Journal of Cognition and Development

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/hjcd20

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To cite this article: Jaccoline E. van 't Noordende , Evelyn H. Kroesbergen , Paul P. M. Leseman & M (Chiel). J. M. Volman (2021) The Role of Non-symbolic and Symbolic Skills in the Development of Early Numerical Cognition from Preschool to Kindergarten Age, Journal of Cognition and Development, 22:1, 68-83, DOI: 10.1080/15248372.2020.1858835

To link to this article: https://doi.org/10.1080/15248372.2020.1858835

Published online: 22 Dec 2020.

JOURNAL OF COGNITION AND DEVELOPMENT
2021, VOL. 22, NO. 1, 68–83
https://doi.org/10.1080/15248372.2020.1858835

The Role of Non-symbolic and Symbolic Skills in the Development of Early Numerical Cognition from Preschool to Kindergarten Age

Jaccoline E. van 't Noordende[a,b], Evelyn H. Kroesbergen[b], Paul P. M. Leseman[a], and M (Chiel). J. M. Volman[a]

[a]Utrecht University, Netherlands; [b]Radboud University, Netherlands

ABSTRACT

The development of (early) numerical cognition builds on children's ability to understand and manipulate quantities and numbers. However, previous research did not find conclusive evidence on the role of symbolic and non-symbolic skills in the development of (early) numerical cognition. The aim of the current study was to clarify the relation between different types of non-symbolic quantity skills, symbolic numerical skills and early numerical cognition. A sample of 43 children was tested at the age of 3.5 years and at the age of 5 years. At 3.5 years, non-symbolic number line estimation, non-symbolic quantity comparison and symbolic enumerating skills were measured. At 5 years, early numerical cognition, defined as symbolic number line estimation and counting, were measured It was found that non-symbolic number line estimation at 3.5 years could predict both symbolic number line estimation and counting at 5 years. Enumerating at 3.5 years could only predict counting at 5 years. This suggests that both non-symbolic and symbolic skills play a role in the development of early numerical cognition, although enumerating skills do not transfer to all types of early numerical cognition. Furthermore, not all non-symbolic skills seem to play an important role in the development of early numerical cognition. The results suggest that non-symbolic quantity comparison does not contribute much to the development of early numerical cognition. Associations between non-symbolic quantities and space, operationalized here as non-symbolic number line estimation, seem central to the development of early math from preschool to kindergarten age.

The nature of children's ability to understand and manipulate numbers is central to the domain of numerical development. An important model in research on the development of (early) numerical cognition, has been the triple-code model of Dehaene (1992). The triple-code model assumes that numbers can be processed in an (1) analogue, (2) Arabic and (3) verbal format ("code"). The analogue code is also referred to as the non-symbolic code, and refers to the ability to manipulate non-symbolic quantities, like a set of objects. The Arabic and the verbal code are also referred to as symbolic skills, like the use of number words and Arabic digits, for example in reciting the counting row, when numbers are recited without connecting them to their underlying quantities (Dehaene & Cohen, 1995). Generally, young children in the preschool age are already able both to use symbolic number words and to discriminate non-symbolic quantities,

CONTACT Jaccoline E. van 't Noordende J.vantNoordende@pwo.ru.nl Department of Special Education, Cognitive and Motor Disabilities, Utrecht University, P.O. Box 9104, 6500, HE Nijmegen, The Netherlands

but they are not always able to connect these two aspects. For example, preschool-aged children can recite the counting sequence, but have difficulties understanding the link between the number words and the objects they are counting. Only from around 3.5 years of age, on average, they come to understand that the last number word in counting represents the total quantity of the objects they counted, i.e. the cardinality aspect of numbers (e.g., Wynn, 1990).

Although symbolic and non-symbolic skills are not yet integrated in young children, the integration of numerical symbols and non-symbolic quantities they represent is essential for numerical understanding and math learning (Brankaer, Ghesquière, & De Smedt, 2014; Friso-van den Bos, Kroesbergen, & van Luit, 2014; Jiménez Lira, Carver, Douglas, & LeFevre, 2017; Kolkman, Kroesbergen, & Leseman, 2013). However, there is not yet consensus on the relative contribution of (the type of) symbolic and non-symbolic skills to the development of (early) numerical cognition. Moreover, most research has focused on children at kindergarten or primary school age. The current study aims to further clarify the relation between non-symbolic skills, symbolic skills, and early numerical cognition. Importantly, we applied a longitudinal design with a first assessment *before children entered kindergarten* and a second assessment after children entered kindergarten. Understanding the contribution of symbolic and non-symbolic skills to early numerical cognition in the early stages is essential to fully understand the processes involved in the development of numerical cognition.

Traditionally, the mainline of research on the development of numerical skills has stressed the importance of non-symbolic skills as underlying ability of numerical cognition. It has been argued that children have to understand non-symbolic quantities before they can apply number words to quantities. In this view, non-symbolic quantities give meaning to the numbers words (e.g., Dehaene, 1992). This seems a plausible line of reasoning, because the ability to process non-symbolic quantities develops earlier than the ability to process symbolic quantities. The ability to process non-symbolic quantities is already present in infancy and can predict math ability at preschool age, even when controlling for general intelligence (Starr, Libertus, & Brannon, 2013). Some even argued that the ability to process (non-symbolic) quantities is innate (e.g., Feigenson, Dehaene, & Spelke, 2004), although it should be emphasized that others have questioned whether this innate ability is numerical in nature (e.g., Cantrell & Smith, 2013; Núñez, 2017).

Some studies have shown that non-symbolic quantity processing is not a unitary construct. Two types of non-symbolic quantity skills that are based on a common non-symbolic quantity processing factor have been identified: quantity comparison and non-symbolic number line estimation (Friso-van den Bos et al., 2014; Kolkman et al., 2013). Quantity comparison refers to the ability to differentiate between quantities and tell which quantity is larger or smaller. Non-symbolic number line estimation refers to associations between quantities and space, i.e., estimating discrete quantities on a number line.

Although both non-symbolic number line estimation and quantity comparison require understanding of quantities, they draw on different underlying mechanisms (Sasanguie & Reynvoet, 2013). The main difference probably is the involvement of space. Number line estimation requires the explicit translation of quantities to space (Siegler & Opfer, 2003). In a non-symbolic number line task, first introduced by Dehaene, Izard, Spelke, and Pica (2008), participants have to estimate the spatial position of discrete quantities (e.g., dot collections) on a line marked with a discrete quantity at the beginning and endpoint (e.g., 0 and 100 dots, respectively). This does not only require participants to understand the quantitative value of the presented items, but also requires them to evaluate the relation between dot collections and translate this to length of the number line. Non-symbolic quantity comparison does not require comprehension or estimation of the distance between quantities nor the explicit translation to space. For example, when comparing four dots with six dots, one only has to know that six dots is more than four dots. It is not necessary to understand *how much* more six dots is than four dots.

Taking into account the differences between quantity comparison and non-symbolic number line estimation, it seems possible that they relate differently to (early) numerical cognition. Although research on the predictive value of non-symbolic number line estimation and quantity comparison on (early) numerical cognition is still rather sparse, several studies point toward larger involvement of non-symbolic number line estimation than quantity comparison in the development of numerical cognition. Correlational analyses suggested that symbolic number line estimation in kindergarten children was more strongly related to non-symbolic number line estimation than to quantity comparison (Kolkman et al., 2013). Furthermore, non-symbolic number line estimation was related to performance on a standardized curriculum-based math test in kindergarten and primary school, whereas quantity comparison was not (Sasanguie, De Smedt, Defever, & Reynvoet, 2012; Sasanguie, Göbel, Moll, Smets, & Reynvoet, 2013; Sasanguie, Van den Bussche, & Reynvoet, 2012).

However, the influence of non-symbolic number line estimation on (early) numerical cognition has not yet been compared to the influence of pure symbolic skills. Most previous research compared non-symbolic number line estimation to symbolic number line estimation, which requires more complex skills to relate symbolic numbers to their underlying quantities (e.g., Sasanguie et al., 2012, 2013). However, it is possible that *pure* symbolic skills, like reciting the count row, play an important role in the development of early numerical cognition as well. For example, using numbers words could help children to relate numbers to their underlying quantities (Kolkman et al., 2013). Although Kolkman et al. (2013) examined the role of pure symbolic skills and non-symbolic skills in the development of early numerical cognition, they used factor scores for symbolic, non-symbolic, and early numerical cognition, which makes it impossible to draw conclusions about the relation between specific symbolic and non-symbolic skills and early numerical cognition. Nevertheless, correlational analyses showed that non-symbolic number line estimation was more strongly related to early numerical cognition than reciting the count row at age 4 years, whereas the strength of the association was strongest for symbolic number naming at age 5 years and for reciting the count row at age 6 years. However, in general, there were no large differences in the strength of the association of symbolic and non-symbolic skills to early numerical cognition (Kolkman et al., 2013).

The current study will further examine the early onset of symbolic and non-symbolic skills, starting before children enter kindergarten, and the predictive value of different types of non-symbolic skills (i.e. non-symbolic number line estimation and quantity comparison) and symbolic skills on early numerical cognition. Early numerical cognition will be operationalized as symbolic number line estimation and counting. Both symbolic number line estimation and counting have been identified in previous research as important predictors of math performance (Kim & Opfer, 2017; Kolkman et al., 2013; Krajewski & Schneider, 2009; Le Corre & Carey, 2007; Lipton & Spelke, 2005; Schneider et al., 2018). By including both symbolic number line estimation and counting as early numerical cognition, it will be possible to analyze if non-symbolic and symbolic skills have a specific effect on different types of early numerical cognition. In contrast to counting, symbolic number line estimation involves the distance between numbers and mapping numbers to space (line length), which might require different non-symbolic and symbolic skills.

To minimize the possible effect of domain-general cognitive skills on the relation between symbolic skills, non-symbolic skills, and early numerical cognition, that has been demonstrated by previous research (Kroesbergen, Van 't Noordende, & Kolkman, 2014; Soltész, Szűcs, & Szűcs, 2010), we will use working memory as a control variable in the analyses.

Methods

Procedure

The current study was part of a larger longitudinal study on quantity-space mapping and early numerical cognition.[1] The study was approved by the local university's ethical research committee. The participants signed up for the study via letters sent to the home addresses of children in the eligible age range in the local area and via internet forums on parenting. The study consisted of two cohorts, of which only one cohort was used in the current study, because of age eligibility. For this cohort, children with no indications of physical or mental health problems and born on-term (≥ 37 weeks of gestation) were selected based on order of application. Parents of all children provided written informed consent. The current study will report on two measurement moments: at age 3.5 years and age 5 years.

The current study will focus on non-symbolic and symbolic skills, early numerical cognition, and working memory, but a larger test battery, including for example also exploration behavior, was administered for the purpose of the larger project which the current study was part of. Testing was done by trained master's students in the university's lab and followed a fixed protocol. Parents were present during the entire session, but were instructed not to give any help to the child to complete the tests.

Participants

Fifty-two children participated at age 3;6 years. One child was excluded from the analyses because of noncompliance during testing. Eight children did not participate in the follow-up at age 5 years, mainly because of parents being too busy to come to the lab.

The resulting sample of 43 children consisted of 11 (25.6%) boys and 32 girls (74.4%). Mean age at the first measurement moment was 3;7 years (SD = 0.86 months) and mean age at follow-up was 4;11 years (SD = 0.55 months). Most of the parents completed higher vocational training or university: 39 (90.7%) of the parents who filled in the background questionnaire and 40 (95.2%) of their partners (one parent did not have a partner). The majority of the sample, 35 children (81.4%), came from Dutch families. Eight children (18.6%) had a combined ethnic background of Dutch and another nationality. Fourteen children (32.6%) went to a play group or preschool at the first measurement moment. The mean frequency of play group/preschool attendance was 2.64 half-days (SD = 1.34) per week. All children attended kindergarten full-time at follow-up.

[1]A first draft of this article was published as part of the first author's doctoral thesis:
Van 't Noordende, J. E. (2018). *Building Blocks of Numerical Cognition: The Development of Quantity-Space Mapping*. Doctoral thesis, Utrecht University, Utrecht. Available at: https://dspace.library.uu.nl/handle/1874/364782.

Instruments

Measurement time 1

At 3.5 years, symbolic skills, non-symbolic skills, and working memory were measured.

Symbolic numerical skills. A block-enumerating task was used to measure symbolic numerical skills. A row of five blocks was presented to the child. The child had to numerate these blocks one by one. Based on the child's performance, blocks were added or removed until the highest number of blocks the child could correctly enumerate was found. There was a maximum of 20 blocks, resulting in a score range from 0 to 20.

Non-symbolic quantity comparison. An adapted version of the quantity comparison task of Friso-van den Bos et al. (2014) was used to measure quantity comparison skills. Two clouds of dots were presented simultaneously to the child. The child had to point out which cloud had the largest number of dots. To ensure that the task measured non-symbolic quantity comparison and not counting skills, the experimenter stimulated the child to estimate the quantities and not count the number of dots. The number of dots ranged from 1 to 9. Dot size did not vary in half of the trials and the size of the presentation area did not vary in the other half of the trials. The outcome measure was the amount of correctly answered items, with a maximum of 26.

Non-symbolic number line estimation. An adjusted version of the non-symbolic number line task of Kolkman et al. (2013) was used to measure non-symbolic number line estimation. A line with zero dots at the beginning point and 100 dots at the endpoint was presented on a computer screen. The computer screen was run at a resolution of 1280 by 1024 pixels and the length of the line was 1000 pixels. First, the experimenter demonstrated the position of "nothing" (0 dots), "a little" (25 dots), "somewhat more" (75 dots) and "a lot" (100 dots) on the line. Next, the children practiced in positioning quantities on the line, to make sure that they understood the concept of the number line. After practice, the child had to place 14 dot quantities on the correct spatial position on the line. The dots were presented inside a box below the number line and were equal in size throughout the entire task. The quantities were semi-randomly selected, to make sure they were equally distributed over the number line range. This resulted in the following items: 6, 14, 21, 27, 33, 39, 47, 52, 59, 71, 76, 84, 90, 95. These items were presented in random order. The percentage absolute estimation error (PAE) was used as the outcome measure, calculated as follows: (response – requested quantity)/range number line * 100.

Working memory. Working memory was included as a control variable. To obtain a general measure of working memory, a composite score of visuo-spatial and verbal memory was used as an index of working memory, using the mean of a visuo-spatial memory task and a verbal memory task.

Visuo-spatial memory. The Dot Matrix from the Automated Working Memory Assessment (AWMA; Alloway, 2007) was used to measure visuo-spatial memory. A dot was presented in a 9 × 9 matrix. The child had to remember the position of the dot and point this out after the dot had disappeared. The amount of dots increased based on the performance of the child. The final score was the number of correctly answered items.

Word recall. The Word Recall from the AWMA (Alloway, 2007) was used to measure verbal memory. The child had to repeat a word presented verbally by the computer. The amount of words increased based on the performance of the child. The final score was the number of correctly answered items.

Follow-up

At age 5 years, early numerical cognition was measured. Early numerical cognition was operationalized as counting skills and symbolic number line estimation.

Counting skills. The counting subscales (cf. Kroesbergen, Van Luit, Van Lieshout, Van Loosbroek, & Van de Rijt, 2009) of the Early Numeracy Test-Revised (ENT-R; Van Luit & Van de Rijt, 2008) were used to measure counting skills. These subscales measure the use of number words (e.g., counting up to 20), structured counting (e.g., counting objects while pointing to the objects), resultative counting (e.g., counting objects without pointing) and general understanding of number words (using numbers in everyday situations). Each subscale consists of five items. The final score was the total amount of correctly answered items.

Symbolic number line estimation. A symbolic number line task ranging from 0 to 10 was used. The child had to place the numbers 1–9 on a line with 0 at the beginning point and 10 at the endpoint of the line. The numbers were presented in random order. The percentage absolute estimation error was used as the outcome measure, calculated as follows: (response – requested number)/range number line * 100.

Statistical analyses

Bayesian statistics were used to analyze the data. There are several important advantages of Bayesian statistics as compared to more traditional frequentist statistics. First, prior knowledge about the variables under investigation can be incorporated into Bayesian statistics. Even if there is not enough information from previous studies to define prior distributions, it is important to incorporate this (lack of) information into the analyses. Second, probabilities of both the null and alternative hypothesis can be derived from Bayesian statistics, whereas frequentist statistics only provide the probability of observing the same or more extreme data when the null hypothesis is true. In other words, Bayesian statistics can tell how likely the null or alternative hypothesis is, whereas frequentist statistics can only tell something about the amount of evidence against the null hypothesis. Third, large samples are not necessarily needed in Bayesian statistics, whereas most frequentist statistics are based on large sample sizes (Van de Schoot et al., 2014).

The analyses were performed in JASP (JASP Team, 2020). Because there is still a lot unknown about the relation between the variables in this study, uninformative priors were used in the analyses. First, Bayesian correlations were used to analyze bidirectional relations between non-symbolic skills, symbolic skills, working memory and early numerical cognition. For each pair of variables, Pearson's r was computed, as well as the 95% credible interval for the posterior coefficients. Furthermore, the evidence for the null and alternative hypothesis was analyzed using the Bayes Factor. The null hypothesis stated that there is no relation between the variables and the alternative hypothesis stated that there is a relation between the variables.

The following classification for the Bayes Factor was used, although it should be emphasized that the Bayes Factor represents a continuous scale and such a classification should therefore "not be misused as an absolute rule for all-or-nothing conclusions" (Van Doorn et al., 2019, p. 17):

Bayes Factor between $\frac{1}{30}$ and $\frac{1}{10}$: strong evidence for the null hypothesis
Bayes Factor between $\frac{1}{10}$ and $\frac{1}{3}$: moderate evidence for the null hypothesis
Bayes Factor between $\frac{1}{3}$ and 1: weak or inconclusive evidence for the null hypothesis
Bayes Factor between 1 and 3: weak or inconclusive evidence for the alternative hypothesis
Bayes Factor between 3 and 10: moderate evidence for the alternative hypothesis
Bayes Factor larger than 10: strong evidence for the alternative hypothesis

Second, Bayesian linear regression analyses were used to analyze the relative contribution of non-symbolic and symbolic skills to the development of early numerical cognition. In the initial models, non-symbolic number line, quantity comparison and enumerating at age 3.5 years were included as predictors of early numerical cognition at age 5 years, while controlling for working memory at age 3.5 years. Separate regression analyses were conducted for the two types of early numerical cognition (symbolic number line and counting skills). Data of one child were excluded from the regression analyses, due to a missing score on enumerating.

Model fit was evaluated using the criteria for the Bayes Factor as described above. The Bayesian Factor was based on comparison of the model to the null model (model including no predictors). The model with the strongest evidence for the alternative hypothesis was analyzed as the final model.

The mean and standard deviation were computed for posterior regression coefficients. The 95% credible interval was also computed for the posterior coefficients. The evidence for the inclusion of the predictors in the regression models was evaluated using the criteria for the Bayes Factor described above.

Results

The descriptive statistics of all variables are shown in Table 1. Table 2 shows the results of the Bayesian correlation analyses.

Table 1. Descriptive statistics of non-symbolic number line estimation, quantity comparison, enumerating, working memory, symbolic number line estimation and counting.

	M	SD
Time 1		
Non-symbolic number line estimation (PAE)	32.11	9.23
Quantity comparison	19.67	4.67
Enumerating	9.21	5.64
Working memory	11.06	2.74
Time 2		
Symbolic number line (PAE)	17.17	5.95
Counting	9.16	3.27
Working memory	16.58	2.68

Note. PAE = percentage absolute estimation error.
N = 43, except for enumerating N = 42.

Table 2. Posterior summaries of the correlation between non-symbolic number line estimation, quantity comparison, enumerating, working memory, symbolic number line estimation and counting.

		Time 1				Time 2
		Non-symbolic number line (PAE)	Quantity comparison	Enumerating	Working memory	Symbolic number line (PAE)
Time 1						
Quantity comparison	Pearson's *r*	−0.31	–			
	95% Credible Interval	−0.55; −0.01	–			
	Bayes Factor	1.44*	–			
Enumerating	Pearson's *r*	−0.10	0.23	–		
	95% Credible Interval	−0.38; 0.20	−0.08; 0.49	–		
	Bayes Factor	0.23°°	0.55°	–		
Working memory	Pearson's *r*	−0.40	0.25	0.23	–	
	95% Credible Interval	−0.61; −0.11	−0.06; 0.50	−0.08; 0.49	–	
	Bayes Factor	6.02**	0.66°	0.54°	–	
Time 2						
Symbolic number line (PAE)	Pearson's *r*	0.42	−0.13	0.03	−0.30	–
	95% Credible Interval	0.13; 0.63	−0.40; 0.17	−0.26; 0.32	−0.54; 0.00	–
	Bayes Factor	9.25**	0.26°°	0.20°°	1.27*	–
Counting	Pearson's *r*	−0.33	−0.03	0.44	0.16	−0.25
	95% Credible Interval	−0.56; −0.02	−0.32; 0.27	0.14; 0.64	−0.14; 0.43	−0.50; 0.05
	Bayes Factor	1.70*	0.19°°	10.60***	0.32°°	0.70°

Note. PAE = percentage absolute estimation error.
° Weak/inconclusive evidence H_0; °° Moderate evidence H_0; °°° Strong evidence H_0.
* Weak/inconclusive evidence H_a; ** Moderate evidence H_a; *** Strong evidence H_a.
N = 43, except for correlations concerning enumerating N = 42.

At time 1, at age 3.5 years, there was weak evidence for a relation between the two non-symbolic quantity skills (non-symbolic number line estimation and quantity comparison). Lower percentages of absolute error on the non-symbolic number line were associated with higher scores on quantity comparison, although the evidence was not conclusive.

No conclusive evidence for the association between the non-symbolic skills and symbolic skills as represented by enumerating was found either. There was moderate evidence for the absence of a relation between non-symbolic number line estimation and enumerating and weak evidence for the absence of a relation between quantity comparison and enumerating.

Working memory only seemed related to non-symbolic number line estimation at time 1. Moderate evidence for a negative relation between these two variables was found. Higher scores on working memory were associated with lower percentages of error on the non-symbolic number line. Weak evidence was found for the lack of an association between quantity comparison and working memory and enumerating and working memory.

At time 2, at age 5 years, the two types of early numerical cognition (symbolic number line and counting) seemed not related to each other. There was weak evidence for the null hypothesis stating there is no relation between these two variables.

Over time, only non-symbolic number line estimation at time 1 correlated with both early numerical skills at time 2, although the evidence for a relation between non-symbolic number line estimation and counting was weak. There was moderate evidence for a relation between non-symbolic number line estimation at time 1 and symbolic number line estimation at time 2. Higher performance on the non-symbolic number line was associated with higher performance on the symbolic number line.

Table 3. Posterior summaries of the regression coefficients of non-symbolic number line estimation, quantity comparison, enumerating, and working memory on symbolic number line estimation and counting (initial models).

		Symbolic number line (PAE)[a]	Counting[b]
Intercept	Mean (SD)	17.24 (0.87)	9.10 (0.45)
	95% Credible Interval	15.49; 19.01	8.18; 10.01
	Bayes Factor Inclusion	1.00	1.00
Non-symbolic number line (PAE)	Mean (SD)	0.16 (0.12)	−0.07 (0.06)
	95% Credible Interval	0.00; 0.36	−0.18; 0.00
	Bayes Factor Inclusion	2.97*	2.62*
Quantity comparison	Mean (SD)	0.00 (0.10)	−0.07 (0.10)
	95% Credible Interval	−0.26; 0.25	−0.28; 0.05
	Bayes Factor Inclusion	0.46°	1.36*
Enumerating	Mean (SD)	0.03 (0.09)	0.19 (0.10)
	95% Credible Interval	−0.13; 0.28	0.00; 0.34
	Bayes Factor Inclusion	0.49°	9.55**
Working memory	Mean (SD)	−0.14 (0.27)	−0.01 (0.11)
	95% Credible Interval	−0.82; 0.17	−0.30; 0.24
	Bayes Factor Inclusion	0.71°	0.81°

Note. PAE = percentage absolute estimation error.
[a]Bayes Factor = 0.87, R^2 =.21.
[b]Bayes Factor = 6.25, R^2 =.31.
° Weak/inconclusive evidence H_0; °° Moderate evidence H_0; °°° Strong evidence H_0.
* Weak/inconclusive evidence H_a; ** Moderate evidence H_a; *** Strong evidence H_a.
N = 42.

The other non-symbolic skill, quantity comparison, did not seem to be related to either of the early numerical skills at time 2. There was moderate evidence for the lack of a relation between quantity comparison at time 1 and symbolic number line estimation and counting at time 2.

Enumerating at time 1 was related to counting at time 2. The evidence for a relation between these two variables was strong. Higher scores on enumerating were associated with higher scores on counting. There did not seem to be a relation between enumerating at time 1 and symbolic number line estimation at time 2. There was moderate evidence for the null hypothesis regarding these variables.

Working memory at time 1 was only marginally related to symbolic number line estimation at time 2. Higher scores working memory scores at time 1 were related to lower percentages of absolute estimation error on the symbolic number line at time 2, although the evidence was weak.

After inspection of the results of the Bayesian correlation analyses, Bayesian regression analyses were conducted. The results of the initial regression models are shown in Table 3. The initial model for symbolic number line estimation did not outperform the null model (Bayes Factor = 0.87). Strongest evidence for the alternative hypothesis was found for the model only including non-symbolic number line estimation as a predictor of symbolic number line estimation (Bayes Factor = 7.55).

Analysis of the initial model for counting showed moderate evidence for the alternative hypothesis (Bayes Factor = 6.25). Strongest evidence was found for the model including non-symbolic number line estimation, quantity comparison and enumerating as predictors of counting (Bayes Factor = 15.40). Table 4 shows the posterior summaries of the final models.

Moderate evidence for inclusion of non-symbolic number line estimation was found in both final models. As expected, lower PAE (i.e. higher accuracy) on non-symbolic number line estimation at time 1 predicted lower PAE on the symbolic number line and higher counting scores at time 2.

Table 4. Posterior summaries of the regression coefficients of non-symbolic number line estimation on symbolic number line estimation and non-symbolic number line estimation, quantity comparison and enumerating on counting (final models).

		Symbolic number line (PAE)[a]	Counting[b]
Intercept	Mean (SD)	17.24 (0.86)	9.10 (0.45)
	95% Credible Interval	15.56; 19.04	8.18; 9.99
	Bayes Factor Inclusion	1.00	1.00
Non-symbolic number line (PAE)	Mean (SD)	0.21 (0.11)	−0.08 (0.06)
	95% Credible Interval	0.00; 0.38	−0.18; 0.00
	Bayes Factor Inclusion	7.55**	3.51**
Quantity comparison	Mean (SD)	-	−0.08 (0.10)
	95% Credible Interval	-	−0.29; 0.05
	Bayes Factor Inclusion	-	1.76*
Enumerating	Mean (SD)	-	0.20 (0.09)
	95% Credible Interval	-	0.00; 0.34
	Bayes Factor Inclusion	-	13.41***

Note. PAE = percentage absolute estimation error.
[a]Bayes Factor = 7.55, R^2 =.18.
[b]Bayes Factor = 15.40, R^2 =.31.
° Weak/inconclusive evidence H_0; °° Moderate evidence H_0; °°° Strong evidence H_0.
* Weak/inconclusive evidence H_a; ** Moderate evidence H_a; *** Strong evidence H_a.
N = 42.

The other non-symbolic skill, quantity comparison, did not predict symbolic number line estimation. The model with the strongest evidence for the alternative hypothesis did not include quantity comparison. In the final model for counting, only weak evidence was found for the inclusion of quantity comparison. Surprisingly, the sign of the posterior regression coefficient of quantity comparison on counting was negative in the final model. This would mean that higher scores on quantity comparison would lead to lower scores on counting, which does not seem likely. Furthermore, there was moderate evidence for a lack of a relation between quantity comparison and counting in the correlation analysis (see Table 2). It seems that the inclusion into the regression model with multiple predictors raised the predictive ability of quantity comparison on counting, a so-called "suppressor effect" (Ludlow & Klein, 2014). It is known that suppressor effects can also change the sign of a predictor (Darlington, 1968), which could be an explanation for the negative regression coefficient. However, no clear explanations for the suppressor effect could be found in this case. The correlation analyses did not show conclusive evidence for a relation between quantity comparison and the other two predictors in the model (see Table 2). Further exploration of the Bayesian regression model showed that only including both non-symbolic number line estimation and enumerating besides quantity comparison, raised the effect of quantity comparison on counting. Including either non-symbolic number line estimation or enumerating resulted in a Bayes Factor for inclusion of quantity comparison of 0.52 and 0.76, respectively, compared to a Bayes Factor of 0.30 when only quantity comparison was included as a predictor of counting. It seems likely that the suppressor effect in this case was merely a statistical artifact (Ludlow & Klein, 2014). Furthermore, excluding quantity comparison from the model would have a marginal effect on the evidence for the total model, the Bayes Factor would decrease from 15.40 to 14.65. This suggests that quantity comparison in itself does not add much to the prediction of counting. It seems that only specific non-symbolic skills, as measured by non-symbolic number line estimation, play a role in the development of early numerical cognition.

Symbolic numerical skills at time 1, as represented by enumerating, also predicted early numerical cognition at time 2. There was strong evidence for inclusion of this predictor in the model for counting. Higher scores on enumerating at time 1 predicted higher scores on counting at time 2. However, enumerating did not predict symbolic number line estimation. The model with the strongest evidence for the alternative hypothesis did not include enumerating. This suggests that symbolic skills are only involved in the development of specific types of early numerical cognition.

Working memory was not included in either of the final models with the strongest evidence for the alternative hypothesis, suggesting that it does not act as a control variable for the effect of non-symbolic and symbolic skills on early numerical cognition.

Discussion

The current study investigated the role of non-symbolic number line estimation, non-symbolic quantity comparison, and symbolic enumerating in the development of early numerical cognition as represented by symbolic number line estimation and counting skills. Previous research did not find conclusive evidence on the role of non-symbolic and symbolic skills in the development of early numerical cognition. As a consequence, there is not yet consensus about the relative contribution of non-symbolic and symbolic skills to early numerical cognition. In the current study, it was found that early numerical cognition could be predicted by both non-symbolic and symbolic skills, although evidence seems to point toward a more central role for non-symbolic number line estimation in the development of early numerical cognition.

Previously, Kolkman et al. (2013) concluded that pure symbolic skills were central to the development of early numerical cognition. They proposed that symbolic skills will help children to relate number words to exact quantities. The current study showed strong evidence that children's symbolic enumerating at age 3.5 years could indeed predict their counting skills at age 5 years. However, the current study did not find evidence that enumerating at age 3.5 years was associated with symbolic number line estimation at age 5 years. The predictive ability of enumerating on symbolic number line estimation was low, thus enumerating was excluded from the final regression model. This leads to the conclusion that not all types of early numerical cognition are based on early symbolic skills; enumerating skills only influence *specific* types of early numerical cognition (i.e., counting).

In contrast, non-symbolic number line estimation at age 3.5 years could predict both counting and symbolic number line estimation at age 5 years. Pre-kindergarten children who performed better at the non-symbolic number line task also performed better on both counting and symbolic number line estimation at kindergarten age. This suggests that early non-symbolic skills play a more central role in the development of early numerical cognition than early symbolic skills, in line with previous research emphasizing the role of non-symbolic skills in the development of math ability (e.g., Dehaene, 1992; Starr et al., 2013).

Nevertheless, the results do not give a conclusive answer to the question if non-symbolic or symbolic skills are most important in the development of early numerical cognition. Although non-symbolic number line estimation could predict both early numerical skills, in contrast to symbolic enumerating, enumerating seems to be the strongest predictor of counting. This suggests that the role of non-symbolic and symbolic skills could vary between different early numerical skills. This stresses the importance of differentiating between various skills when investigating the development of early numerical cognition, instead of using early numerical cognition as a unidimensional construct.

The current study also showed that it is important to differentiate between various non-symbolic skills, as non-symbolic number line estimation seems to play a more important role in the development of early numerical cognition than quantity comparison. Although no conclusive evidence for a null effect of quantity comparison on early numerical cognition was found, the results suggest that quantity comparison does not contribute much to the development of early numerical cognition. Quantity comparison was not included in the final regression model on symbolic number line estimation (the model with the strongest evidence for the alternative hypothesis) due to its low predictive ability. In the final model for counting, weak evidence was found for the inclusion of quantity comparison. However, as was explained in the results section, this was probably caused by a so-called suppressor effect. This means that there was no evidence for a relation between quantity comparison and counting, but the inclusion into the regression model with multiple predictors raised the predictive ability of quantity comparison on counting (Ludlow & Klein, 2014). No clear explanations could be found for this effect to occur. It seems likely that the suppressor effect in this case was merely a statistical artifact (Ludlow & Klein, 2014) and quantity comparison does not play an important role in the development of counting.

Although the evidence was not conclusive and replication of these results within a larger sample is needed, this is an important first indication that only specific types of non-symbolic skills play an important role in the development of early numerical cognition. Quantity comparison and non-symbolic number line estimation both involve the ability to understand the relation between non-symbolic quantities in terms of small/large, less/more, etc., non-symbolic number line estimation can be distinguished from quantity comparison by its involvement of space, as was also explained in the introduction paragraph. In quantity comparison, non-symbolic quantities are compared without explicit translation to space. Therefore, the finding that only non-symbolic number line estimation was related to early numerical cognition suggests that not non-symbolic skills in general, but the association between quantity and space is essential in the development of early numerical cognition.

Interestingly, non-symbolic number line estimation also transfers to non-spatial numerical skills, i.e. counting, although the evidence was only moderate. This extends previous research that found that non-symbolic number line estimation was related to general math tests (Sasanguie et al., 2012, 2013, 2012). The association between quantity and space in non-symbolic number line estimation probably originates from a general magnitude system, which refers to a nonspecific biological predisposition for processing of all types of quantity (like discrete and continuous quantity), and facilitates the development of children's general understanding of number (e.g., Cantrell & Smith, 2013; Lourenco & Longo, 2010). The processing of different types of quantities through one general system causes high associations between these types of quantities, like mapping of discrete (dot collections) and continuous (number line) quantity in non-symbolic number line estimation. This is further enhanced through experience, because there is a strong relation between numerical quantity and spatial quantity in real life. For example, a larger number of blocks has a larger total surface area or contour length, if the blocks are of the same size. This makes it difficult for young children to dissociate number from space (e.g., Clearfield & Mix, 2001). Therefore, the dot collections in the current number line tasks were probably processed as continuous quantities based on total presentation area (larger dot collections had a larger total presentation area) instead of discrete numerical entities. This makes it likely that non-symbolic number line estimation in the current study does not represent non-symbolic *numerical* processing, but instead processing of different types of quantities (i.e., dot collections and the number line).

However, a general association between quantity and space is not sufficient for correct positioning of quantities on a number line. Previous research has shown that children use various ordering strategies on a non-symbolic number line estimation task (Kim & Opfer, 2018; Van 't Noordende et al., 2018). A crucial aspect of number line estimation strategies is understanding the order of quantities and the distance between quantities. The development of these strategies probably relies on both ordinality and cardinality aspects (Van 't Noordende et al., 2018). This shows that further refinement of the general magnitude system is necessary to develop early numerical cognition, which is probably enhanced through experience with both quantities and numbers. Eventually, the association between quantities and space in real life probably helps children to grasp the concept of number, as for example, changes in non-numerical cues will facilitate understanding of changes in discrete number (e.g., Cantrell & Smith, 2013; McCrink & Opfer, 2014).

It is also possible that the influence of associations between quantity and space on (early) numerical cognition changes over time. A meta-analysis of 19 studies showed that the influence of non-symbolic skills on numerical cognition is strongest before the age of 6 years (Fazio, Bailey, Thompson, & Siegler, 2014). Furthermore, the relation between non-symbolic and pure symbolic skills becomes stronger over time (Friso-van den Bos et al., 2014; Kolkman et al., 2013). After integration of non-symbolic and pure symbolic skills has taken place, they probably do not contribute separately to numerical cognition any more and more complex skills will become more important. These more complex skills probably have a larger influence on numerical cognition than non-symbolic number line estimation in kindergarten and the first years of primary school (cf. Sasanguie et al., 2012, 2013). Future research is recommended to investigate the development of numerical skills from the early onset before children enter kindergarten, until primary school, to further clarify the relation between non-symbolic and symbolic skills and early numerical cognition and later math performance throughout development.

When interpreting the results of the current study, it should be taken into account that it cannot be excluded that children counted instead of estimated the quantities in the quantity comparison task, as each item was shown on screen until the child's response was recorded. However, it does not seem likely that children's performance on the quantity comparison task did heavily rely on counting, as the researcher did encourage the children to estimate and not count and weak to moderate evidence was found for the lack of a relation between quantity comparison and both enumerating and counting.

It should also be noted that working memory was included in the initial Bayesian regression models as a control variable, but was excluded from the final regression models, due to its low predictive ability. Nevertheless, Bayesian correlation analyses showed that there was moderate evidence for a relation between working memory and non-symbolic number line estimation and weak evidence for a relation between working memory and symbolic number line estimation. A more in depth investigation of the role of working memory in the development of early numerical cognition is therefore recommended.

In the current study, symbolic skills were only operationalized as enumerating skills. It was not possible to measure other symbolic skills, like naming symbolic digits, because these tasks are too difficult for 3.5-year-olds. However, it is possible that there is a differential effect of different symbolic skills on (early) math skills in older children (cf. Kolkman et al., 2013). Therefore, future research should investigate the role of different symbolic skills as well.

It is also important to note that most participants had a higher social economic status background, which may limit the external validity of the study. Furthermore, the sample was relatively small, which may have reduced the power of the analyses. Nevertheless, the current study gives important insights in the relations between non-symbolic and symbolic skills and early numerical cognition, by comparing the role of different types of non-symbolic skills to the role of pure symbolic skills in the development of early numerical cognition. The current study showed that both non-symbolic and symbolic skills are related to the development of early numerical cognition. However, symbolic numerical skills could not predict all types of early numerical cognition. Furthermore, quantity comparison does not seem to play an important role in the development of early numerical cognition. In the current study, non-symbolic number line estimation was found to be the only variable that could predict both types of early numerical cognition at age 5 years. This stresses the importance to take into account associations between quantities and space in the development of early numerical cognition.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by the Nederlandse Organisatie voor Wetenschappelijk Onderzoek [404-10-506].

ORCID

Jaccoline E. van ‘t Noordende http://orcid.org/0000-0002-1899-2189
Evelyn H. Kroesbergen http://orcid.org/0000-0001-9856-096X
Paul P. M. Leseman http://orcid.org/0000-0003-1286-0510
M (Chiel). J. M. Volman http://orcid.org/0000-0002-2442-9464

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