7.5). All these children spoke English and used English exclusively in child care; 59 often or always spoke English at home, 27 sometimes spoke another language at home, and 6 spoke another language at home about half of the time. The Turkish children were recruited from three preschools and one child care facility. They ranged in age from 35 to 58 months (M = 48.1, SD = 5.7). All were monolingual Turkish speakers. Despite the similar range of ages, the Turkish children were significantly older than the Canadian children, $t(173.56) = -2.80$, $p = .006$. The distribution of gender across countries did not differ significantly.

Parents who completed the consent form were asked to specify the level of education of both mother and father. Parents' highest level of education was coded from 0 to 4, with 0 = less than high school, 1 = high school, 2 = community college degree, 3 = university degree, and 4 = postgraduate degree. The level of education of mothers and fathers was strongly related, $\chi^2(16, N = 170) = 150.59$, $p < .001$. Forty Canadian respondents provided education information for both parents; but they did not specify if they were the mother or the father, and nine respondents did not report education for a second parent. Parents in Canada had higher levels of education than parents in Turkey, $\chi^2(4, N = 179) = 30.02$, $p < .001$. The median was a university degree for Canadian parents versus a community college degree for Turkish parents. Accordingly, because parent education was so highly correlated across mothers and fathers, we used the highest reported level for either parent in further analyses.

Materials

Table 1 shows the tasks given to children in Study 2. All the early numeracy measures were given both at pre-test and at post-test. However, Canadian children did speeded naming of letters at pre-test whereas Turkish children did speeded naming of colours; both groups did speeded naming of colours at post-test. Two of the numeracy tasks given in Study 1 and Study 2 were the same (i.e., nonsymbolic arithmetic and KeyMath numeration), and two were different (i.e., verbal counting and object counting). In Study 2, the spatial span task was administered on iPads rather than on a computer (Study 1), but the pattern of locations and the sequences were the same. The children touched the locations in order after they watched each sequence. In Study 2, the vocabulary measure used with the Turkish children was based on the Turkish version of the Peabody Picture Vocabulary Test (Oner, 1997). Vocabulary scores (number correct) were converted to z-scores within each group.

Speeded Naming Tasks — The stimuli used in the speeded naming tasks were exactly the same as in Study 1 for the quantity and letter naming versions. The speeded naming of colors (i.e., red, blue, and black) version of the task was also used in the current study, because pilot testing showed that the Turkish children were not familiar with letters. The other difference from Study 1 was that the procedure used to administer the measures was modified because the children were so much younger than in the first study. Specifically, the experimenter pointed to each stimulus and the child was asked to name them. If the child hesitated for more than (approximately) two seconds, the experimenter moved on to the next item and recorded an error for that item. As in Study 1, children were shown practice items before attempting the test. If they were unable to name the practice stimuli, then the testing was discontinued. Further details are given in Appendix A.

Verbal Counting — Children were asked to count as high as possible, ostensibly to help a puppet count. When the child stopped counting, they were prompted with the preceding number (e.g., if they stopped at 12, then the experimenter asked if they could count higher and said "12 and …" with a rising intonation. Highest count, allowing for one error, was used as the index of performance. For example, if children counted 1, 2, 3, 4, 5, 7, 8, they were credited with a highest count of 8. If, however, they counted 1, 2, 3, 4, 6, 8, 9, they were credited with a highest count of 6 (i.e., allowing for one error on 5).

Object Counting — Children were given a group of small animal figures and asked to place a certain number on a place mat in front of them. First, children were asked to show a set of small numbers, that is, 3, 4, 5, and 6 (small set); next they were asked for larger quantities, that is 7, 8, 9, and 10 (medium set). If children were successful on the previous two trials, they were asked for 14, 15, 16, and 17 (large set). Testing was always terminated after children made two unsuccessful attempts or if they said "I don't know" for two trials in a row. Within each set size, a fixed random order was used, starting with 4 for the initial trial. The number of successful trials was used as the index of performance (i.e., 0 to 12), however, the majority of children were stopped before they reached the large set size.

Procedure

Children were administered the tasks in two 15- to 20-min sessions which constituted the pre-test assessment for the intervention study and in one or two sessions at post-test, six weeks later (Cankaya et al., 2014). In addition to the measures described here, children also completed two versions of a number line task, however, performance was very poor and so the data were not analyzed. Children also completed a number recognition task, however, the administration of the number recognition task varied between countries and so it was not analyzed in the present study. In session one, the children completed the object counting, nonsymbolic arithmetic, verbal counting, number recognition, and KeyMath numeration tasks. In session two, the Turkish children completed the speeded naming tasks, the spatial span task, the number line estimation tasks, and the vocabulary task. The Canadian children were given the tasks in session two in a different order, that is, number line, spatial span, vocabulary, and speeded naming.

Results

Descriptive Statistics

Speeded Naming Tasks — Although all of the children who attempted the two pages of the task could name the stimuli, nevertheless, the speeded tasks were more challenging for 3- and 4-year-olds than for the older children in Study 1. The experimenters noted that it was sometimes difficult to ensure that children followed the instructions and occasionally response times were not valid if children did not understand the requirement to continue from horizontally from one item to the next. Average data for each page of each test is shown in Table 1. As in Study 1, a corrected items-per-second score was calculated on each page for those children who had a valid naming time and made fewer than 12 errors on that page (i.e., [24 − errors]/naming time; see Table 6). The criterion of a maximum of 12 errors was chosen because 50% correct was significantly greater than chance (binomial probability with three alternatives), $p < .05$. Next, to maximize children's performance, their best items-per-second score across the two pages (i.e., the page for which they had a higher score if they had two valid pages) was chosen for use in further analyses. Between 84% and 92% of children who attempted the speeded naming tasks (depending on the specific measure) had valid speeded naming scores (i.e., items-per-second, best performance), as described in detail in Appendix A. Thus, this implementation of speeded naming was appropriate for most of the children in the study.

Table 6

Mean Pre-test and Post-test Performance in Study 2 and Comparison of Turkish and Canadian Children in Study 2

	Canadian			Turkish			Comparison		
Variable	*N*	*M*	*SD*	*N*	*M*	*SD*	*F*	*df*	*p*
Pre-test Scores									
SN-Letters (items-per-s)	56	.68	.25						
SN-Colours (items-per-s)				73	.55	.20			
SN-Quantity (items-per-s)	55	.59	.21	82	.46	.19	13.07	113.76	< .001
Vocabulary (number correct)	71	41.14	12.41	87	51.95	9.78			
Spatial Span (sequences)	55	2.29	2.02	82	2.18	1.49	.13	124.51	.719
Verbal Counting	55	18.71	17.51	82	15.67	9.89	1.68	114.17	.198
Nonsymbolic Arithmetic	55	2.76	2.53	82	2.85	1.69	.06	153.16	.803
Numeration (number correct)	55	3.22	1.64	82	2.12	1.73	13.76	124.19	< .001
Object Counting	55	4.49	3.58	82	2.48	2.89	13.17	138.86	< .001
Post-test Scores									
SN-Quantity (items-per-s)	48	.71	.22	38	.47	.21	25.08	84	< .001
SN-Colours (items-per-s)	48	.71	.19	38	.55	.21	14.81	84	< .001
Verbal Counting	48	21.15	10.01	38	16.58	8.10	5.20	84	.025
Nonsymbolic Arithmetic	48	3.60	2.29	38	3.45	2.23	.10	84	.751
Object Counting	48	6.21	3.13	38	2.50	2.50	35.43	84	< .001
Numeration	48	3.54	1.50	38	2.68	1.40	7.35	84	.008

Note. The vocabulary measures are different for the two groups, so they were not compared directly. For the regression analyses, *z*-scores within groups were calculated; *df* are corrected for unequal variances. Comparisons across country were done with listwise deletion of missing data.

Early Numeracy and Cognitive Tasks — Mean performance on the early numeracy and cognitive tasks are shown in Table 7 for pre- and post-test measures. Turkish children performed worse on some measures than Canadian children, including speeded quantity naming, however, there were no significant differences on spatial span, nonsymbolic arithmetic, or verbal counting. Differences in speeded quantity naming, object counting, and numeration indicate that the Turkish children had less advanced conceptual knowledge of number symbols and of the connections between symbols (e.g., number words) and magnitude (Hurst et al., 2017; Jiménez Lira et al., 2017). Verbal counting is simpler in Turkish than in English because the numbers in the teens decade are more predictable; moreover, verbal counting does not require mapping between quantities and symbols. Similarly, nonsymbolic arithmetic does not require knowledge of number words, although counting skills can support better performance (Jordan et al., 1992). Thus, although Turkish children were older, their numeracy knowledge was lower than that of the Canadian children, despite comparable cognitive capacity. In subsequent analyses, we controlled for country.

Test-retest reliabilities for efficiency scores were calculated for those subsets of children who did both versions of a measure at pre- and post-test. For quantities, the test-retest correlation was $r(82) = .788$, $p < .001$. For colours, which only the Turkish children did at both pretest and post-test, the correlation was $r(33) = .730$, $p < .001$. Children improved between the pre- and post-test on speeded quantity naming (.50 vs. .61 items-per-s), $t(83) = -6.57$, $p < .001$, and on speeded colour naming (.48 vs. .54), $t(34) = -2.92$, $p < .006$. In summary, the overall completion rate, internal reliability, and test-retest reliabilities suggest that the speeded naming tasks were reliable measures for most 3- and 4-year-old children. The frequency of valid scores was not significantly different for the Turkish versus Canadian group or for boys versus girls. Children who had a valid score on the SN-quantity task were older ($n = 136$, $M = 47.6$ months) than children who did not have a valid score ($n = 23$, $M = 43.0$ months), $t(157) = 3.21$, $p = .002$. Thus, age was controlled in further analyses.

Table 7

Correlations Among All Variables in Study 2 (Listwise): Pre-Test (N = 114) Below Diagonal and Post-Test (N = 86) Above Diagonal

Variable	1	2	3	4	5	6	7	8	9	10	11
1. Parent Edu		-.076	.281*	-.425**	.099	.239*	.162	.285**	.036	.075	.183
2. Age (months)	-.210*		.464**	-.005	.440**	.424**	.265*	.327**	.392**	.404**	.360**
3. Vocabulary	.162	.395**		-.225*	.357**	.493**	.304**	.384**	.417**	.407**	.419**
4. Country	-.468**	.150	-.092		-.104	-.510**	-.238*	-.524**	.002	-.462**	-.437**
5. Spatial Span	-.021	.482**	.319**	.039		.328**	.190	.332**	.260*	.397**	.180
6. Numeration	.137	.448**	.490**	-.298**	.394**		.366**	.602**	.514**	.458**	.316**
7. Verbal Count	.079	.357**	.363**	-.071	.391**	.549**		.595**	.337**	.431**	.274**
8. Object Count	.161	.412**	.454**	-.251**	.443**	.682**	.551**		.417**	.571**	.397**
9. NS Arithmetic	-.134	.435**	.371**	.111	.474**	.404**	.435**	.486**		.282*	.209
10. SN-Quantity[a]	-.007	.518**	.451**	-.220*	.503**	.579**	.414**	.591**	.414**		.583**
11. SN-Control	.007	.395**	.447**	.075	.501**	.379**	.361**	.441**	.342**	.579**	

Note. Parent Edu = Parent Education; NS Arithmetic = Nonsymbolic arithmetic; SN-Quantity = speeded naming of quantities; SN-Control = speeded naming of letters (Canadian children) or colors (Turkish children).

[a]At pretest, the correlation for the Canadian children between SN-Quantities and SN-Letters was $r(46) = .728$, $p < .001$. The correlation for the Turkish children between SN-Quantities and SN-Colors was $r(61) = .597$, $p < .001$.

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

Relations Between Speeded Naming and Early Numeracy Measures

As in Study 1, we used multiple regression to assess whether speeded naming of quantities was uniquely related to the numeracy outcomes, after controlling for individual differences in visual-spatial attention (i.e., spatial span), linguistic skills (i.e., vocabulary), and demographic (i.e., age and group) factors. Because the control speeded naming task was different for the two groups at pre-test, we calculated the *z*-scores within group for each control naming task, and used those in the regressions. As shown in Table 8, block one included the control variables (parent's highest education, age, spatial span, vocabulary, and control speeded naming). Speeded naming of quantities was added in Block 2 to assess whether it added unique variance.

As shown in Table 8, the SN-Quantity score was a unique predictor of children's verbal counting[4], numeration, and object counting performance at pretest. These measures require knowledge of number words, and the latter two require knowledge of the mappings between number words and quantities. In contrast, speeded naming of quantities did not predict unique variance in nonsymbolic arithmetic. As a further test of the relation between speeded naming of quantities and numeracy outcomes, the same analyses were done with post-test data. Parents' education was excluded from these analyses because it never predicted unique variance at pre-test or in initial post-test analyses. As shown in Table 9, the results are the same for the post- as for the pre-test measures. Speeded naming of quantities accounted for significant unique variance in object counting, numeration, and verbal counting but not in nonsymbolic arithmetic.

4) Three students whose verbal counting scores were outliers (i.e., much higher than expected) were excluded from the analysis at pretest because they had very large residuals and thus influenced the results.

Table 8

Hierarchical Multiple Regression Analyses of Numeracy Outcomes at Pre-Test in Study 2

	Verbal Counting (N = 111)		Object Counting (N = 114)		Numeration (N = 114)		Nonsymbolic Arithmetic (N = 114)	
Variable	β	p	β	p	β	p	β	p
Model 1								
Parent Education	-.019	.846	.057	.515	.005	.954	-.110	.242
Age	.142	.180	.221	.019	.293	.002	.160	.112
Country[a]	-.100	.301	-.263	.002	-.330	< .001	.042	.645
Vocabulary	.270	.008	.192	.038	.131	.145	.312	.002
Spatial Span	.092	.379	.186	.038	.252	.004	.220	.023
SN-Control	.162	.127	.193	.037	.110	.223	.021	.831
R^2 Model	*.259*	*< .001*	*.421*	*< .001*	*.447*	*< .001*	*.326*	*< .001*
Model 2								
Parent Education	.026	.794	.094	.274	.038	.654	-.089	.347
Age	.053	.622	.141	.139	.223	.019	.116	.272
Country	.022	.836	-.163	.072	-.242	.007	.098	.327
Vocabulary	.230	.022	.145	.112	.089	.317	.286	.005
Spatial Span	.021	.843	.152	.084	.222	.011	.201	.039
SN-Control	.049	.656	.088	.370	.017	.860	-.038	.727
SN-Quantity	.334	.009	.290	.009	.255	.018	.162	.180
R^2 change	*.048*	*.009*	*.037*	*.009*	*.028*	*.018*	*.011*	*.180*
R^2 Model	*.306*		*.458*		*.476*		*.337*	

Note. Model 1 R^2: $F(6, 104) = 6.05$, $p < .001$; $Fs(7, 107) = 12.96, 14.23, 8.62$, $ps < .001$. Model 2 R^2: $F(7, 113) = 6.50$, $p < .001$; $Fs(7, 106) = 12.77, 13.74, 7.71$, $ps < .001$.

[a]Country coded 1 = Canada, 2 = Turkey.

Table 9

Hierarchical Multiple Regression Analyses of Post-Test Outcomes in Study 2 (N = 85)

	Verbal Counting		Object Counting		Numeration		Nonsymbolic Arithmetic	
Variable	β	p	β	p	β	p	β	p
Model 1								
Age	.108	.419	.180	.094	.257	.037	.270	.037
Country[a]	-.203	.088	-.475	< .001	-.221	.041	.026	.817
Vocabulary	.176	.166	.131	.194	.224	.053	.274	.025
Spatial Span	.018	.880	.162	.097	.092	.405	.018	.878
SN-Control	-.009	.943	.038	.716	-.019	.875	-.010	.934
R^2 Model	*.118*	*.073*	*.442*	*< .001*	*.277*	*< .001*	*.215*	*.002*
Model 2								
Age	.050	.706	.132	.213	.185	.114	.242	.064
Country	-.098	.427	-.389	< .001	-.092	.395	.077	.524
Vocabulary	.156	.208	.115	.243	.199	.069	.264	.030
Spatial Span	-.044	.715	.110	.254	.015	.888	-.013	.914
SN-Control	-.107	.427	-.042	.692	-.139	.243	-.057	.661
SN-Quantity	.334	.021	.275	.017	.409	.002	.159	.256
R^2 change	*.058*	*.021*	*.039*	*.017*	*.087*	*.002*	*.013*	*.256*
R^2 Model	*.176*		*.481*		*.364*		*.228*	

Note. Model 1 R^2: $Fs(7, 107) = 2.11$, $p = .073$; 12.49, 6.05, $ps < .001$; 4.26, $p = .002$. Model 2 R^2: $Fs(7, 106) = 2.77$, $p = .017$; 12.05, 7.45, $ps < .001$; 3.78, $p = .002$.

[a]Country coded 1 = Canada, 2 = Turkey.

Discussion

In this study, between 85% and 92% of the 3- and 4-year-old children were successful on the speeded naming tasks (depending on which version) and their performance was consistent across pages. Multiple regression analyses (controlling for age, gender, parents' education, country, and spatial span) indicated that speeded naming of quantities was a significant predictor of children's performance on object counting, verbal counting, and numeration, both at pre-test and after a six-week intervention. All of these measures involve children's knowledge of the number words, with the object counting and numeration measures requiring mapping between number words and quantities. In contrast, speeded naming of quantities did not predict nonsymbolic arithmetic. This measure involves memory and one-to-one matching processes, but does not require children to use number names (Jordan et al., 1992).

General Discussion

The goal of the present research was to determine whether a measure of children's efficiency on speeded naming of small quantities was a reliable and valid measure for 3- to 6-year-old children. We used a speeded naming task that is assumed to index the efficiency with which children access the identity of small exact quantities. In adults, the efficiency of access to small quantities via naming is referred to as subitizing (Landerl, 2013; Trick & Pylyshyn, 1994; van Oeffelen & Vos, 1984). Notably, we do not refer to the speeded naming of quantities measure as subitizing in the present study because, in the traditional subitizing tasks used with adults, the stimuli are shown only briefly. That methodology is difficult to implement for young children and is not suitable for a paper-and-pencil measure. We showed that the speeded naming of quantities task has excellent internal reliability (across two pages of items) for 3- to 6-year-old children and very good test-retest reliability for 3- and 4-year-olds (i.e., across a six-week interval). In support of the construct validity of the measure, it was a predictor of a composite early numeracy measure (i.e., KeyMath Numeration) for 3- to 6-year-old children (Studies 1 and 2), of nonsymbolic arithmetic for 5- and 6-year-olds (Study 1), and of verbal and object counting for 3- and 4-year-old children (Study 2).

In support of the domain-specific nature of speeded naming, in Study 1, speeded naming of letters predicted word reading whereas speeded naming of quantities predicted numeracy measures. A large literature links word reading ability to speeded naming of letter names (i.e., RAN or rapid automatized naming; Norton & Wolf, 2012). Speeded naming of letters is also correlated with mathematics, especially fluency tasks such as arithmetic (Koponen et al., 2017), when speeded quantity naming is not assessed. A similar pattern was shown in the present research—when speeded naming of quantities was not included in the regressions, speeded naming of letters was a significant predictor of early numeracy performance (Study 1). However, in Study 2, only speeded naming of quantities (not of letters or colours) predicted the numeracy outcomes in the multiple regressions, despite simple correlations between control speeded naming tasks and the outcomes. Thus, the present results suggest that the unique portion of the relation between quantity naming and numeracy measures is a domain-specific skill, whereas the shared portion reflects children's more general ability to quickly and accurately retrieve verbal labels for symbols (Willburger et al., 2008).

Developmentally, the SN-Quantity task was easier for older than for younger children. Speeded naming of quantities improved with age, as did the various numeracy measures. Longitudinal studies which measure both speeded naming of quantities and other numeracy measures across time are needed to better understand whether any causal links exist among these indices, or whether shared variance can be attributed to improvements in more general cognitive abilities (Gray & Reeve, 2016; Peng & Kievit, 2020; Soltész et al., 2010).

The present results are consistent with the results of Sowinski (2016) who found that the speeded naming of quantities predicted arithmetic fluency and calculation among adults, even after controlling for approximate numerosity comparisons (i.e., the AMS; Study 1) and symbolic number comparisons (Study 2). The current findings support the view that efficient access to small exact quantities may help children connect their knowledge of quantity to the symbolic number system. More specifically, efficient access to small quantities may facilitate the development of counting skills by supporting children's understanding of the cardinality principle (Cheung & Le Corre, 2018; Le Corre & Carey, 2007). Cardinality, that is, the understanding that the final counting word produced when enumerating a set of objects indicates the quantity of that set, is a critical precursor of number system knowledge more generally (Butterworth, 2005; Lyons & Ansari, 2015a; Merkley & Ansari, 2016).

For somewhat older children, a similar measure of speeded naming of the quantities 1, 2, and 3 predicted more advanced symbolic number knowledge, specifically number comparison (i.e., which is larger 4 or 7?; LeFevre et al., 2010). For 7- and 8-year-old children, symbolic number comparison was a unique predictor of children's arithmetic performance, as well as their calculation knowledge, backward counting, and number system knowledge, whereas it did not uniquely predict word reading (Sowinski et al., 2015). Vanbinst, Ansari, Ghesquière, and De Smedt (2016) have suggested that number comparison is a key numerical process for children's arithmetic development, equivalent to the relation between phonological awareness and reading (cf. Lyons & Ansari, 2015a; Lyons, Price, Vaessen, Blomert, & Ansari, 2014) and it is consistently correlated with arithmetic, even for adults (Schneider et al., 2017). Thus, it is important to understand how the exact magnitude system supports children's acquisition of number comparison skills and other core mathematical skills, such as arithmetic. The SN-Quantity task could be used in the present form, or in an adapted version, to collect data to address this issue among young children (cf. Hawes et al., 2019).

Limitations

Although the present results show that the SN-Quantity task is reliable and valid for 3- to 6-year-old children, modifications were needed to help the younger children successfully perform the task. Simpler versions, for example, providing a smaller set of items per page, would reduce the task demands further. Researchers have used less complex mapping tasks, for example, choosing between two quantities to match a spoken word or digit to evaluate the earliest levels of symbol-quantity mapping abilities in young children (Hurst et al., 2017; Jiménez Lira et al., 2017). The present results are valuable in showing that speeded naming of small exact quantities predicted these young children's object counting ability, in support of the view that the exact magnitude system is central to the development of cardinality knowledge (Le Corre et al., 2006; Le Corre & Carey, 2007; Odic et al., 2015). Nevertheless, further research using the speeded naming of quantities task is important. The reanalyzed data sets used in the current studies were not collected with the primary aim of addressing the role of speeded naming in early numeracy development.

Further research should be undertaken to explore the limits of speeded quantity naming as a predictor of mathematical skills. In Study 1, speeded naming of quantities was a predictor of nonsymbolic arithmetic. In Study 2, speeded naming of quantities did not uniquely predict nonsymbolic arithmetic (although the simple correlation was significant), instead, speeded quantity naming predicted unique variance in tasks which required symbolic number knowledge. Older children, as in Study 1, are more likely to use counting in nonsymbolic arithmetic tasks (Canobi & Bethune, 2008), compared to the younger, less-knowledgeable children, as in Study 2 (Jordan et al., 1992). Thus, the results supporting the general notion that the development of counting skills, including the cardinal principle, is closely linked to knowledge of small exact quantities.

Conclusions and Implications

In the present paper, we focused on a very simple index of the mapping between the earliest symbolic number codes (i.e., verbal number words) and nonsymbolic quantities. The results show that individual differences in the efficiency of naming small exact quantities predicts children's developing number skills from ages three to seven (Mejias et al., 2012; Noël & Rousselle, 2011). These findings are consistent with the model of developmental dyscalculia proposed by Noël and Rousselle (2011) in which they argued that the earliest deficit among children with dyscalculia involved the process of mapping exact quantities to symbolic representations. The speeded naming of quantity task appears to exactly fulfill the requirements for a measure of this mapping process and could help to identify children who lag behind their peers. The task, as originally designed, can be used with children from age five, and for most children from age four. Incorporating a version of the SN-Quantity task into studies of early numeracy development could help to enhance models of how children's quantitative knowledge and verbal mapping skills support their acquisition of the symbolic number system.

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Supplementary Materials

All the speeded naming tasks are provided in the supplementary materials, along with the instructions and practice pages (for access see Index of Supplementary Materials below)

Index of Supplementary Materials

LeFevre, J., Skwarchuk, S., Sowinski, C., & Cankaya, O. (2021). *Supplementary materials to "Linking quantities and symbols in early numeracy learning"* [Additional information]. OSF. https://osf.io/uz6s3/

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Appendix A

The primary focus of the research project for which the data for Study 2 were collected was a number game intervention that was intended to support children's verbal counting skills (Cankaya et al., 2014; Dunbar et al., 2017). As expected, verbal counting performance improved for children in the number game intervention conditions compared to those in colour (control) game conditions. However, none of the other early numeracy measures differentially improved across conditions. The speeded naming tasks were included in the larger study so that the reliability and validity of these measures could be evaluated in relation to other commonly used early numeracy measures. These speeded naming measures were not analyzed for the intervention component of the study.

Table A1 shows the total number of participants in each phase of the study, the number who attempted the speeded naming tasks (by country), and the number who had complete data (i.e., both pages completed with valid response times). Because the speeded naming tasks were not the focus of the intervention study, if time was short, then the experimenter could decide not to administer the speeded naming tasks. This situation only occurred among the Canadian children. The differences between the total number of children and the number who attempted the task are shown in the table. All of those differences for Canadian children occurred because they were not asked to do the task, whereas for Turkish children, the differences reflect children who did not continue after the instructions because they were unable to name the stimuli or did not understand the task requirements. For children who attempted the task, some children were only given one page to solve, and for other children, response times were not recorded. Finally, if children made more than 12 errors on a page their data for that page were not included. Thus, the total number of children who had valid item-per-second scores was less than the total who were tested. Moreover, more children were recruited at pre-test than were included in the intervention, which lasted for six weeks, and so the post-test numbers are smaller. Inclusion in the intervention was random.

Table A1

Availability of Participants and Data for Analyses of Speeded Naming (Number Per Group/Test) in Study 2

	Pre-test			Post-test		
Group	**Canadian**	**Turkish**	**Total**	**Canadian**	**Turkish**	**Total**
Total Participants	94	88	182	78	45	123
Quantities						
Administered	66	86	152	65	42	107
Completed	58	78	136	57	42	99
Valid Score	58	82	140	53	41	94
Letters/Colours[a]						
Administered	66	87	153	70	43	113
Completed	58	76	134	62	43	105
Valid Score	56	73	129	61	42	103

Note. Completed indicates that the children completed the task (i.e., provided answers and response times for both pages). Children who only completed a single page were included in the valid scores, however—so the number of valid scores could be higher than the number who completed both pages.

[a]At pre-test, Canadian children did letter naming and Turkish children did colour naming. Both groups did colour naming at post-test.

Corrected scores for each page were calculated as [24 − errors]/response times. Pages with more than 12 errors ($p < .05$) were discarded. If children had a valid score on both pages for a speeded naming measure, we selected the best score of the two, to ensure that factors which might lead to lower scores, such as fatigue and administration error, were minimized. These best performance scores were used in the analyses reported in the body of the paper.

As shown in Table A.1, of the children who were administered the measures, 92% and 88% (pre- and post-test, respectively) had valid speeded naming of quantity scores; 85% had valid speeded naming of letter naming scores (pre-test); and 84% and 91% had valid scores for colour naming, at pre-test and post-test, respectively. Thus, the majority of children had valid scores on these tasks. Correlations between age and speeded naming scores were: .509, .493, and .384 for quantities, letters, and colours, respectively, at pre-test; and .403 and .396 for quantities and colours at post-test, all *p*s < .001. Children's scores on the speeded naming of quantities task improved from pre- to post-test (.50 vs. .61 items-per-second), $t(83) = -6.57$, $p < .001$. Similarly, scores improved from pre- to post-test for speeded naming of colours (.47 vs. .54, items-per-second), $t(36) = -3.03$, $p = .004$. Correlations between pre- and post-test performance were .788 and .724 for quantities and colours, respectively, *p*s < .001. Thus, these measures were reliable, but also showed improvement with experience.

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