





Exploring Cognitive Predictors: Examining Varied Impact on Early Number Skills in a Longitudinal Study

Anna M. C. Karlsson¹ , Kenny Skagerlund^{1,2,3} , Mikael Skagenholt^{1,2} , Ulf Träff¹ 

[1] Department of Behavioural Sciences and Learning, Linköping University, Linköping, Sweden. [2] JEDILab, Division of Economics, Department of Management and Engineering, Linköping University, Linköping, Sweden. [3] Center for Social and Affective Neuroscience, Department of Clinical and Experimental Medicine, Linköping University, Linköping, Sweden.

Journal of Numerical Cognition, 2026, Vol. 12, Article e15049, <https://doi.org/10.5964/jnc.15049>

Received: 2024-07-05 • Accepted: 2026-02-11 • Published (VoR): 2026-03-19

Handling Editor: Victoria Simms, Loughborough University, Loughborough, United Kingdom

Corresponding Author: Anna M. C. Karlsson, Department of Behavioural Sciences and Learning, Linköping University, Campus Valla, SE-581 83 Linköping, Sweden. E-mail: anna.m.c.karlsson@liu.se

Supplementary Materials: Data, Materials [see [Index of Supplementary Materials](#)]



Abstract

This longitudinal study investigates the role of domain-general cognitive abilities in predicting domain-specific numerical abilities across early school years. Using von Aster and Shalev's four-step developmental model of numerical cognition (2007) and Ackerman's general theory of skill acquisition (1988), we examined how cognitive abilities (e.g., phonological processing, verbal working memory) contribute to children's counting knowledge, digit magnitude comparison, and number line estimation from kindergarten through second grade. The sample comprised 296 children (50.3% girls), who began participation at approximately six years ($M_{age} = 6.7$ years). Findings highlight the influence of domain-general cognitive functions throughout early numerical development. Specifically, phonological processes and processing speed significantly predict prior to formal education, while verbal working memory and nonverbal logical reasoning become more important after starting formal education. While the importance of certain domain-general abilities increases over time, others decline. Our results align with both von Aster and Shalev's (2007) model (positing that cognitive demands increase when learning new, more complex numerical abilities) and with Ackerman's (1988) theory (suggesting that reliance on cognitive abilities decreases as skills become more automated). Together, these frameworks complement each other, offering a comprehensive understanding of how cognitive abilities support numerical development. Our study highlights the important role of early cognitive abilities in forming the foundation for



successively more complex numerical skills. While each framework provides valuable insights, integrating them may better capture the complexities of early numerical development. These findings emphasize the varying roles of domain-general cognitive abilities and the nuanced trajectories depicted by these theoretical models.

Keywords

cognitive abilities, longitudinal study, mathematical development, number skills, domain-generality, domain-specificity

Number skills are foundational in mathematical development (Núñez, 2017). More specifically, well-developed basic number skills are vital for the acquisition of arithmetic skills, and arithmetic skills are in turn important for future mathematical learning (Qi et al., 2023). For example, research suggests numerical proficiency (i.e., comprehension of numerical sequences, counting principles) is associated with mathematical achievement in later childhood and adulthood (Duncan et al., 2007; Geary et al., 2017; Jordan et al., 2009; Siegler & Braithwaite, 2017). Furthermore, preschoolers' individual number skills vary at school entry (Duncan et al., 2007; Jordan et al., 2009). Multiple theoretical accounts also suggest that variation in domain-general cognitive abilities (e.g., working memory [WM], logical reasoning) contributes to the individual differences in young children's basic number processing skills (Geary et al., 2017; LeFevre et al., 2010; von Aster & Shalev, 2007). Thus, the purpose of this study was to deepen our understanding of the mechanisms underlying children's early number skills based on von Aster and Shalev's (2007) *four-step-developmental model of numerical cognition*, and Ackerman's (1988) *general theory of skill acquisition* as theoretical foundations. Our longitudinal study assessed numerical skills across kindergarten, first grade, and second grade, while also examining a set of general abilities. The aim was to investigate to what extent the contribution of domain-general cognitive abilities and specific number abilities vary between different aspects of number processing, and how this composition of underlying abilities may change over time.

Two Theoretical Framework Models

The four-step-developmental model of numerical cognition by von Aster and Shalev (2007), outlines children's hierarchical numerical development in four sequential steps. Each step builds on the previous one, emphasizing that earlier developmental milestones are important for advancing to more sophisticated phases. This model suggests that children are born with a cardinal magnitude system (Step 1) involving abilities like subitizing (i.e., quickly recognizing small quantities without counting) and approximation (i.e., estimating larger quantities without counting), laying the groundwork for early mathematical understanding before language acquisition (Carey, 2004; Dehaene, 1992; Xu et al., 2005).

As children advance to the next stage (Step 2), they start forming a verbal number magnitude system, involving the association of number words (e.g., “three”) with numerical concepts (e.g., ●●●). This development is important for understanding the symbolic number system (cf. Dehaene, 1992; Dresen et al., 2022; Geary, 2013; LeFevre et al., 2010). Once a verbal number magnitude system is established, children successively learn the Arabic number magnitude system (Step 3). This marks the transition from verbal to written numerals (i.e., “three” to “3”), indicating that the understanding of numerical magnitudes increases. The fourth and final step is the development of a spatially represented mental number line, incorporating both cardinality and ordinality (the numerical order). The model assumes that acquiring number symbols and integrating them with the core magnitude system increasingly relies on general cognitive abilities like language, executive functions, and WM. This suggests that cognitive load is initially high when learning new numerical skills due to the heavy reliance on these domain-general cognitive abilities. However, as these numerical skills become more automated, the reliance on general cognitive abilities decreases, leading to a reduction in cognitive load. In later stages, the cognitive load may shift towards domain-specific abilities, as the basic number processing abilities have been learned and require less domain-general cognitive support.

Ackerman's (1988) general theory of skill acquisition complements von Aster and Shalev's (2007) model, suggesting a gradual decrease in reliance on general cognitive abilities over time. Ackerman's theory consists of three phases: *the cognitive*, *the associative*, and *the autonomous phases*. The cognitive phase marks the initial stage, focusing on task-related knowledge and a higher cognitive demand. In numerical development, this could encompass learning basic number concepts/skills, such as counting, associating verbal and written numbers with their magnitudes. As numerical skills advance, establishing learning strategies, the child enters the second (associative) phase. With practice, both speed and accuracy in numerical tasks improve, and the cognitive load decreases. As the association between number symbols and their magnitudes becomes more refined and strengthened, the cognitive load further decreases. Thus, to enhance numerical and mathematical abilities, children need a foundation of acquired counting skills and an understanding of number magnitude (Hirsch et al., 2018; Siegler & Booth, 2004). After training, tasks become more automated or autonomous (Phase 3). The tasks are then executed quickly and accurately even when attention may be devoted elsewhere (cf., Sweller, 1988). It still remains an open question how different domain-general cognitive abilities scaffold the acquisition of numerical skills.

Basic Number Abilities Supporting Later Developed Number Processing

According to Gelman and Gallistel (1978), a full comprehension of counting involves mastering several core principles, such as: one-to-one correspondence (i.e., each object

corresponds to one counting word), stable order (i.e., counting words follow a consistent order), cardinality (i.e., final counting-word represent the total quantity), abstraction (i.e., counting applies to any collection of items, physical or abstract), and order irrelevance (i.e., the order in which objects are counted does not affect final count). These principles provide the scaffolding for numerical development, shaping skills such as counting, cardinality and ordinality, aligning with [Sasanguie and Vos \(2018\)](#), who suggest that younger children rely more on cardinal processing while older children and adults show a shift towards ordinal processing in numerical tasks.

An increasing number of studies show that basic number abilities support later-developed number abilities. For instance, basic number skills in kindergartners predict later math fluency, even after accounting for age, reading ability, vocabulary, memory, and spatial reasoning ([Locuniak & Jordan, 2008](#)). Early calculation skills, influenced by counting and magnitude comparison, significantly predict later mathematical performance ([Tobia et al., 2021](#)). A longitudinal study found that successful numerical estimation in children from kindergarten through 4th grade required a robust understanding of various basic number skills, including counting, recognizing Arabic numerals and understanding ordinality ([Booth & Siegler, 2006](#)). Furthermore, basic symbolic number skills, such as symbolic comparison ([Daker & Lyons, 2018](#)) and symbolic semantic tasks ([Meloni et al., 2023](#)), predict performance on number line estimation (NLE) tasks but not non-symbolic number tasks. These abilities are important for proficiency in calculating and understanding the underlying mathematical concepts and principles ([Kilpatrick et al., 2001](#)).

[LeFevre et al. \(2010\)](#) found that subitizing relates to non-symbolic arithmetic, NLE, and digit magnitude comparison (DMC), but not to number naming in children aged 4.5 to 7.5 years. These findings align with [von Aster and Shalev's \(2007\)](#) model, implying each numerical step lays the groundwork for the next, advancing the child's competence and number knowledge. Cardinal value knowledge is important for children's later numerical development and performance, helping them to understand and compare digits when they start school ([Geary & vanMarle, 2018](#); [Scalise & Ramani, 2021](#)). [Sarnecka et al. \(2023\)](#) studied 500 preschoolers and found that the understanding of cardinality and knowledge of written number symbols are important for children's ability to successfully use the number line.

Furthermore, [Fuchs et al. \(2010\)](#) corroborate [von Aster and Shalev's \(2007\)](#) model, indicating that both numerical skills (e.g., digit comprehension, cardinality, ordinality) and domain-general abilities support mathematical learning. This is important as complex skills like arithmetic likely develop in stages, with cognitive processes varying across these stages ([Ackerman, 2007](#)).

Domain-General Cognitive Predictors of Basic Number Processing

Several models assume that children's development of basic symbolic number skills is dependent on support from domain-general cognitive abilities (cf. [Geary, 2013](#); [LeFevre](#)

et al., 2010; von Aster, 2000). Examples of these abilities include *phonological processing* (Cirino, 2011; Passolunghi et al., 2015; Träff et al., 2017), *processing speed* (Cirino, 2011; Geary, 2011; Krajewski & Schneider, 2009; Passolunghi et al., 2015; Träff et al., 2017), *nonverbal logical reasoning* (Koponen et al., 2018), and *verbal WM* (Geary, 2011; Träff et al., 2020), all of which have been associated with early numerical skills.

Phonological Processes

Phonological awareness involves using the sound structure of language to comprehend written and spoken information (Wagner & Torgesen, 1987). Cirino's (2011) study of 276 kindergartners found that phonological awareness is important for correctly identifying and naming numerical symbols, such as rote counting and number recognition. Children with stronger phonological awareness performed better on symbolic tasks that required number recognition and sequencing. Furthermore, phonological awareness has been identified as cognitive predictors in early numerical skills, including counting sequences and magnitude comparisons tasks (Passolunghi et al., 2015). Träff et al. (2020) found that children with high mathematical achievement demonstrated superior executive functions and phonological fluency, from kindergarten to third grade, suggesting its importance for later numerical skills.

Cognitive Processing Speed

Cognitive processing speed is important in numerical tasks. For instance, Cirino (2011) found that Rapid Automatized Naming (RAN) predicts numerical performance, particularly in tasks requiring fast identification. He suggests that faster processing speed is important for both symbolic and non-symbolic comparison tasks, as well as for counting and identifying missing numbers in sequences. Geary (2011) found, in a longitudinal study, that faster processing speed, measured through RAN, enabled children to perform counting and NLE tasks more efficiently. Higher RAN scores facilitated quicker understanding of numerical relationships, enhancing performance in DMC and estimation. Faster processing speed allowed children to navigate these tasks more efficiently, which in turn supported their overall mathematical development. Furthermore, in a longitudinal study, Passolunghi et al. (2015), found that general processing speed supports rote counting and DMC.

Nonverbal Logical Reasoning

Nonverbal logical reasoning is important for understanding numerical relationships without verbal explanations. For example, it has been demonstrated by Koponen et al. (2018) that nonverbal logical reasoning was associated with performance in rote counting and NLE. Children who were better at solving problems using nonverbal information had a stronger grasp of counting sequences, which suggests that nonverbal reasoning supports early numerical skill development. Passolunghi et al. (2015) suggested that, non-

verbal reasoning became increasingly important as tasks became more complex (i.e., in NLE or comparing larger numbers). Geary (2011) found that intelligence (i.e., nonverbal reasoning) predicts performance in NLE and complex counting tasks. This suggests that nonverbal reasoning is not only important for early numerical skills but also for later mathematical achievement.

Working Memory (WM)

WM plays an important role in early numerical abilities. For instance, Passolunghi et al. (2015) concluded that WM sustains the development of early numerical abilities, surpassing the influence of domain-specific abilities in last year of kindergarten. Krajewski and Schneider (2009) found that children's ability to hold number words in mind while counting was closely linked to their success in rote counting and other foundational numerical tasks. In their longitudinal study with children from preschool to fourth grade, they demonstrated that verbal WM supported children's ability to keep track of number sequences. Similarly, Koponen et al. (2018) showed, in a longitudinal sample, that verbal short-term memory, a component of WM, strongly predicted rote counting abilities in first graders. This indicates that children with better verbal short-term memory can process number sequences more efficiently.

The Present Study

In summary, studies reviewed above show, in accordance with von Aster and Shalev's (2007) four-step developmental model, how different domain-general cognitive abilities, such as phonological processes, processing speed, nonverbal logical reasoning, and WM, contribute to various aspects of early numerical skill, such as counting skills, DMC, and NLE.

This study aims to fill a knowledge gap by investigating how number skills fit within two distinct theoretical frameworks: von Aster and Shalev's (2007) four-step developmental model and Ackerman (1988) general theory of skill acquisition. Our longitudinal design allowed us to follow the same children from kindergarten to second grade, providing deeper insights into early mathematical learning. The overall aim of the present study was to investigate how domain-general cognitive abilities and number-specific abilities support children's performance and development (across three time-points) in basic numerical processing tasks.

Grounded in von Aster and Shalev's (2007) development model and Ackerman's (1988) theory, we employed a series of regression analyses to examine the variance of domain-general abilities in dependent variables (domain-specific numerical abilities) and the unique variance accounted for by each general cognitive ability.

Building upon Booth and Siegler's (2006) and in alignment with von Aster and Shalev's (2007) four-step developmental model, our first hypothesis is that prior early-developed number skills support later-acquired ones. Specifically, each step provides

support for the next step in the developmental process. This means that counting skills is anticipated to facilitate children's symbolic number magnitude comparison performance, and that these in tandem provide support for NLE. Although not specifically addressed by either model, this developmental process may also entail that reliance on more distal abilities (e.g., counting knowledge) decreases as children begin to master later developmental steps (e.g., NLE).

The second hypothesis, aligned with the four-step developmental model, posits that domain-general cognitive abilities predict children's number processing skills, but to different extents. Specifically, later developed number skills such as NLE (i.e., Step 4) demand more domain-general cognitive support during the learning process than earlier developed number skills such as counting (i.e., Step 2) and symbolic number magnitude comparison (i.e., Step 3).

The third hypothesis is founded on [Ackerman's \(1988\)](#) theory of skill acquisition, stating that the importance of general cognitive abilities diminishes over time as children become more adept at various numerical abilities. More precisely, as children become more proficient in numerical tasks such as counting, digit comparison, and NLE, their reliance on domain-general cognitive abilities is expected to decrease. Initially, higher-order cognitive abilities such as WM and logical reasoning are important; however, as proficiency increases, reliance shifts towards lower-order abilities like phonological awareness.

To examine this shift, we analyze the cognitive abilities' complete and unique variance in the three dependent variables (the domain-specific numerical abilities). Also, by integrating our variables into [von Aster and Shalev's \(2007\)](#) and [Ackerman's \(1988\)](#) theoretical frameworks, we aimed to elucidate the intricate interplay of cognitive processes underlying children's numerical development. This approach allows us to explore the relationship between the general cognitive and specific numerical skills measured at each stage in von Aster's and Shalev's model and Ackerman's phases of skill acquisition.

Method

Participants

Initially, 315 six-year-olds were recruited from 22 schools located in a city with 155,000 inhabitants, in southern Sweden. Participants diagnosed with neuropsychological disorders (e.g., attention-deficit/hyperactivity disorder), based on the *Diagnostic and Statistical Manual of Mental Disorders* ([American Psychiatric Association, 1994](#)) or the *ICD-10* ([World Health Organization, 1992](#)) criteria, were not included in the study. Participants were assessed on domain-specific numerical abilities one year before formal school entry. One year later, 305 participants from the initial sample underwent reevaluation for domain-specific and general cognitive abilities. The ten missing participants had relocated

to other parts of the country. Two years after initial measurement, another round of testing was conducted for domain-specific numerical abilities and domain-general cognitive abilities. Three of the remaining 305 participants lacked response time data at the third measurement and were excluded. Additionally, five participants did not participate in cognitive tests and were excluded, along with one identified outlier. After exclusions, 296 participants (50.3% girls) remained. The age of the sample ranged from 5 years and 10 months to 7 years and 4 months ($M_{age} = 6$ years and 8 months, $SD = \pm 4$ months) at first measurement, at second between 6 years and 9 months to 8 years and 4 months ($M_{age} = 7$ years and 7 months, $SD = \pm 4$ months), and at third between 7 years and 10 months to 9 years and 4 months ($M_{age} = 8$ years and 7 months, $SD = \pm 4$ months).

General Procedure

Participants were recruited by distributing a letter of consent to the children, which they brought home from school. All children who obtained written parental consent were included in the study. The sample primarily consisted of families with middle-class backgrounds, determined by factors such as parental education, income, and housing standards. Participating schools were mostly located in middle-class neighborhoods. All children were fluent in Swedish, had normal or corrected-to-normal visual acuity, and did not experience hearing loss.

Throughout all three measurement points, each child underwent a total testing of approximately 90 minutes. Test sessions were interspersed with breaks, ranging from 15 to 60 minutes (e.g., lunch break). To ensure consistency and minimize variability in the data, the test order remained the same for all children. This approach reduces noise and ensures that any differences observed were due to the variables being studied rather than inconsistencies in the testing procedure, as recommended in Field (2018). All testing activities took place within the child's school, ensuring a familiar environment, and in a one-on-one setting. Oral instructions were provided for all tasks to ensure clarity and uniformity in administration by ten experimenters. Each child was tested around the same month (from October to May) during each of the three measurement points to ensure consistency. For instance, if a child's first session occurred in December the following session took place during the same month (up to one month's variability) in following years.

This research project was approved by the Regional Ethics Committee in Linköping, Sweden (Protocol 33-09).

Measures

Domain-Specific Number Abilities

All measurements were conducted in kindergarten, first grade, and second grade, except counting knowledge which was only measured at first and second time point due to the

simplicity of the tasks. We have assessed reliability through different methods (split-half, Cronbach's alpha, and correlation) depending on the task.

Counting Skills – This task evaluated counting proficiency through five different assignments. In the first assignment, children were asked to count from 1 to 50, and from 1 to 30 (twice) as fast as possible. For each of these tasks the children earned 1 point for the correct performance, with a maximum score of 3. The second assignment involved counting forward five numbers from a predetermined number (e.g., 8 to 13). The maximum score was 4 in the first measurement. In the second measurement, the second assignment included two additional tasks (e.g., 97 to 102), which increased the total maximum score to 6. The counting score for each participant was calculated by summing the number of correct answers across all tasks. The third assignment involved counting backwards from a specified initial number to 1 (e.g., 10 down to 1). The maximum available points was 3. The fourth and fifth assignment involved identifying succeeding and preceding numbers. For example, the child was asked: “What number comes after 6?” and if the child answered “7” s/he earned one point (maximum score: 5). In the last task, the child was asked for example: “What number comes before 9?”. If the child answered correctly s/he received 1 point for each trial, a maximum score of five. The total counting score for each participant was calculated by summing the points earned across all five tasks. The maximum score was 20 at the first measurement (Kindergarten) and 22 at the second measurement (1st Grade), due to the inclusion of two additional items in the second assignment. At the second measurement, 12 outliers were addressed through Winsorization at the 5th percentile. Reliability was assessed using split-half: at first measurement $r_{sh} = .83$ and second measurement $r_{sh} = .78$.

Digit Magnitude Comparison (DMC) – This task tested the child's ability to access quantities associated with symbolic representations and was presented on four different sheets of paper. The first sheet featured single-digit pairs with a numerical distance of 1 (e.g., 2 and 3). The second sheet contained single-digit pairs with a numerical distance of 4 to 5 (e.g., 7 and 2). The third sheet contained two-digit pairs with a numerical distance of 1. Lastly, the fourth sheet also featured two-digit pairs, but with a numerical distance of 4 to 5. All four sheets contained a total of 14 items each (56 in total). The children responded by crossing out the larger number on the papers. Response time and accuracy were registered and combined into a total efficiency measure (RT/proportion correct) for each year. Response time and accuracy outliers (15 in all) were addressed through Winsorization at the 95th percentile. The scores were inverted by multiplying them by -1 to facilitate interpretation, so that higher scores reflect better (i.e., faster and more accurate) performance. Internal reliability was assessed using Cronbach's alpha for digit magnitude efficiency: at first measurement $\alpha = .89$, at second $\alpha = .89$, and at third measurement $\alpha = .90$.

Number Line Estimation (NLE) – The NLE task assessed children’s spatial numerical ability across 16 items. Participants used a pencil to mark the placement of numbers on a 0–100 number line (0 to the left of the line, 100 to the right) in 16 trials. The task included a booklet with eight pages, each featuring two 21-cm number lines. Estimations were evaluated by comparing them to a perfect linear function, using percentage absolute error. For interpretation purposes, the scores were inverted using the formula $100 - X$, so that higher values represent more accurate estimations. Administered at three time points, NLE showed internal reliability of Cronbach’s alpha at first measurement $\alpha = .85$, at second $\alpha = .87$, and at third measurement $\alpha = .91$.

Domain-General Cognitive Abilities

All domain-general cognitive abilities were assessed at all three measurement time points: kindergarten, first grade, and second grade. We employed various methods to assess the reliability of the measures, depending on the nature of the task and the number of available data points. For some tasks, repeated measures allowed for the use of correlation analyses to assess test-retest reliability, whereas for others, Cronbach’s Alpha or Split-Half reliability testing were more suitable. This variability in reliability testing aligns with recommendations by McCrae et al. (2011), suggesting that reliability assessment should consider the structure and characteristics of the data.

Phonological Awareness – An ability assessed via a segment subtraction, an indicator of phonological awareness (Taube et al., 1984). The children identified omitted segments from Swedish words (e.g., "What's removed from 'kamera' if only 'mera' remains?"). The task consisted of 15 items, ending after four consecutive unsuccessful trials. Analysis utilized the total accurately solved problems, with a maximum score of 15. To evaluate reliability over the three measurement time points, test-retest correlations were computed. The correlation between the first and second measurement was $r_{tr} = .58$, between the first and the third measurement was $r_{tr} = .53$, and between the second and third measurement was $r_{tr} = .60$. All correlations were significant with $p < .001$.

Phonological Verbal Fluency – In this task, children generate as many words as possible during sixty seconds in specific phonological categories, assessing verbal fluency (cf. Andersson & Lyxell, 2007). They were naming words beginning with "f" and "s" sounds. The number of words the child correctly retrieved during the allotted time, was counted, granting one point each. At year 1, scores range from 0 to 22, and split-half reliability was $r_{sh} = .66$, second was $r_{sh} = .56$, and third measurement was $r_{sh} = .50$.

Rapid Automated Naming (RAN) – This task was used to assess swift and automated access to information stored in long-term memory (cf. Andersson & Östergren, 2012). The assessment materials comprised two sheets of paper, each containing 30 red,

blue, green, yellow, and black XXX (Arial, 22-point font), arranged in two columns with 15 in each column. The child was instructed to name the color of the XXX as fast and accurately as possible. A stopwatch recorded the time taken to complete all 30 trials. Additionally, the experimenter monitored the child's responses throughout the task, noting any errors made. The cumulative response times for both sheets of paper were utilized as the primary outcome measure. The scores were inverted by multiplying them by -1 to ensure that higher scores reflect faster performance. First year split-half reliability was $r_{sh} = .88$, second $r_{sh} = .79$, and third $r_{sh} = .79$.

General Processing Speed — Participants swiftly identified and struck through duplicate digits within 15 rows of numbers, each containing seven digits, within a 90-second limit (cf. Andersson, 2008). A quotient variable determined processing speed, calculated as the time taken to complete correct rows (e.g., if 12 rows were correct in 90 sec, resulting in 7.5 seconds per row, higher scores indicate slower general processing speed). The variable gauged participants' efficiency in identifying duplicates within the allotted time. The scores were inverted by multiplying them by -1 to ensure that higher scores reflect faster performance. Test-retest reliability calculated between measurement one and two was $r_{tr} = .55$, year one and three $r_{tr} = .39$, and measurement two and three $r_{tr} = .46$. All correlations were statistically significant, at $p < .001$.

Nonverbal Logical Reasoning — This ability was measured using the Matrix Reasoning subtest from Wechsler's Intelligence Scale for Children (Wechsler, 2003). Participants selected the missing piece to complete designs, responding verbally or through pointing. Each item offered five possible responses. The subtest comprised 35 items, with testing stopping after four consecutive incorrect answers or four wrong responses within five trials, yielding a maximum score of 35. Test-retest reliability between the first and second measurement was $r_{tr} = .54$, between the first and the third measurement $r_{tr} = .50$, and between the second and third measurement $r_{tr} = .60$. All correlations were significant at $p < .001$.

Verbal Working Memory — Children performed a word span task, identifying whether each presented word represented an animal before the next word was said by the researcher (cf. Östergren & Träff, 2013). They then recalled the words in proper serial order. Each trial was repeated with different words. Starting at a span size of two, it increased to seven. Testing extended beyond span four if successful, ceasing only after two failed trials at the same span length. About 43% of words were animals. Reliability across the three measurement points was assessed using test-retest correlations. The total sum of completely and perfectly recalled list sequences was the dependent measure (cf. Baddeley et al., 1975). The correlation between the first and second measurements was $r_{tr} = .36$, between the first and third measurements $r_{tr} = .35$, and between the second and third measurements $r_{tr} = .40$. All correlations were statistically significant, at $p < .001$.

Study Design and Data Analysis

Missing Data and Outliers – No variable exceeded 2.4% missing data. According to [Kline \(2016\)](#) up to 5% missing data is generally manageable and does not significantly bias the results. In one variable, general processing speed at second measurement, the instrument measuring the children's answer was malfunctioning for 7 responses. We decided to move forward with the analysis without any manipulations. All other missing data was at completely random (Little's MCAR test: $\chi^2 = 35.842$, $df = 45$, $p = .834$).

In two variables (counting skills and DMC) we encountered possible outliers. To ensure the appropriateness of the regression analyses and obtain a representative sample, Winsorization at 5% and 95% was applied to the two variables using IBM SPSS Statistics for Windows (version 29). By Winsorizing, we adjusted outlying values to the nearest non-outlier value.

Distribution, Correlation Analysis, Strength, and Direction – Skewness and kurtosis assessments indicated low skewness (-1.876 to 1.041) and acceptable kurtosis (-1.031 to 4.948), suggesting a normal distribution for the variables. Consequently, parametric analyses were conducted. [Cohen's \(1988\)](#) guidelines were applied to assess significance and effect sizes for regression coefficients (β) in regression analyses.

Results

Descriptive statistics for the nine tasks at measurement 1 (i.e., kindergarten), 2 (i.e., first grade), and 3 (i.e., second grade) are presented in [Table 1](#). Note that counting skills were only measured in kindergarten and in first grade due to the task's simplicity. The correlation matrix can be seen in [Appendix A](#), homoscedasticity and linearity in [Appendix B](#), and additional analyses can be found in the [Supplementary Materials](#).

Table 1
Descriptive Statistics for All Measures Used in the Study

Tasks	Kindergarten						1st Grade						2nd Grade					
	M	SD	Min.	Max.	Skew	Kurt	M	SD	Min.	Max.	Skew	Kurt	M	SD	Min.	Max.	Skew	Kurt
1. CS	13.76	4.92	1	20	-.32	-1.03	20.01	2.51	12.95	22	-1.65	1.84	-	-	-	-	-	-
2. DMC	-39.96	16.27	-107.41	-17.03	-1.56	2.64	-24.25	5.92	-41.13	-12.90	-67	-0.00	-18.45	3.85	-27.37	-11.03	-33	-56
3. NLE	83.93	7.65	53.29	97.50	-.55	-.03	90.72	5.33	62.13	98.16	-1.54	3.34	94.30	2.91	84.64	98.33	-1.78	3.50
4. PhA	4.53	3.07	0	13	.62	-.36	6.62	3.56	0	15	.17	-.90	9.22	3.22	1	15	-.43	-.44
5. PVF	6.60	4.30	0	22	.80	.61	13.53	5.34	0	30	.37	.09	15.75	5.64	3	50	1.04	4.02
6. RAN	-80.40	21.47	-143	-41	-.84	.39	-66.95	17.74	-150	-8	-.99	2.24	-60.21	14.23	-123	-36	-1.11	2.03
7. GPS	-9.94	3.87	-22.60	-4.09	-1.47	2.22	-7.06	2.57	-18	-3.18	-1.88	4.95	-5.31	1.43	-11.25	-2.84	-1.07	1.82
8. NLR	12.39	3.81	3	27	.74	.84	15.46	4.63	4	33	.44	-.05	18.04	4.47	8	30	-.11	-.62
9. VWM	7.04	3.49	1	19	.49	.44	8.89	3.92	0	23	.89	.83	11.70	4.64	4	29	1.03	1.34

Note. $N = 296$. Skewness $SE = .142$; Kurtosis $SE = .282$. Abbreviations: $M =$ Means; $SD =$ Standard Deviations; $CS =$ Counting Skills; $DMC =$ Digit Magnitude Comparison; $NLE =$ Number Line Estimation; $PVF =$ Phonological Verbal Fluency; $RAN =$ Rapid Automated Naming; $RAN =$ Rapid Automated Naming; $NLR =$ Nonverbal Logical Reasoning; $VWM =$ Verbal Working Memory; $GPS =$ General Processing Speed; $PhA =$ Phonological Awareness. CS is measured in kindergarten and in first grade.

We conducted 14 regression analyses to examine whether domain-general cognitive abilities can predict domain-specific numerical abilities, following the frameworks of von Aster and Shalev (2007) and Ackerman (1988). For DMC and NLE, we used hierarchical regression. In Model 1, domain-specific numerical abilities were entered first, followed by domain-general cognitive abilities, based on von Aster and Shalev's theory that counting knowledge precedes DMC, which in turn precedes NLE. In Model 2, we reversed the order to assess the importance of cognitive abilities in predicting numerical skills. We focused on each predictor's unique variance in the criterion variables.

Predicting Counting Skills

Kindergarten

The first model explained 37% of the variation in counting skills, $F(6, 288) = 28.146, p < .001; R^2 = .37$. Unique contributions (Table 2) were seen in kindergarten for phonological verbal fluency (5%), phonological awareness (4%), RAN (3%), and general processing speed (1%).

Table 2

Two Linear Regression Analyses of Counting Skill: The Unique Contribution of Domain-General Cognitive Tasks in Measurement One and Two

Predictor	Kindergarten						1st Grade					
	B	SE	β	t	Sig.	Pr ²	B	SE	β	t	Sig.	Pr ²
	$F(6, 288) = 28.146, p < .001; R^2 = .37$						$F(6, 278) = 13.730, p < .001; R^2 = .23$					
PhA	.37	.09	.23	4.02	< .001	.04	.10	.04	.15	2.31	.022	.01
PVF	.31	.06	.27	4.81	< .001	.05	.06	.03	.13	2.08	.038	.01
RAN	.05	.01	-.20	3.88	< .001	.03	.02	.01	.11	1.88	.061	.01
GPS	.16	.07	-.13	2.38	.018	.01	.05	.06	.05	.79	.429	.00
NLR	.07	.07	.06	1.08	.283	.00	.13	.03	.23	3.75	< .001	.04
VWM	.07	.07	.05	1.02	.309	.00	.04	.04	.07	1.26	.208	.00

Note. $N = 296$. Abbreviations: B = unstandardized beta coefficient; SE = Standard Error; β = standardized beta coefficient; t = t-value; Pr² = squared part correlation; PhA = Phonological Awareness; PVF = Phonological Verbal Fluency; RAN = Rapid Automatized Naming; GPS = General Processing Speed; NLR = Nonverbal Logical Reasoning; VWM = Verbal Working Memory. No significant autocorrelation noted in the residuals (Durbin-Watson kindergarten = 1.980; Durbin-Watson 1st Grade = 2.122). No collinearity discovered (VIF kindergarten = 1.176 – 1.486; VIF 1st Grade = 1.098 – 1.452). Homoscedasticity and linearity are available in Appendix B.

First Grade

In first grade, the model explained 23% of the variation, $F(6, 278) = 13.730, p < .001; R^2 = .23$. The general cognitive abilities declined by 14% from kindergarten to first grade in counting skills. The unique contributors were nonverbal logical reasoning (4%),

phonological awareness (1%) and phonological verbal fluency (1%). This indicates a rise in the role of nonverbal logical reasoning in first grade, while RAN no longer is significant. Phonological processes and general processing speed slightly decreased from kindergarten.

Predicting Digit Magnitude Comparison (DMC)

Kindergarten

In Model 1 (Table 3), counting skills (Block 1) accounted for 19% of the variance in DMC, $R^2 = .19$, $F(1, 293) = 70.471$, $p < .001$. Adding cognitive abilities in Block 2 contributed an additional 17% variance, $\Delta R^2 = .17$, $F_{change}(6, 287) = 13.168$, $p < .001$. Significant unique contributors (Block 2) were general processing speed (8%), counting skills (4%), and RAN (3%) in that order.

In Model 2, cognitive abilities (Block 1) explained 33% of the variance, $F(6, 288) = 23.282$, $p < .001$; $R^2 = .33$. When adding counting skills in Block 2, the variance increased to 37%, $R^2 = .37$, $F(7, 287) = 23.863$, $p < .001$, with counting skills adding additional 4% variance, $\Delta R^2 = .04$, $F_{change} = 18.743$, $p < .001$. Significant unique cognitive contributors were (Block 1) general processing speed (9%), RAN (5%), nonverbal logical reasoning (1%).

First Grade

In first grade (Model 1), counting skills (Block 1) explained 18% of the variance in DMC, $R^2 = .18$, $F(1, 283) = 59.950$, $p < .001$. General cognitive abilities (Block 2) added 17% variance, $\Delta R^2 = .17$, $F_{change}(6, 277) = 11.766$, $p < .001$. Significant unique contributors (Block 2) were general processing speed (7%), counting skills (6%), RAN (3%), verbal working memory (WM) (1%).

In Model 2, cognitive abilities (Block 1) accounted for 28% variance, $R^2 = .28$, $F(6, 278) = 18.124$, $p < .001$. When adding counting skills (Block 2), the variance increased to 34%, $R^2 = .34$, $F(7, 277) = 20.604$, $p < .001$, with counting skills adding additional 6%, $\Delta R^2 = .06$, $F_{change}(1, 277) = 25.787$, $p < .001$. Significant cognitive contributors were (Block 1) general processing speed (7%), RAN (4%), and verbal WM (2%). The cognitive contributions remained largely consistent even when counting skills were accounted for.

Second Grade

In second grade, counting skills (Model 1, Block 1) accounted for 6% of the variance in DMC, $R^2 = .06$, $F(1, 291) = 19.505$, $p < .001$, decreasing 11% from first grade. General cognitive abilities (Block 2) added 23%, $\Delta R^2 = .23$, $F_{change}(6, 285) = 15.567$, $p < .001$. This represented a 6% increase from first grade. The significant contributors were (Block 1) general processing speed (11%), RAN (4%), and counting skills (1%) in that order.

Table 3
Six Hierarchical Multiple Regression Analyses of the Digit Magnitude Comparison Tasks for the Three Measurements

Predictors	Kindergarten					1st Grade					2nd Grade							
	B	SE	β	t	Sig.	Pr ²	B	SE	β	t	Sig.	Pr ²	B	SE	β	t	Sig.	Pr ²
Model 1																		
Block 1	$F(1, 293) = 70.471, p < .001; R^2 = .19$					$F(1, 283) = 59.950, p < .001; R^2 = .18$					$F(1, 291) = 19.505, p < .001; R^2 = .06$							
CS ^a	1.46	.17	.44	8.40	<.001	.19	.99	.13	.42	7.74	<.001	.17	.38	.09	.25	4.42	<.001	.06
Block 2	$F(7, 287) = 23.863, p < .001; R^2 = .37, \Delta R^2 = .17, F_{avg} = 13.168, p < .001$					$F(7, 277) = 20.604, p < .001; R^2 = .34, \Delta R^2 = .17, F_{avg} = 11.766, p < .001$					$F(7, 285) = 16.966, p < .001; R^2 = .29, \Delta R^2 = .23, F_{avg} = 15.567, p < .001$							
CS ^a	.85	.20	.26	4.33	<.001	.04	.66	.13	.28	5.08	<.001	.06	.19	.09	.13	2.22	.028	.01
PhA	-.42	.31	-.08	-1.34	.182	.00	-.08	.10	-.05	-.81	.421	.00	.06	.07	.05	.79	.432	.00
PVF	.17	.22	.04	.73	.452	.00	.04	.06	.04	.70	.483	.00	.05	.04	.06	1.25	.214	.00
RAN	.15	.04	.20	3.74	<.001	.03	.06	.02	.19	3.65	<.001	.03	.06	.02	.21	3.86	<.001	.04
GPS	1.31	.22	.31	5.86	<.001	.08	.67	.13	.30	5.29	<.001	.07	.96	.15	.35	6.53	<.001	.11
NLR	.43	.22	.10	1.94	.053	.01	-.00	.08	-.00	-.03	.977	.00	-.05	.05	-.06	-1.01	.315	.00
VWM	-.01	.24	-.00	-.05	.957	.00	.17	.08	.12	2.24	.026	.01	.05	.05	.06	1.07	.286	.00

Predictors	Kindergarten					1st Grade					2nd Grade									
	B	SE	β	t	Sig.	Pr^2	B	SE	β	t	Sig.	Pr^2	B	SE	β	t	Sig.	Pr^2		
Model 2																				
Block 1	$F(6, 288) = 23.282, p < .001; R^2 = .33$										$F(6, 278) = 18.124, p < .001; R^2 = .28$									
PhA	-.11	.31	-.02	.34	.735	.00	-.01	.10	-.01	-.11	.915	.00	.10	.07	.08	1.42	.157	.01		
PVF	.43	.22	.11	-1.95	.052	.01	.08	.06	.08	1.29	.200	.00	.05	.04	.07	1.28	.201	.00		
RAN	.19	.04	.24	4.69	<.001	.05	.07	.02	.22	4.07	<.001	.04	.06	.02	.22	4.11	<.001	.04		
GPS	1.44	.23	.34	6.33	<.001	.09	.70	.13	.31	5.31	<.001	.07	.98	.15	.36	6.62	<.001	.11		
NLR	.49	.23	.12	2.15	.032	.01	.08	.08	.06	1.07	.287	.00	-.02	.05	-.03	-.47	.641	.00		
VWM	.05	.25	.01	-.20	.842	.00	.20	.08	.13	2.52	.012	.02	.04	.05	.05	.92	.358	.00		
Block 2	$F(7, 287) = 23.863, p < .001; R^2 = .37,$										$F(7, 277) = 20.604, p < .001; R^2 = .34,$									
	$\Delta R^2 = .04, F_{change} = 18.743, p < .001$										$\Delta R^2 = .06, F_{change} = 25.787, p < .001$									

Note. $N = 296$. Abbreviations: B = unstandardized beta coefficient; SE = Standard Error; β = standardized beta coefficient; t = t-value; Pr^2 = squared part correlation; CS = Counting Skill; PhA = Phonological Awareness; PVF = Phonological Verbal Fluency; RAN = Rapid Automated Naming; GPS = General Processing Speed; NLR = Nonverbal Logical Reasoning; VWM = Verbal Working Memory. To avoid redundancy, only Block 1 from Model 2 is presented in the table. *In 2nd Grade, CS from 1st Grade was used. No significant autocorrelation noted in the residuals (Durbin-Watson kindergarten = 1.674; Durbin-Watson 1st Grade = 1.968; Durbin-Watson 2nd Grade = 1.799). No collinearity discovered (VIF kindergarten = 1.000 – 1.586; VIF 1st Grade = 1.000 – 1.448; VIF 2nd Grade = 1.000 – 1.388). Homoscedasticity and linearity are available in Appendix B.

In the inverted Model 2, general cognitive abilities (Block 1) explained 28% of the variance, $R^2 = .28$, $F(6, 286) = 18.721$, $p < .001$. Adding counting skills (Block 2), the variance increased with 1%, $\Delta R^2 = .01$, $F_{change}(1, 285) = 4.905$, $p < .001$, bringing the full model to 29% variance, $R^2 = .29$, $F(7, 285) = 16.966$, $p < .001$, in DMC performance. The significant unique cognitive contributors (Block 1) explained were general processing speed (11%) and RAN (4%).

Counting skills showed a downward trend across the three measurement points (Model 1, Block 1), while delta (ΔR^2 , Model 2, Block 2) increased from kindergarten to first grade, then decreased to second grade. Cognitive abilities declined between kindergarten and first grade but remained stable in second grade. Delta followed a different path. When general cognitive abilities (Model 1, Block 2) were included, delta was the same in kindergarten and first grade but increased in second grade.

Predicting Number Line Estimation (NLE)

Kindergarten

In Model 1, counting skills and DMC (Block 1) accounted for 43% of the variation in NLE, $R^2 = .43$, $F(2, 292) = 109.971$, $p < .001$. When the general cognitive abilities were included, the model (Block 2) explained an additional 6% ($\Delta R^2 = .06$, $F_{change}(6, 286) = 6.066$, $p < .001$), bringing the total explained variance to 49%, $R^2 = .49$, $F(8, 276) = 28.510$, $p < .001$. Significant unique contributors were counting skills (17%), verbal WM (2%), phonological awareness (1%), and general processing speed (1%).

In Model 2 (Block 1), general cognitive abilities accounted for 31%, $R^2 = .31$, $F(6, 288) = 21.067$, $p < .001$. When numerical skills were added into the model (Block 2) the variance increased by 19%, $\Delta R^2 = .19$, $F_{change}(2, 286) = 53.411$, $p < .001$ in NLE performance. This brought the total variance to 49%, $R^2 = .49$, $F(8, 286) = 34.904$, $p < .001$. The unique cognitive contributions (Block 1) came from phonological awareness (4%), general processing speed (3%), and verbal WM (3%).

First Grade

In Model 1, counting skills and DMC (Block 1) explained 42% of the variation in NLE, $R^2 = .42$, $F(2, 282) = 102.007$, $p < .001$. The cognitive abilities (Block 2) accounted for an additional 3% variance, $\Delta R^2 = .03$, $F_{change}(6, 276) = 2.747$, $p < .001$, bringing the total explained variance to 45%, $R^2 = .45$, $F(8, 276) = 28.510$, $p < .001$. The unique contributors were counting skills (17%), DMC (2%), and nonverbal logical reasoning (2%).

In the reverted Model 2 (Block 1), the domain-general cognitive abilities accounted for 22%, $R^2 = .22$, $F(6, 278) = 12.660$, $p < .001$ variance in NLE. When adding additional numerical skills, the variance increased by 24%, $\Delta R^2 = .24$, $F_{change} = 59.952$, $p < .001$, bringing the total variance to 45%, $R^2 = .45$, $F(8, 276) = 28.510$, $p < .001$. The unique cognitive contribution (Block 1) came from nonverbal logical reasoning (6%) and phonological verbal fluency (1%).

Table 4
Six Hierarchical Multiple Regression Analyses of the Number Line Estimation Tasks for the Three Measurements

Predictors	Kindergarten					1st Grade					2nd Grade							
	B	SE	β	t	Sig.	Pr ²	B	SE	β	t	Sig.	Pr ²	B	SE	β	t	Sig.	Pr ²
Block 1																		
	$F(2, 292) = 109.971, p < .001; R^2 = .43$					$F(2, 282) = 102.007, p < .001; R^2 = .42$					$F(2, 290) = 33.984, p < .001; R^2 = .19$							
CS ^a	.97	.08	.63	12.71	<.001	.32	1.18	.11	.55	10.94	<.001	.25	.35	.06	.32	5.79	<.001	.09
DMC	.03	.02	.06	1.27	.207	.00	.17	.05	.19	3.76	<.001	.03	.17	.04	.23	4.24	<.001	.05
Block 2																		
	$F(8, 286) = 34.904, p < .001; R^2 = .49$					$F(8, 276) = 28.510, p < .001; R^2 = .45$					$F(8, 284) = 13.162, p < .001; R^2 = .27$							
	$\Delta R^2 = .06, F_{\text{change}} = 6.066, p < .001$					$\Delta R^2 = .03, F_{\text{change}} = 2.747, p = .013$					$\Delta R^2 = .08, F_{\text{change}} = 5.230, p < .001$							
CS ^a	.83	.09	.54	9.84	<.001	.17	1.06	.11	.49	9.29	<.001	.17	.22	.06	.21	3.52	<.001	.03
DMC	.02	.03	.03	.62	.535	.00	.14	.05	.16	2.83	.005	.02	.11	.04	.16	2.57	.011	.02
PhA	.29	.13	.12	2.19	.030	.01	-.08	.08	-.06	-1.01	.313	.00	.05	.05	.06	.97	.333	.00
PVF	-.07	.09	-.04	-.73	.469	.00	.05	.05	.05	1.03	.306	.00	-.05	.03	-.10	-1.79	.074	.01
RAN	-.03	.02	-.09	-1.82	.070	.01	-.01	.02	-.05	-.94	.347	.00	.01	.01	.06	1.01	.313	.00
GPS	.20	.10	.10	2.05	.041	.01	.09	.11	.04	.81	.421	.00	.29	.11	.15	2.52	.012	.02
NLR	.10	.09	.05	1.07	.286	.00	.20	.06	.17	3.19	.002	.02	.14	.04	.23	3.84	<.001	.04
VWM	.37	.10	.17	3.71	<.001	.02	.03	.07	.02	.51	.613	.00	-.04	.03	-.06	-1.15	.250	.00

Predictors	Kindergarten					1st Grade					2nd Grade								
	B	SE	β	t	Sig.	Pr^2	B	SE	β	t	Sig.	Pr^2	B	SE	β	t	Sig.	Pr^2	
Model 2																			
Block 1	$F(6, 288) = 21.067, p < .001; R^2 = .31$																		
PhA	.59	.15	.24	3.98	< .001	.04	.02	.10	.02	.25	.800	.00	.11	.05	.13	2.14	.034	.01	$F(6, 286) = 13.032, p < .001; R^2 = .22$
PVF	.20	.10	.11	1.88	.061	.01	.13	.06	.13	2.07	.039	.01	-.04	.03	-.08	-1.48	.140	.01	
RAN	.01	.02	.03	.50	.615	.00	.01	.02	.04	.71	.479	.00	.02	.01	.11	2.01	.046	.01	
GPS	.36	.11	.18	3.30	.001	.03	.24	.13	.12	1.89	.060	.01	.42	.11	.22	3.81	< .001	.04	
NLR	.17	.11	.08	1.54	.124	.01	.35	.07	.30	4.73	< .001	.06	.17	.04	.28	4.65	< .001	.05	
VWM	.43	.12	.20	3.71	< .001	.03	.11	.08	.08	1.42	.157	.01	-.04	.03	-.07	-1.21	.228	.00	
Block 2	$F(8, 286) = 34.904, p < .001; R^2 = .49,$ $\Delta R^2 = .19, F_{change} = 53.411, p < .001$																		
$F(8, 276) = 28.510, p < .001; R^2 = .45,$ $\Delta R^2 = .24, F_{change} = 59.952, p < .001$																			
$F(8, 284) = 13.162, p < .001; R^2 = .27,$ $\Delta R^2 = .06, F_{change} = 10.856, p < .001$																			

Note. $N = 296$. Abbreviations: B = unstandardized beta coefficient; SE = Standard Error; b = standardized beta coefficient; t = t-value; Pr^2 = squared Part correlation; CS = Counting Skill; DMC = Digit Magnitude Comparison; NLE = Number Line Estimation; PhA = Phonological Awareness; PVF = Phonological Verbal Fluency; RAN = Rapid Automated Naming; GPS = General Processing Speed; NLR = Nonverbal Logical Reasoning; VWM = Verbal Working Memory. To avoid redundancy, only Block 1 from Model 2 is presented in the table. *In 2nd Grade, CS from 1st Grade was used. No significant autocorrelation noted in the residuals (Durbin-Watson kindergarten = 1.848; Durbin-Watson 1st Grade = 2.034; Durbin-Watson 2nd Grade = 1.601). No collinearity discovered (VIF kindergarten = 1.180 – 1.690; VIF 1st Grade = 1.125 – 1.521; VIF 2nd Grade = 1.067 – 1.417). Homoscedasticity and linearity are available in Appendix B.

Second Grade

In Model 1, counting skills and DMC (Block 1) accounted for 19%, $R^2 = .19$, $F(2, 290) = 33.984$, $p < .001$. When the domain-general cognitive abilities were included (Block 2) the overall variance increased with 8%, $\Delta R^2 = .08$, $F_{change} = 5.230$, $p < .001$, bringing the total variance to 27%, $R^2 = .27$, $F(8, 284) = 13.162$, $p < .001$, in NLE performance. Significant contributors were nonverbal logical reasoning (4%), counting skills (3%), DMC (2%), and general processing speed (1%).

In the reverted Model 2, the general cognitive abilities (Block 2) explained 22%, $R^2 = .22$, $F(6, 286) = 13.032$, $p < .001$, same as in first grade. However, when including the numerical skills, the increase was 6%, $\Delta R^2 = .06$, $F_{change} = 10.856$, $p < .001$, bringing the total variance to 27%, $R^2 = .27$, $F(8, 284) = 13.162$, $p < .001$. The unique cognitive contributors (Block 1) were nonverbal logical reasoning (5%), general processing speed (4%), phonological awareness (1%), and RAN (1%).

Numerical skills showed a general overall decreasing trend across the three measurement points (Model 1, Block 1); however, it was an increasing trend for specifically DMC. Delta (Model 2, Block 2) showed an increase over the three years for the numerical predictors.

As for the general cognitive abilities (Model 2, Block 1), there was a decrease from kindergarten to first grade, and it stayed stable in second grade. The delta trajectory (Model 1, Block 2) for the cognitive abilities declined from kindergarten to first grade and then increased in second grade.

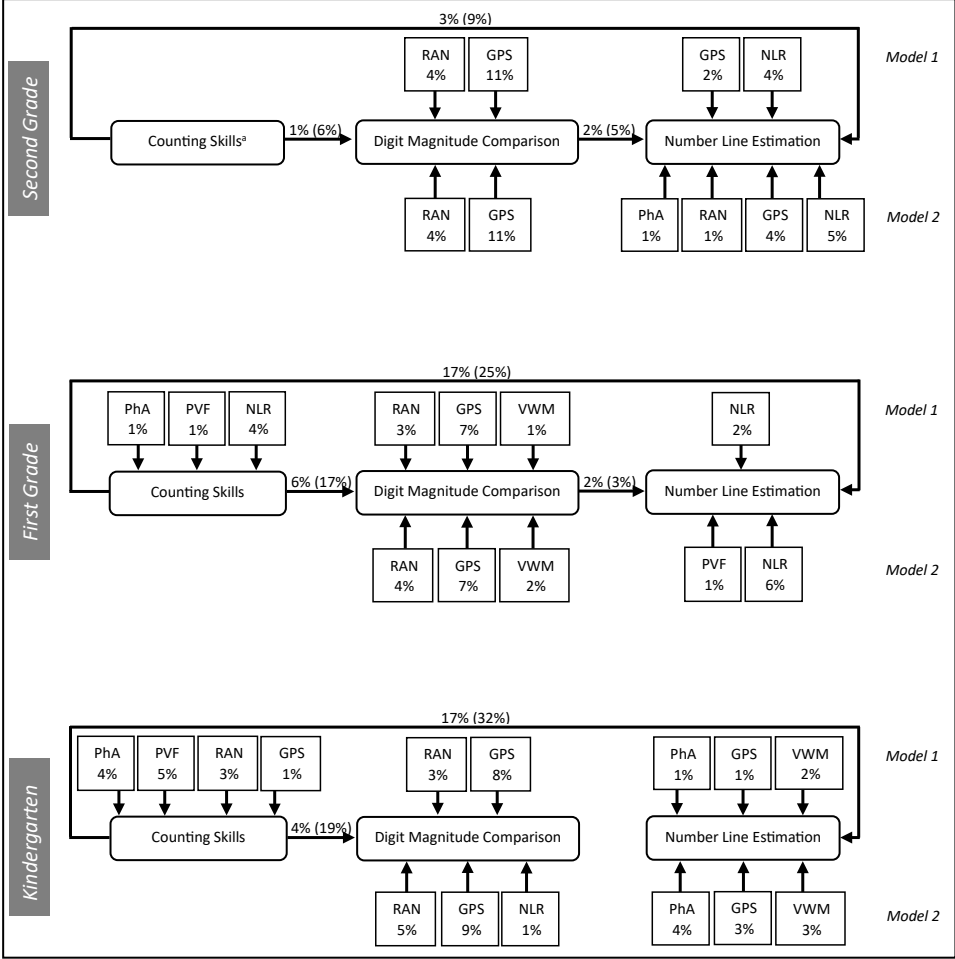
Discussion

The primary objective of this study was to examine the extent to which domain-general cognitive abilities and domain-specific abilities contribute to various aspects of number processing, and how these contributions may change from kindergarten to second grade. We utilized two theoretical frameworks: von Aster and Shalev's (2007) four-step-developmental model of numerical cognition, and Ackerman's (1988) general theory of skill acquisition as theoretical foundations.

For a simplified overview of the results see Table 5 (presenting overall explained variance and the unique variance [ΔR^2]) and Figure 1 (presenting unique contributions).

Figure 1

Hierarchical Regression of Cognitive Predictors' Unique Variance in Numerical Skill Development



Note. Significant predictors at three educational stages are shown. Model 1 includes both numerical (Block 1) and cognitive abilities (Block 2); Model 2 includes only cognitive abilities. The unique variance in parentheses is for when the variable stands alone in Model 1, Block 1. Abbreviations: PhA = Phonological Awareness; PVF = Phonological Verbal Fluency; RAN = Rapid Automated Naming; GPS = General Processing Speed; NLR = Nonverbal Logical Reasoning; VWM = Verbal Working Memory. Counting Skills^a is measured in 1st Grade.

Table 5

Simplified Overview of Results for Hypothesis 1 to 3

Grades	Counting skills	Digit Magnitude Comparison				Number Line Estimation			
	D-G cog. abilities	Model 1, Block 1	Model 1, Block 2	Model 2, Block 1	Model 2, Block 2	Model 1, Block 1	Model 1, Block 2	Model 2, Block 1	Model 2, Block 2
Kindergarten	$R^2 = .37$	$R^2 = .19$	$\Delta R^2 = .17$	$R^2 = .33$	$\Delta R^2 = .04$	$R^2 = .43$	$\Delta R^2 = .06$	$R^2 = .31$	$\Delta R^2 = .19$
1 st grade	$R^2 = .23$	$R^2 = .18$	$\Delta R^2 = .17$	$R^2 = .28$	$\Delta R^2 = .06$	$R^2 = .42$	$\Delta R^2 = .03$	$R^2 = .22$	$\Delta R^2 = .24$
2 nd grade		$R^2 = .06$	$\Delta R^2 = .23$	$R^2 = .28$	$\Delta R^2 = .01$	$R^2 = .19$	$\Delta R^2 = .08$	$R^2 = .22$	$\Delta R^2 = .06$

Note. This Table presents overall cognitive support from Table 2, 3, and 4, for easier tracking of our results when explaining the 3 hypotheses (H1, H2, H3). H1 compares numerical skills, with a focus on Model 1, Block 1, and delta (R^2) in Model 2, Block 2. H2 compares overall cognitive support when learning numerical skills, i.e., Step 2, Step 3, and Step 4 in von Aster and Shalev’s (2007) model, with focus on Model 2, Block 1. H3 compares each numerical skill over time, focusing on Model 1, Block 2 and Model 2, Block 1 including unique contributions as presented in Figure 1. For counting skills, only D-G cog. abilities (domain-general cognitive abilities) are presented.

Prior Early-Developed Number Skills Provide Support for Later-Acquired Ones

Our findings partly support the first hypothesis (H1) proposing that prior early-developed number skills support later-acquired ones, aligning with von Aster and Shalev’s (2007) model. For example, in kindergarten, counting skills predict DMC and NLE (Figure 1, Model 1). However, DMC does not predict NLE in our sample in kindergarten and therefore does not support H1. In first and second grade, our results indicate that counting skills continue to predict DMC and NLE (Figure 1, Model 1), supporting H1, although their unique contribution diminishes in second grade. DMC becomes a significant predictor for NLE and therefore supports H1 and the unique contribution increases from first to second grade.

Kindergarten

Meloni et al. (2023) studied 5-year-olds before formal schooling and found that semantic number knowledge predicts NLE. These findings diverge from our results; however, it is important to note that their variable included not only digit magnitude comparison tasks but also a digit linear order task, leading to an assessment of both cardinality and ordinality. Our variable, counting skills, only include the child’s ability to count.

Gelman and Gallistel’s (1978) counting principles might give one possible explanation for the present non-significant relationship between DMC and NLE. Specifically, children in kindergarten may still be consolidating their understanding of the stable-order principle, one-to-one correspondence, and the cardinality principle, which form the foundation of counting and sequence understanding. In von Aster and Shalev’s (2007) model, Step 2,

they showed that in kindergarten children are still using verbal strategies for counting without necessarily understanding the quantitative relationship between them. These skills are important for understanding the symbolic number system (Dehaene, 1992; Dresen et al., 2022; LeFevre et al., 2010). This is probably the reason why counting skills predicts NLE. While cardinality is fundamental, its influence on NLE may be less direct during early development, as successful number line placement requires children to map not only their relative order onto a spatial representation but also their quantities.

Our findings suggest that skills leaning more on the ordinality-related aspect (i.e., counting skills) are more predictive of NLE in kindergarten, whereas cardinality-related skills play a more prominent role in later stages of numerical development when children have a more robust understanding of numerical relations. This aligns with Booth and Siegler's (2006) findings that a robust foundational understanding of various basic number skills, including counting, recognizing Arabic numerals, estimating numerosity, and understanding ordinality, is needed for placing a number correctly on a number line. This reasoning and these findings are in support of the H1 and with von Aster and Shalev's (2007) model, suggesting that early skills like counting support skills like DMC.

First Grade and Second Grade

Digit Magnitude Comparison (DMC) — There is a general declining trend in the explained overall variance by counting skills over time (Table 5, Model 1, Block 1). This suggests that while earlier numerical skills are significant predictors, their explained power decreases as other (possibly cognitive) factors gain influence. In the reversed model (Table 5, Model 2, Block 2), results (ΔR^2) show a 2% increase in variance explained from kindergarten to first grade, but a 5% decrease from first to second grade. These results indicate that while the importance of numerical skills diminishes overall, first grade marks an important period where children adopt more effective numerical strategies, likely due to the introduction of formal education.

DMC becomes a significant predictor of NLE in first grade (Figure 1, Model 1) and increases its unique variance in second grade (Figure 1, Model 1). This indicates that abilities leaning heavier on cardinality gain importance at this stage of development, as von Aster and Shalev's (2007) model shows in Step 3, where the understanding of written symbols and their quantities increase. These findings support H1, aligning with Booth and Siegler (2006) and von Aster and Shalev's proposition that early developed skills, such as counting, provide a foundation for later-acquired skills like DMC. The change in relative predictive strength concerning counting and DMC reflects a developmental shift from reliance on immature strategies, such as verbal counting, to a more integrated understanding of cardinality and ordinality.

Number Line Estimation (NLE) — As for NLE, the trends are distinct. In Model 1, Block 1 (Table 5), a declining trend is observed in the overall variance explained by

counting skills and DMC. However, in the reversed model (Table 5, Model 2, Block 2), the unique variance (ΔR^2) increases steadily across the years indicating that when controlling for cognitive abilities in Block 1, the unique contribution of counting skills and DMC (in Block 2) becomes increasingly apparent. This pattern suggests that as children grow older, numerical skills play a more distinct role in tasks like NLE, possibly due to their integration into more advanced numerical strategies. Furthermore, the increasing delta (ΔR^2) highlights how counting skills and DMC complement cognitive abilities, especially as NLE requires greater precision and an understanding of numerical relationships.

H1 in Relation to the Findings

In summary, while there is a declining trend for earlier acquired numerical skills in later acquired numerical skills, this still supports H1. The results indicate that early numerical skills are foundational, but their influence evolves as children receive formal education and develop more complex numerical strategies. Interestingly, in kindergarten the combined cardinality- and ordinality aspect of numerical ability is significant, not the purer cardinality aspect, in NLE.

In the [Supplementary Materials](#), we provide additional regression analyses for a deeper understanding of the developmental trajectories and potential bidirectional relationships between counting skills, DMC, and NLE. These analyses support H1, illustrating that early-developed number skills significantly contribute to later-acquired skills, with both unidirectional and bidirectional influences aligning with [von Aster and Shalev's \(2007\)](#) four-step-developmental model of numerical cognition.

Domain-General Cognitive Abilities Unevenly Predict Number Processing Skills

Our findings partly support the second hypothesis (H2), which states that later-acquired number skills, such as NLE tasks, require more domain-cognitive support during the learning process than earlier-acquired number skills like counting and symbolic number magnitude comparison. We examined how the overall explained variance of general cognitive abilities predicts each numerical skill and whether cognitive support increases with the complexity of the numerical skill (Table 5). For instance, the overall domain-general cognitive abilities' explanatory variance declines in counting skills from kindergarten to first grade, and for DMC and NLE the cognitive abilities also decline from kindergarten to first grade but stagnate to second grade. This aligns with H2. However, the unique variance (ΔR^2 , Table 5, Model 1, Block 2) shows a different trend and therefore only partly aligning with H2.

Kindergarten

In kindergarten (Table 5, Model 2, Block 1), the domain-general cognitive abilities accounted for 37%, 33%, and 31% of the variance in counting skills, DMC, and NLE, respectively. The unique variance (ΔR^2 , Table 5, Model 1, Block 2) in DMC was 17%, and the more complex numerical skill, according to von Aster and Shalev's (2007) model, NLE, showed $\Delta R^2 = 6\%$. These results do not support H2. However, it is possible that skills like counting knowledge could overlap with some of the cognitive support, indicating that as children develop, some cognitive abilities might be tied to specific numerical skills. For instance, counting requires an understanding of numerical order and magnitude, but also memory and attention to track and maintain progress.

First Grade and Second Grade

In first grade (Table 5, Model 2, Block 1), the corresponding accounted variances were 23% (counting skills), 28% (DMC), and 22% (NLE). When considering the unique variance (ΔR^2 , Table 5, Model 1, Block 2) it was 17% for DMC and 3% for NLE. In second grade, the accounted variance (Table 5, Model 2, Block 1) were 28% (DMC) and 22% (NLE), and the unique variance (ΔR^2 , Table 5, Model 1, Block 2) accounted for by the domain-general cognitive abilities was 23% for DMC and 8% for NLE.

When comparing the results from kindergarten to second grade, our results do not support H2. Later-acquired number skills require less cognitive support than earlier acquired number skills. It is possible that as the children reach second grade, they have acquired full understanding of the five principles (Gelman & Gallistel, 1978) and no longer need equal cognitive support as in kindergarten or first grade, but rather the skill could have become more automatic.

H2 in Relation to the Findings

In summary, our results indicate that the overall explained variance of domain-general cognitive abilities decreases for each more demanding numerical skills in kindergarten, first grade, and second grade. These findings contradict H2, which suggests that more advanced numerical skills require more cognitive support, as proposed by von Aster and Shalev (2007). Even though cognitive support decreased, our results indicate that domain-general cognitive abilities are still important in acquiring numerical skills.

The Importance of Domain-General Cognitive Abilities Diminishes Over Time

Based on Ackerman's theory of skill acquisition (1988), the third hypothesis (H3) suggests that the importance of general cognitive abilities diminishes over time as children become more adept at various numerical abilities. This theory posits that as number processing abilities become more automated; they require less cognitive resources.

Furthermore, initially, higher-order cognitive abilities such as working memory (WM) and logical reasoning are important; however, as proficiency increases, reliance shifts towards lower-order skills like processing speed and RAN. In this section, we will discuss how and to what extent different general cognitive ability supports the individual numerical skills over time, and how this pattern of important cognitive abilities changes over time.

Unlike H2, which suggests that more general cognitive abilities are needed when learning new complex skills, H3 focuses on the reduction of cognitive effort as proficiency increases. H3 emphasizes decreasing reliance on domain-general cognitive abilities as skills become automated.

Counting Skills

The overall cognitive support declines from kindergarten to first grade in counting skills (Table 5), suggesting that as children gain proficiency in counting skills less cognitive support is needed. This indicates that, aligning with H3, the skill becomes more automated.

In kindergarten, phonological awareness and verbal fluency, RAN, and general processing speed are significant unique contributors in counting skills (Figure 1), suggesting that these general cognitive abilities are important as children learn early numerical concepts. They can recite numbers but may not fully understand the five principles of counting (Gelman & Gallistel, 1978). However, our results did not align with prior research indicating that WM is important in counting skills (e.g., Koponen et al., 2018; Krajewski & Schneider, 2009; Passolunghi et al., 2015). This discrepancy may be due to our use of verbal WM as, while others have used e.g. visuospatial WM. It could also be that the children have already passed that developmental stage when verbal WM might have been more important than when they first learn, for instance, rote counting.

In first grade, phonological awareness and verbal fluency remain significant predictors of counting skills, albeit with reduced effect. This outcome supports H3, positing that the influence of these skills diminishes over time. The emergence of nonverbal logical reasoning as a significant predictor is more complex to explain. However, this can also be interpreted through Ackerman's theory, suggesting that as children receive formal education, they revisit the cognitive phase described by Ackerman (1988). This implies that a higher cognitive load from nonverbal logical reasoning is expected in first grade as children begin to grasp counting concepts, such as the five principles (Gelman & Gallistel, 1978). Our results also align with Cirino (2011) who found that phonological awareness is important for naming and identifying numerical symbols, while Passolunghi et al. (2015) identified same cognitive ability as predictor in counting sequences and magnitude comparisons.

Digit Magnitude Comparison (DMC)

The overall cognitive support (Table 5, Model 2, Block 1) for DMC declined from kindergarten to first grade and then stabilized in second grade. This pattern supports H3, indicating less cognitive support is needed as children's skills become more automated. When observing the results in Table 5, Model 1, Block 2, the unique variance (ΔR^2) increases over time. This increase suggests that the contribution of general cognitive abilities in DMC becomes more pronounced over time, which is contrary to what H3 predicts. According to H3, we would expect the reliance on general cognitive abilities to decrease as children become more proficient and their skills become more automated. To explain this further we look at the unique contributions in each year for DMC.

In kindergarten, RAN, general processing speed, and nonverbal logical reasoning are significant contributors (Figure 1). Interestingly, the role of logical reasoning suggests that informal counting knowledge learned before kindergarten is the foundation from which they either: a) use logical thinking in performing a DMC, or b) logical thinking is more indirectly involved through the learning process of the cardinality principle. This in turn enhances the performance of DMC.

In first grade, RAN and general processing speed remain significant predictors of DMC. These predictors are supplemented by verbal WM, whereas nonverbal logical reasoning is no longer significant (Figure 1). This developmental change could reflect a change in cognitive strategies, aligning with the start of formal education. The reduced influence of processing speed partly supports H3. The emergence of verbal WM mirrors Cirino's (2011) findings, indicating that verbal WM is important for magnitude comparison. An increased reliance on verbal WM may also mirror Ackerman's (1988) cognitive phase, where children rely on higher-order cognitive processes to integrate and apply learned concepts. Given that having more developed counting skills entails having a (basic) conceptual understanding of relationships between digits and their numerical magnitudes, it may be the case that children—at this stage—increasingly rely on verbal WM to represent numerical information and retrieve relevant numerical facts (e.g., $4 > 2$ and the count-list) from long-term memory. This, together with an increased reliance on developing counting skills, could explain why nonverbal logical reasoning no longer is a significant predictor of DMC as children learn to rely on already established numerical facts for comparison purposes.

In second grade, RAN and general processing speed remained significant predictors, regardless of with no difference observed whether counting skills are included or not (Figure 1). This stage aligns with Ackerman's (1988) associative or autonomous phase, where DMC entails less cognitive demand.

Our results align with prior research indicating that phonological processes, cognitive processing speed, nonverbal logical reasoning, and WM (Passolunghi et al., 2015) are important domain-general cognitive abilities in DMC performance.

Number Line Estimation (NLE)

The overall cognitive support (Table 5, Model 2, Block 1) showed a declining trend from kindergarten to first grade but stagnated in second grade. This partially supports H3. However, the unique variance (ΔR^2 , Model 1, Block 2) shows varying results. From kindergarten to first grade there is a decline from 6% to 3%, but an increase to 8% in second grade. This trajectory partially supports H3 and Ackerman's theory. For clearer understanding we need to study the unique contribution of each significant general cognitive ability.

In kindergarten, phonological awareness, general processing speed, and verbal WM are significant contributors in NLE (Figure 1). Even if counting skills and DMC are included, the same three general cognitive abilities are significant, though with reduced effect sizes. The significance of phonological awareness aligns with findings by Cirino (2011), who showed that children with stronger phonological skills performed better on symbolic tasks requiring number recognition and sequencing. Furthermore, it is no surprise that at least one of the processing speed tasks (general processing speed) is significant since the task was to perform as quickly as possible. Geary (2011) found that RAN enabled children to perform counting and NLE tasks more efficiently. In our results we found that RAN was significant in counting and DMC but not in NLE, at least not in kindergarten and first grade. The reason for this might be that children in kindergarten have not yet received formal education, i.e., not fully internalized Gelman and Gallistel's (1978) five counting principles. Verbal WM is a predictor for NLE in kindergarten, suggesting that the counting knowledge children had prior to school is used as foundation from which the children use verbal WM to hold and manipulate information in their minds, facilitating accurate placement of numbers on the number line. This aligns with Passolunghi et al.'s (2015) findings that WM is important for early numerical skills, as it helps children keep track of multiple pieces of information simultaneously.

In first grade, new domain-general cognitive abilities became significant: phonological verbal fluency and nonverbal logical reasoning, and with only nonverbal logical reasoning remaining significant when counting and DMC are included (Figure 1). This could suggest that prior unique contributions from verbal abilities, in earlier development, are subsumed by more developed (verbally dependent) counting and DMC skills. Nonverbal logical reasoning may instead tap into visuospatial abilities (read limitations below), which could indicate that children also learn to integrate spatial cues in number line estimation. This suggests that children partly re-enter cognitive phase of Ackerman's (1988) theory to learn new strategies and to better understand the five principles of counting (Gelman & Gallistel, 1978). Our results partially support H3, showing a decline in less demanding cognitive support like phonological awareness and general processing speed.

In second grade, phonological awareness, RAN, general processing speed, and nonverbal logical reasoning are significant (Figure 1) when no numerical skills are included

in the model. Nonverbal logical reasoning remains significant from first grade in NLE performance, suggesting that logical thinking has an ongoing role in applying logical principles as children's numerical skills become more sophisticated. This corroborates findings from [Koponen et al. \(2018\)](#) indicating that nonverbal logical reasoning is associated with NLE performance. The re-emerging of general processing speed suggests its continued importance in quickly processing numerical information as children advance in their skills.

When earlier-developed numerical skills are included in the model for NLE, only general processing speed and nonverbal logical reasoning remain significant ([Figure 1](#)). This suggests that phonological awareness and RAN overlap with the variance explained by earlier-developed numerical skills, while general processing speed and nonverbal logical reasoning remain important for efficient and accurate task performance as children better understand numerical concepts.

H3 in Relation to the Findings

Overall, these results indicate a dynamic interplay between different general cognitive abilities as children develop their numerical skills. While some abilities become less significant, others emerge or re-emerge to support the increasing complexity of numerical tasks. This nuanced pattern of cognitive support partly aligns with H3, showing that while the overall reliance on cognitive abilities may not decrease uniformly, the specific contributions of different general cognitive abilities evolve as children's proficiency increases.

Theoretical Implications

In summary, counting skills in kindergarten appear to reflect the associative or even the automatic phase described by [Ackerman \(1988\)](#). At this stage, children have started to learn rote counting, but they still struggle to fully grasp numerical concepts. As children go from counting skills to understanding the cardinal aspect of number concepts, supporting DMC, nonverbal logical reasoning becomes a small contributor alongside processing speed. Regarding NLE performance, our findings indicate associations with both foundational cognitive skills (e.g., phonological processes, processing speed) and higher-order abilities such as verbal WM.

At the onset of formal schooling, in first grade, children may start thinking more logically and move beyond the rote counting they previously learned, working instead to understand the five counting principles outlined by [Gelman and Gallistel \(1978\)](#). Here, logical thinking becomes more prominent, although phonological processes and processing speed are still present. Verbal WM also shifts and becomes significant in first grade as evident in DMC, possibly reflecting increased cognitive demands associated with learning the counting principles. It appears that numerical knowledge is intertwined with general cognitive abilities, meaning that improvements in one area can positively

influence another area. For instance, numerical knowledge, relies on various cognitive processes, including memory, attention, logical reasoning etc. For example, to count accurately, a child must remember the sequence of numbers (memory), focus on the counting task (attention), and understand the concept of quantity (logical reasoning).

By second grade, counting tasks become too simple, indicating that children have mastered rote counting to the extent that results on these tasks would likely reach a ceiling effect. In DMC, only processing speed remains significant, suggesting that children have acquired cardinality knowledge. In NLE, logical thinking is present, along with phonological awareness, RAN, and general processing speed. When numerical knowledge (counting and DMC) is included in hierarchical regression analysis, only general processing speed and nonverbal logical reasoning remain significant. Thus, it seems that second graders have a good grasp of the five counting principles, and the development of counting, DMC, and NLE may occur more simultaneously than von Aster and Shalev's model suggests. It may be that as children learn ordinality and cardinality, they also develop an understanding of NLE, as in overlapping waves and not in distinct steps (cf. Siegler, 1996).

One limitation in our study is the general processing speed task we used. Although it measures processing speed, we utilized a symbolic number task, which could impact on the results as it inherently involves numerical skills. Specifically, the task required participants to quickly identify and strike through duplicate digits. This process does not only measure the general processing speed but also engages numerical recognition and comparison skills, potentially confounding the results. Another limitation of this study is the lack of a measure of visuospatial ability (e.g., visuospatial working-memory, mental rotation), which would allow us to further parse out the unique contribution of intelligence.

Conclusion

Our findings illustrate the diverse ways in which domain-general cognitive abilities predict numerical skills. These contributions vary not only across different numerical domains but also change over time. Our approach clarifies the relationship between domain-specific numerical abilities and domain-general cognitive abilities. We suggest that von Aster and Shalev's (2007) model and Ackerman's (1988) theory can complement each other by explaining different aspects of cognitive development in numerical skills. While von Aster and Shalev's model highlights the importance of general cognitive abilities at different stages, Ackerman's theory provides insight into how these abilities evolve and become automated over time. This complementary relationship enhances our understanding of the dynamic nature of cognitive development in early numerical skills. We also observed that early numerical skills support the development of later and more complex numerical skills, aligning with prior research.

These findings could be considered when developing individualized mathematical support for children. However, further research is necessary to fully determine which general cognitive abilities should be targeted in training to support children as they learn mathematical skills. Future research should also employ other types of analyses such as Structural Equation Modeling, to enhance our understanding of development of numerical skills.

Funding: This research was supported by a grant from the Swedish Council for Working Life and Social Research (2008-0238) and a grant from the Swedish Research Council (2020-03220), both awarded to Dr. Ulf Träff. The funders did not influence the study design, data collection or the analysis, the decision to publish, or the preparation of the manuscript.

Acknowledgments: The authors have no additional (i.e., non-financial) support to report.

Competing Interests: The authors have declared that no competing interests exist.

Data Availability: All data files (including the dataset and codebook) and supplementary materials are openly available (see [Karlsson et al., 2026S-a](#), [2026S-b](#)).

Supplementary Materials

The Supplementary Materials consist of the following files:

- **Research Data and Codebook (Karlsson et al., 2026S-a):**
 - *Dataset (CSV):* Full longitudinal dataset including demographics (age, gender, handedness), domain-specific numerical skills (Counting Skills, Digit Magnitude Comparison, Number Line Estimation), and domain-general cognitive abilities (Phonological Awareness, Phonological Verbal Fluency, RAN, General Processing Speed, Nonverbal Logical Reasoning, Verbal Working Memory) measured at three time points (Kindergarten, 1st Grade, 2nd Grade).
 - *Codebook (PDF):* Variable definitions, coding schemes, labels, measurement-year mapping, and notes on transformations (e.g., inverted timing/efficiency, $NLE = 100 - PAE$).
- **Additional Materials (Karlsson et al., 2026S-b):**
 - *Appendix A:* Descriptive statistics and Pearson correlation for all domain-general and domain-specific variables across the three measurement points (kindergarten, first grade, second grade).
 - *Appendix B:* Homoscedasticity and linearity plots for all regression analyses reported in the manuscript. These figures are directly exported from SPSS to ensure full transparency.
 - *Supplementary Material:* Additional hierarchical regression analyses conducted to address reviewer comments regarding Hypothesis 1. Includes extended models examining unidirectional and bidirectional relationships among Counting Skills, Digit Magnitude Comparison, and Number Line Estimation, as well as expanded domain-specific predictor sets.

Index of Supplementary Materials

Karlsson, A. M. C., Skagerlund, K., Skagenholt, M., & Träff, U. (2026S-a). *Supplementary materials to "Exploring cognitive predictors: Examining varied impact on early number skills in a longitudinal study"* [Research data and codebook]. PsychOpen GOLD.
<https://doi.org/10.23668/psycharchives.21747>

Karlsson, A. M. C., Skagerlund, K., Skagenholt, M., & Träff, U. (2026S-b). *Supplementary materials to "Exploring cognitive predictors: Examining varied impact on early number skills in a longitudinal study"* [Additional materials]. PsychOpen GOLD. <https://doi.org/10.23668/psycharchives.21748>

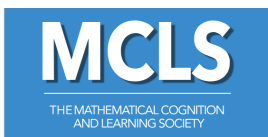
References

- Ackerman, P. L. (1988). Determinants of individual differences during skill acquisition: Cognitive abilities and information processing. *Journal of Experimental Psychology: General*, *117*(3), 288–318. <https://doi.org/10.1037/0096-3445.117.3.288>
- Ackerman, P. L. (2007). New developments in understanding skilled performance. *Current Directions in Psychological Science*, *16*(5), 235–239. <https://doi.org/10.1111/j.1467-8721.2007.00511.x>
- American Psychiatric Association (Ed.). (1994). *Diagnostic and statistical manual of mental disorders: DSM-IV* (4th ed.). American Psychiatric Publishing.
- Andersson, U., & Lyxell, B. (2007). Working memory deficit in children with mathematical difficulties: A general or specific deficit? *Journal of Experimental Child Psychology*, *96*(3), 197–228. <https://doi.org/10.1016/j.jecp.2006.10.001>
- Andersson, U., & Östergren, R. (2012). Number magnitude processing and basic cognitive functions in children with mathematical learning disabilities. *Learning and Individual Differences*, *22*(6), 701–714. <https://doi.org/10.1016/j.lindif.2012.05.004>
- Andersson, U. (2008). Working memory as a predictor of written arithmetical skills in children: The importance of central executive functions. *British Journal of Educational Psychology*, *78*(2), 181–203. <https://doi.org/10.1348/000709907X209854>
- Baddeley, A. D., Thomson, N., & Buchanan, M. (1975). Word length and the structure of short-term memory. *Journal of Verbal Learning and Verbal Behavior*, *14*(6), 575–589. [https://doi.org/10.1016/S0022-5371\(75\)80045-4](https://doi.org/10.1016/S0022-5371(75)80045-4)
- Booth, J. L., & Siegler, R. S. (2006). Developmental and individual differences in pure numerical estimation. *Developmental Psychology*, *42*(1), 189–201. <https://doi.org/10.1037/0012-1649.41.6.189>
- Carey, S. (2004). Bootstrapping and the origin of concepts. *Daedalus*, *133*(1), 59–68. <https://doi.org/10.1162/001152604772746701>
- Cirino, P. T. (2011). The interrelationships of mathematical precursors in kindergarten. *Journal of Experimental Child Psychology*, *108*(4), 713–733. <https://doi.org/10.1016/j.jecp.2010.11.004>
- Cohen, J. (1988). *Statistical power analysis for the behavioral sciences* (2nd ed.). Routledge. <https://doi.org/10.4324/9780203771587>

- Daker, R. J., & Lyons, I. M. (2018). Numerical and non-numerical predictors of first graders' number-line estimation ability. *Frontiers in Psychology, 9*, Article 2336. <https://doi.org/10.3389/fpsyg.2018.02336>
- Dehaene, S. (1992). Varieties of numerical abilities. *Cognition, 44*(1–2), 1–42. [https://doi.org/10.1016/0010-0277\(92\)90049-N](https://doi.org/10.1016/0010-0277(92)90049-N)
- Dresen, V., Moeller, K., & Pixner, S. (2022). Association between language and early numerical development – The case of quantifiers. *European Journal of Developmental Psychology, 19*(4), 477–493. <https://doi.org/10.1080/17405629.2021.1916463>
- Duncan, G. J., Dowsett, C. J., Claessens, A., Magnuson, K., Huston, A. C., Klebanov, P., Pagani, L. S., Feinstein, L., Engel, M., Brooks-Gunn, J., Sexton, H., Duckworth, K., & Japel, C. (2007). School readiness and later achievement. *Developmental Psychology, 43*(6), 1428–1446. <https://doi.org/10.1037/0012-1649.43.6.1428>
- Field, A. (2018). *Discovering statistics using IBM SPSS statistics* (5th ed.). SAGE.
- Fuchs, L. S., Geary, D. C., Compton, D. L., Fuchs, D., Hamlett, C. L., Seethaler, P. M., Bryant, J. D., & Schatschneider, C. (2010). Do different types of school mathematics development depend on different constellations of numerical versus general cognitive abilities? *Developmental Psychology, 46*(6), 1731–1746. <https://doi.org/10.1037/a0020662>
- Geary, D. C. (2011). Cognitive predictors of achievement growth in mathematics: A 5-year longitudinal study. *Developmental Psychology, 47*(6), 1539–1552. <https://doi.org/10.1037/a0025510>
- Geary, D. C. (2013). Early foundations for mathematics learning and their relations to learning disabilities. *Current Directions in Psychological Science, 22*(1), 23–27. <https://doi.org/10.1177/0963721412469398>
- Geary, D. C., Nicholas, A., Li, Y., & Sun, J. (2017). Developmental change in the influence of domain-general abilities and domain-specific knowledge on mathematics achievement: An eight-year longitudinal study. *Journal of Educational Psychology, 109*(5), 680–693. <https://doi.org/10.1037/edu0000159>
- Geary, D. C., & vanMarle, K. (2018). Growth of symbolic number knowledge accelerates after children understand cardinality. *Cognition, 177*, 69–78. <https://doi.org/10.1016/j.cognition.2018.04.002>
- Gelman, R., & Gallistel, C. R. (1978). *The child's understanding of number*. Harvard University Press.
- Hirsch, S., Lambert, K., Coppens, K., & Moeller, K. (2018). Basic numerical competences in large-scale assessment data: Structure and long-term relevance. *Journal of Experimental Child Psychology, 167*, 32–48. <https://doi.org/10.1016/j.jecp.2017.09.015>
- Jordan, N. C., Kaplan, D., Ramineni, C., & Locuniak, M. N. (2009). Early math matters: Kindergarten number competence and later mathematics outcomes. *Developmental Psychology, 45*(3), 850–867. <https://doi.org/10.1037/a0014939>
- Kilpatrick, J., Swafford, J., Findell, B., & National Research Council (U.S.) (Eds.). (2001). *Adding it up: Helping children learn mathematics*. National Academy Press.

- Kline, R. B. (2016). *Principles and practice of structural equation modeling* (4th ed.). The Guilford Press.
- Koponen, T., Eklund, K., & Salmi, P. (2018). Cognitive predictors of counting skills. *Journal of Numerical Cognition*, 4(2), 410–428. <https://doi.org/10.5964/jnc.v4i2.116>
- Krajewski, K., & Schneider, W. (2009). Early development of quantity to number-word linkage as a precursor of mathematical school achievement and mathematical difficulties: Findings from a four-year longitudinal study. *Learning and Instruction*, 19(6), 513–526. <https://doi.org/10.1016/j.learninstruc.2008.10.002>
- LeFevre, J.-A., Fast, L., Skwarchuk, S.-L., Smith-Chant, B. L., Bisanz, J., Kamawar, D., & Penner-Wilger, M. (2010). Pathways to mathematics: Longitudinal predictors of performance. *Child Development*, 81(6), 1753–1767. <https://doi.org/10.1111/j.1467-8624.2010.01508.x>
- Locuniak, M. N., & Jordan, N. C. (2008). Using kindergarten number sense to predict calculation fluency in second grade. *Journal of Learning Disabilities*, 41(5), 451–459. <https://doi.org/10.1177/0022219408321126>
- McCrae, R. R., Kurtz, J. E., Yamagata, S., & Terracciano, A. (2011). Internal consistency, retest reliability, and their implications for personality scale validity. *Personality and Social Psychology Review*, 15(1), 28–50. <https://doi.org/10.1177/1088868310366253>
- Meloni, C., Delogu, F., & Fanari, R. (2023). Symbolic and non-symbolic predictors of number line task in Italian kindergarteners. *Frontiers in Psychology*, 14, Article 1137607. <https://doi.org/10.3389/fpsyg.2023.1137607>
- Núñez, R. E. (2017). Is there really an evolved capacity for number? *Trends in Cognitive Sciences*, 21(6), 409–424. <https://doi.org/10.1016/j.tics.2017.03.005>
- Östergren, R., & Träff, U. (2013). Early number knowledge and cognitive ability affect early arithmetic ability. *Journal of Experimental Child Psychology*, 115(3), 405–421. <https://doi.org/10.1016/j.jecp.2013.03.007>
- Passolunghi, M. C., Lanfranchi, S., Altoè, G., & Sollazzo, N. (2015). Early numerical abilities and cognitive skills in kindergarten children. *Journal of Experimental Child Psychology*, 135, 25–42. <https://doi.org/10.1016/j.jecp.2015.02.001>
- Qi, Y., Chen, Y., Yang, X., & Hao, Y. (2023). How does working memory matter in young children's arithmetic skills: The mediating role of basic number processing. *Current Psychology*, 42(21), 18150–18162. <https://doi.org/10.1007/s12144-022-02998-z>
- Sarnecka, B. W., Negen, J., Scalise, N. R., Goldman, M. C., & Rouder, J. N. (2023). The real preschoolers of Orange County: Early number learning in a diverse group of children. *Journal of Numerical Cognition*, 9(1), 65–88. <https://doi.org/10.5964/jnc.6577>
- Sasanguie, D., & Vos, H. (2018). About why there is a shift from cardinal to ordinal processing in the association with arithmetic between first and second grade. *Developmental Science*, 21(5), Article e12653. <https://doi.org/10.1111/desc.12653>
- Scalise, N. R., & Ramani, G. B. (2021). Symbolic magnitude understanding predicts preschoolers' later addition skills. *Journal of Cognition and Development*, 22(2), 185–202. <https://doi.org/10.1080/15248372.2021.1888732>

- Siegler, R. S. (1996). *Emerging minds: The process of change in children's thinking*. Oxford University Press. <https://doi.org/10.1093/oso/9780195077872.001.0001>
- Siegler, R. S., & Booth, J. L. (2004). Development of numerical estimation in young children. *Child Development*, 75(2), 428–444. <https://doi.org/10.1111/j.1467-8624.2004.00684.x>
- Siegler, R. S., & Braithwaite, D. W. (2017). Numerical development. *Annual Review of Psychology*, 68(1), 187–213. <https://doi.org/10.1146/annurev-psych-010416-044101>
- Sweller, J. (1988). Cognitive load during problem solving: Effects on learning. *Cognitive Science*, 12(2), 257–285. https://doi.org/10.1207/s15516709cog1202_4
- Taube, K., Tornéus, M., & Lundberg, I. (1984). *UMESOL: Umeå skriv- och läsmaterial för lågstadiet*. Psykologiförl.
- Tobia, V., Bonifacci, P., & Marzocchi, G. M. (2021). Symbolic versus non-symbolic training for improving early numeracy in preschoolers at risk of developing difficulties in mathematics. *Research in Developmental Disabilities*, 111, Article 103893. <https://doi.org/10.1016/j.ridd.2021.103893>
- Träff, U., Olsson, L., Östergren, R., & Skagerlund, K. (2020). Development of early domain-specific and domain-general cognitive precursors of high and low math achievers in Grade 6. *Child Neuropsychology*, 26(8), 1065–1090. <https://doi.org/10.1080/09297049.2020.1739259>
- Träff, U., Skagerlund, K., Olsson, L., & Östergren, R. (2017). Pathways to arithmetic fact retrieval and percentage calculation in adolescents. *British Journal of Educational Psychology*, 87(4), 647–663. <https://doi.org/10.1111/bjep.12170>
- von Aster, M. (2000). Developmental cognitive neuropsychology of number processing and calculation: Varieties of developmental dyscalculia. *European Child & Adolescent Psychiatry*, 9(2), S41–S57. <https://doi.org/10.1007/s007870070008>
- von Aster, M. G., & Shalev, R. S. (2007). Number development and developmental dyscalculia. *Developmental Medicine and Child Neurology*, 49(11), 868–873. <https://doi.org/10.1111/j.1469-8749.2007.00868.x>
- Wagner, R. K., & Torgesen, J. K. (1987). The nature of phonological processing and its causal role in the acquisition of reading skills. *Psychological Bulletin*, 101(2), 192–212. <https://doi.org/10.1037/0033-2909.101.2.192>
- Wechsler, D. (2003). *WISC-IV: Wechsler Intelligence Scale for Children* (4th ed). NCS Pearson, Inc.: PsychCorp.
- World Health Organization (Ed.). (1992). *The ICD-10 classification of mental and behavioural disorders: Clinical descriptions and diagnostic guidelines*. World Health Organization.
- Xu, F., Spelke, E. S., & Goddard, S. (2005). Number sense in human infants. *Developmental Science*, 8(1), 88–101. <https://doi.org/10.1111/j.1467-7687.2005.00395.x>



Journal of Numerical Cognition (JNC)
is the official journal of the
Mathematical Cognition and Learning
Society (MCLS).



Leibniz-Institut für
Psychologie

PsychOpen GOLD is a publishing
service provided by the Leibniz
Institute for Psychology (ZPID),
Germany.