

Predicting mathematical abilities from early mathematics and number-specific executive functions in informal and formal schooling

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Abstract

Background Current evidence on an integrative role of the domain-specific early mathematical skills and domain-general executive functions (EFs) from informal to formal schooling and their effect on mathematical abilities is so far unclear. The main objectives of this study were to (i) compare the domain-specific early mathematics, the number-specific EFs, and the mathematical abilities between preschool and primary school children, and (ii) examine the relationship among the domain-specific early mathematics, the number-specific EFs, and the mathematics abilities among preschool and primary school children.

Methods In the present study, we recruited six- and seven-year-old children ($N_{\text{total}}=505$, $n_{6\text{yrs}}=238$, and $n_{7\text{yrs}}=267$). We compared domain-specific early mathematics as measured by symbolic and non-symbolic tasks, number-specific EFs tasks, and mathematics tasks between these preschool and primary school children. In addition, we tested the predictive power of domain-specific numerical and number-specific EFs on mathematics abilities among preschool and primary school children. MANOVA and Structural Equation Modeling (SEM) were used to test research hypotheses.

Results We found that primary school children were superior to preschool children over more complex tests of the domain-specific early mathematics, the number-specific EFs, the mathematics abilities, particularly, for more sophisticated numerical knowledge and the number-specific EFs components. The SEM revealed that both the domain-specific early numerical and the number-specific EFs could predict the mathematics abilities across age groups. Nevertheless, the number comparison test and mental number line of the domain-specific early mathematics were clearly pronounced in predicting the mathematics abilities for formal school children. These results highlight the benefits of both the domain-specific early mathematics and the number-specific EFs in mathematical development, especially at the key stages of formal schooling. Understanding the causal effect of EFs in improving mathematical attainments could allow a more powerful approach in improving mathematical education at this developmental stage.

Introduction

Mathematical skills have been regarded as an important tool and an integral part for effective functioning in everyday life (1, 2). These skills are the keys to analyze and to interpret information and also to make basic or complex decisions (3). Meanwhile, several lines of evidence have also suggested that early mathematical attainment can predict an individual's career success and economic growth (4, 5). With the promising predictability of later positive outcomes as a result of early numerical abilities, understanding these developmental trajectories and cognitive underpinnings is essential.

At present, researchers from a wide variety of disciplines have begun to reveal underlying cognitive and brain architectures of our numerical processing abilities (e.g., 6-11). One theoretical perspective explains the variation of early numerical abilities in terms of a development of the domain-specific approach. According to this theory early numerical abilities and difficulties are closely associated with numerical core systems (i.e., the approximate number system: ANS) (12, 13). Typically, a multitude of studies on infants and young children suggested progressive acquisitions of numerical development (14-16), in which the ANS non-symbolic and symbolic numerical magnitude processing ability (as indexed by dot-dot and dot-number comparison tests and a mental number line) were assumed to form the basis of numerical skills among preschoolers who had not yet been taught a formal mathematics lesson (12). Later, a more precise ANS or symbolic magnitude comparison ability (e.g. a number comparison test) and symbolic magnitude estimation ability (e.g. the mental number line) (17, 18) were developed. This continuing numerical ability incorporates the prenumerical ANS and is also being conceived of as the numerical development from subitizing, counting and estimating to arithmetic (16). These early numerical systems have also been called the 'core-systems of number' (12). The critical question, nevertheless, is whether the developmental change of mathematics skills is mediated by a progressive acquisition of these numerical core systems as being observed from informal (i.e., preschoolers) to formal schooling (i.e., primary school children).

At the same time, other studies have alternatively revealed the main roles of executive functions (EFs) (19) as a crucial predictor of early numerical abilities. According to this domain-general theoretical framework, symbolic numerical magnitude estimating ability, as indexed by the mental number line, may require more than intact core-systems of number (20, 21). It has been suggested that this process involves general cognitive functions, such as EFs, which are acting together with numerical processing to shape numerical development throughout childhood (22). EFs in early childhood, show significant improvements after age five that are also demonstrated in abilities such as shifting (cognitive flexibility), inhibition of dominant or prepotent responses, and updating of working memory (23-26). Accordingly, much of the research suggests the domain-general skills contribute to early numerical development, especially during the transition from preschool to kindergarten (27, 28). Nonetheless, some conflicting results regarding the contribution of domain-general skills to numerical development as well as the mechanisms underlying their entrainment remain unclear (29). Specifically, how, why, and what components of EFs are essential and whether or not EFs are genuinely malleable to leverage early mathematical development from informal to formal schooling (30, 31).

A multi-component framework of mathematics, which highlights the main role of EFs on domain-specific numerical skills, and early numerical abilities as being an indirect and stable relationship from age eight years through to young adults has been documented (31). Nonetheless, this study did not capture the early stage of informal mathematical growth. In addition, the unique contributions of either the general EFs or EFs in numerical contexts on domain-specific numerical skills and also early numerical abilities across age groups are unclear (32). A recent study has revealed a null effect of general EFs skills on mathematics achievement across age and grade (preschool-4th grade) (33), but a recent longitudinal finding has suggested that only the EFs in a numerical context was by far more important than ANS or general EFs to predict developmental dyscalculia and numerical attainment (34). This result is in line with previous evidence that found a distinct contribution of EFs-related numerical, but not non-numerical, content on the mathematics abilities in 93 children (35). Further, only EFs in numerical context, beyond general EFs, could predict developmental dyscalculia and mathematics achievement from ages four to 13 (34).

In summary, several studies have focused on numerical and domain-general executive functioning skills (36, 37). The main roles of the domain-specific early mathematical skills (i.e., ANS) and domain-specific EFs (i.e., EFs in numerical contexts) from informal to formal schooling are relatively scarce. Such knowledge could shed light on the alteration of mathematical attainment. Accordingly, in the current study we aimed to: i) compare the domain-specific early mathematics, the number-specific EFs, and the mathematical abilities between preschool and primary school children, and ii) examine the relationship among

the domain-specific early mathematics, the number-specific EFs, and the mathematics abilities among preschool and primary school children. We used Structural Equation Modeling (SEM) to test direct and indirect effects of the domain-specific early mathematics and number-specific EFs on mathematical abilities among preschool (six-year-old) and primary school (seven-year-old) children. Domain-specific early mathematics were indexed by the dot-dot comparison task, the dot-number comparison task, the number comparison task, and the mental number line. Number-specific EFs were represented by the numerical Stroop test and the numerical shifting test. Formal and Informal mathematical abilities were measured by the number set test (38) and the numerical operation test (Figure 1).

Methods

Participants

A total of 511 six- to seven-year-old children took part in the current study (238 or 47.1% for six-year-old preschoolers and 267 or 52.9% for seven-year-old first graders), six children were excluded due to missing values, thus leaving 505 children (50.2% females) for final analysis. All participants were native Thai and attended twelve public schools in Chonburi province, Thailand. No participant was clinically referred for learning difficulties (LD) or attention deficit hyperactivity disorder (ADHD). The study was approved by the Burapha University Institutional Review Board (BUU-IRB 6200/01533). Written informed consent was obtained from all participant's parent/guardian. All methods were carried out in accordance with Good Clinical Practices and the Declaration of Helsinki Ethical Principles.

Measures

There are eight paper-and-pencil tests of the domain-specific early mathematics (Dot-Dot comparison test, Dot-Number comparison test, Number comparison tests (also termed Symbolic Magnitude Processing (SYMP) test, (1), and mental number line), the number-specific EFs (numerical Stroop and shifting tests), and the mathematics abilities (number sets and numerical operation tests). These tests were administered in quiet rooms that were provided by the schools and a group-administered test was used for all children at their schools. All children were not allowed to count and/or take notes and these behaviors were monitored by researchers. The constructs, tests, test lengths, and time spent is shown in **Table 1**. All children were assessed across eight tests and the test administration took approximately 33 minutes for each child.

The Dot-Dot comparison (DD) test

The DD test was used to assess the enumerating ability by comparing two sets of dots, which reflect subitizing and counting systems of children's early numerical abilities (39). The DD test is composed of 30 items and each item contains two sets of black dots with a pseudo-random arrangement on a white background (see **Figure 1A**). The average distance between the centers of the two black-dot sets was 2.93 cm (minimum = 2.80 cm and maximum = 3.0 cm). Each dot was equated in size (0.30 cm in diameter), each group of dots was also comparable in size (1.00 cm in diameter), and numerosity (a number of dots from 1 to 9) varied across items. All children were instructed to circle which a set of dots contained more dots without counting, as accurately and quickly as possible within 2.5 minutes. A response was scored as correct (1 point) and incorrect (0 point) with a range of scores between 0 and 30. The correct answer for each item was counterbalanced and no more than three consecutive right answers on the same side were shown (1). The Kuder-Richardson (KR)-20 reliability coefficient of this test was .97.

The Dot-Number comparison (DN) test

The DN test was used to assess the numerical ability in associating and comparing a perceived number of objects (dots) with Arabic numerals (nonsymbolic vs symbolic numbers). An Arabic symbolization constitutes a precondition for developing the mental number line as representing a relation of magnitude and ordinality to visual space (40). The DN test contained 30 items and each item contains two different sets of black dots and a single digit presenting on a white background with a pseudo-random arrangement on the left side and the single digit on the right side (see **Figure 1B**). The mean distance between the centers of the dot-number pairs was 2.99 cm (minimum = 2.9 cm and maximum = 3.2 cm). All dots were equated in size (0.3 cm in diameter), each group of dots was also equal in size (1 cm) and a number of dots ranged from 1 to 9. All the single digits were displayed in 20-point Times New Roman font. All children were instructed to circle which of two sets between the dot-number pair is larger without counting, as accurately and quickly as possible within 2.5 minutes. A response was scored as correct (1 point) and incorrect (0 point) with a range of scores between 0 and 30. The correct answer for each item was also counterbalanced and no more than three successive correct answers on the same side were shown (1). The KR-20 reliability coefficient of this test was .97.

Number comparison test (NC)

The NC test was used to examine symbolic numerical magnitudes (1). The NC test comprised two numerical magnitude comparison subtests: A single-digit subtest with digits ranging from 1 to 9 and a two-digit subtest with digits between 11 and 99. The 120 digit pairs (60 pairs for single and 60 pairs for two-digit subtests) were displayed in four columns of 15 pairs in 12-point Verdana font for each subtest (see **Figure 1C**). The number pairs were randomly presented and four factors were taken into account: (1) a counterbalance of the correct answer on the side in each column, (2) different numbers in subsequent or neighboring number pairs, (3) no more than three consecutive correct answers presenting on the same side, and (4) no similar or inverse number pairs (e.g., 6-2 vs. 2-6) presenting in the same row or column. All children were instructed to circle the larger of the single or two-number pairs as accurately and quickly as possible within 2 and 3 minutes for single and two-digit subtests. A response was also scored as correct (1 point) and incorrect (0 point) with a range of scores between 0 and 60 for both single and two-digit subtests. The KR-20 reliability coefficient of this test was .99 for the single-digit subtest, .98 for the two-digit subtest, and .99 for overall NC test.

Mental Number Line (MNL) test

The MNL test was used to assess the proficiency in numerical magnitude processes and representations (41). The MNL test contained 10 items and all children were instructed to estimate by crossing out a location of 10 target numbers on 13 cm number lines. Each horizontal number line started with a target number and a 0 at the left endpoint and numbers (i.e. 10, 20, 50, and 100) at the right endpoint (see **Figure 1D**). All digits were displayed in 12-point and 16-point Times New Roman font for target numbers and for anchored numbers at the left and right endpoint of the mental number line, respectively. They were instructed to complete the test as accurately and quickly as possible within 5 minutes. A response was scored in line with the Percent Absolute Error (PAE) formula (21), in which it was defined as the absolute difference between target number and children's estimate divided by the scale of each item and expressed as a percentage (i.e., $|\text{target number} - \text{participant's estimated number}| / \text{numerical range} * 100$). The PAE scores ranged from 0 to 100% and a higher PAE score indicated a less accurate series of estimates. The internal consistency with Cronbach's α was .77.

Numerical Stroop test

The numerical Stroop test was used to assess a cognitive inhibition or the ability to automatically inhibit irrelevant responses and adjust control (42-44) on physical and numerical pairs. The numerical Stroop test contained two subscales, that is, a one-digit subtest with digits ranging from 1 to 9 and a two-digit subtest with digits ranging from 11 to 99. The 60 digit pairs (30 pairs for single and 30 pairs for two-digit subtests) were displayed in three columns of 10 pairs in 22-point and 26-point Times New Roman font for smaller and larger physical sizes. The distances between two digits of each number pair were six, four, and two for the first, second, and third columns (e.g., 1 7, 2 6, and 3 5) (see **Figure 1E**). The number pairs were randomly showed and four factors were also taken into consideration: (1) a counterbalance of the right answer on the side in each column, (2) different numbers in subsequent or neighboring number pairs, (3) no more than three consecutive correct answers showing on the same side, and (4) no similar or inverse number pairs (e.g., 1 5 vs. 5 1) presenting in the same row or column. All children were instructed to compare the physical sizes of two numbers and circle the larger of the single or two-number pairs as accurately and quickly as possible within 2 and 3 minutes for single and two-digit subtests. A response was scored as correct (1 point) and incorrect (0 point) with a range of scores between 0 and 30 for both single and two-digit subtests. The KR-20 reliability coefficient of this test was .98 for the single-digit subtest, .95 for the two-digit subtest, and .98 for overall test.

Numerical Shifting test

The numerical shifting test was used to assess children's cognitive flexibility performance or the ability to shift attention based on changing (numerical) conditions demands (45). The numerical shifting test contained 36 items with digit pairs ranging from 1 to 9. The 36 digit pairs were showed in three columns of 12 pairs in 26-point Times New Roman font for each column. The digit pairs were displayed in red or black, in which the red digit pairs signaled to the children that it was a greater-than-five condition but black digit pairs indicated that it was an odd-even condition. Each column composed of three set shifts between a greater-than-five and odd-even conditions (see **Figure 1F**). The number pairs were randomly displayed and four factors were also taken into consideration: (1) a counterbalance of the correct answer on the side in each column, (2) different numbers in subsequent or neighboring number pairs, (3) no more than three consecutive correct answers showing on the same side, and (4) no similar or inverse number pairs (e.g., 5 2 vs 2 5) presenting in the same row or column. All children were instructed to decide which red digit is greater than five and black digit is odd or even, as accurately and quickly as possible within 3 minutes. A response was scored as correct (1 point) and incorrect (0 point) with a range of scores between 0 and 36. The KR-20 reliability coefficient of this test was .95.

Number sets test

The number sets test was used to assess mathematical abilities in young children (46). The number sets test composed of 32 items with 16 items for each target numbers 'five' and 'nine'. Each item contained a pair or trio of Arabic numbers with 18-point font in a half-inch square, object sets (stars, circles, diamonds, and triangles) in a half-inch square, or both of them and the Arabic numbers and object sets were combined to create domino-like rectangles (see **Figure 1G** and further details in (38)). All children were instructed to circle any groups that can be put together to make the number at the top of the page, which could be 5 or 9 and to complete as quickly as possible within 2 and 3 minutes for the target '5' and '9', respectively. A response was scored as correct (1 point) and incorrect (0 point) with a range of scores between 0 and 16 for the target '5' and '9' and between 0 and 32 for both targets. The KR-20 reliability coefficient for the target '5' and '9' were .94 and .95 and .96 for both targets.

Numerical operation test

The numerical operation test was adapted and used to assess children's storage and manipulation of numerical operations (47, 48). This test was also called 'arithmetic facts' in the literature but it included only addition and subtraction in simple forms. The test items were reviewed and all items were consistent with education and curriculum in preschool and primary school levels. The numerical operation test comprised 20 items, with eight items for single-digit numerical operations and 12 items for double-digit numerical operations. The 20 items of numerical operations were showed in four columns in 22-point Times New Roman font for each column (see **Figure 1H**). All children were only asked to write down the answer as the final outcome of numerical operations such as adding and carrying. A response was scored as correct (1 point) and incorrect (0 point) with a range of scores between 0 and 20. The KR-20 reliability coefficient of this test was .95.

Statistical analysis

To answer the research questions and test the research hypotheses, MANOVA was used to test the age group differences between preschool (six-year-old) and primary school (seven-year-old) children across eight dependent variables (i.e., DD, DN, NC, MNL, IN, SH, NS, and NO). In addition, the partial h^2 was calculated to represent the magnitude of difference between groups (49, 50). In measurement and structural models of the SEM, the first latent variable for the domain-specific early mathematics was derived from four observed variables, that is, DD, DN, NC, and MNL and the second latent variable for the number-specific EFs

was created from two observed variables, namely IN and SH. In addition, the third variable for the mathematics abilities was derived from two observed variables, that is, NS and NO. Finally, the direct paths among the first latent variable, the second latent variable, and the third latent variable were estimated.

No missing value was found for the current study. The outliers were detected in NS and NO for the six-year-old dataset. Data analyses were carried out using IBM SPSS statistics for Window, version 26 (IBM Corp., Armonk, N.Y., USA) and SPSS Amos version 26.0 (51). The model parameters were estimated by using the maximum likelihood procedure. The goodness-of-fit indices of the estimated models were evaluated by using five indicators, that is, the p value of Chi-square (χ^2) above .05 and χ^2/df smaller than 3 are preferred, the p value of Root Mean Square Error of Approximation (RMSEA) lower than .07 indicates a well-fitting model, the Comparative Fit Index (CFI), the Goodness of Fit Index (GFI), and the Adjusted GFI (AGFI), the values over .90 suggest a good fit (52, 53).

Results

Descriptive statistics, group difference, and correlation coefficients among variables.

Table 2 shows the domain-specific early mathematics was represented by four variables, that is, DD, DN, NC, and MNL. The number-specific EFs were indexed by two variables, namely, IN, and SH. In addition, the mathematics abilities were represented by two variables, that is, NS and NO. In general, the domain-specific early mathematics of six-year-old children was significantly lower than that of seven-year-old children, but it was clearly shown for NC that the six-year-old children had a lower score on the number comparison test with a large effect size than that of the seven-year-old children. Likewise, the number-specific EFs were also greater for seven-year-old children, however, the effect sizes for all variables in the number-specific EFs between two age groups were moderate. The mathematics abilities were obviously better for seven-year-old children and a strong effect size was observed.

The coefficient alpha (α) for all measures were generally excellent ($\alpha \geq .93$) but it was only acceptable for MNL ($\alpha = .76$). Nearly all variables were normally distributed, as measured by skewness and kurtosis, however, only NS and NO values were out of normal range for a group of six-year-old children (see **Table 2**). To reduce kurtosis of NS and NO values for the six-year-old dataset, the base-10 logarithmic transformation was employed (54) to achieve normal distributions for NS (Skewness_{transformed} = -0.11 and Kurtosis_{transformed} = -0.96) and NO (Skewness_{transformed} = 1.44 and Kurtosis_{transformed} = 1.09). In **Table 3**, the correlation coefficients among variables representing the domain-specific early mathematics, the number-specific EFs, and the mathematics abilities for the overall pooled children ($N = 505$) broadly demonstrated a moderate relationship, that is, the correlations between variables in the domain-specific early mathematics, the number-specific EFs, and the mathematics abilities ranged from -.43 and .64 for NS. In **Table 4**, a moderate correlation between variables reflecting the domain-specific early mathematics and the number-specific EFs and NS (-.30 to .51) and NO (-.31 to .51) were observed for six-year-old children. On the other hand, a weak-to-moderate relationship was also observed between variables indexing the domain-specific early mathematics and the number-specific EFs and NS (.34 to .54) and NO (.29 to .51) for seven-year-old children. The multicollinearity tests were performed using the Value Inflation Factor (VIF) and all VIF scores were less than the threshold of 5 (the highest scores were for pooled children, for six-year-old children, and for seven-year-old children), which indicated that the multicollinearity is not a problem in current datasets.

SEM analyses to test the relationship among for the overall pooled children ($N = 505$), six-year-old children ($n=238$), and seven-year-old children ($n=267$).

As illustrated by the results in **Figure 2**, the goodness-of-fit indices of SEM models for the overall pooled, six-year-old, and seven-year-old children suggested that the proposed models fitted with empirical data ($\chi^2=7.47$, $df=8$, $p=.49$, $\chi^2/df < 3$, RMSEA<.01, GFI=1.00, CFI=1.00, and AGFI=.98 for overall pooled children; $\chi^2=15.80$, $df=8$, $p=.05$, $\chi^2/df < 3$, RMSEA=.07, GFI=.98, CFI=.99, and AGFI=.93 for six-year-old children; $\chi^2=6.66$, $df=8$, $p=.57$, $\chi^2/df < 3$, RMSEA<.01, GFI=.99, CFI=1.00, and AGFI=.97 for seven-year-old children, respectively). For the SEM model of six-year-old children, DD, DN, and NC exerted comparable and strong effects ($b = .85$, $p < .01$; $b = .85$, $p < .01$; $b = .80$, $p < .01$, respectively) on the domain-specific early mathematics but MNL showed the lowest factor loading ($b = -.30$, $p < .01$) on the given latent variable. Further, IN and SH also showed strong and similar effects ($b = .79$, $p < .01$; $b = .75$, $p < .01$, respectively) on the number-specific EFs latent variable. Both latent variables could significantly and positively predict ($b = .67$, $p < .01$; $b = .69$, $p < .01$) the mathematics abilities factor as measured by NS and NO.

For the SEM model of seven-year-old children, DD, DN, and MNL exerted proportional and low-to-moderate effects ($b = .51$, $p < .01$; $b = .67$, $p < .01$; $b = -.37$, $p < .01$, respectively) on the domain-specific early mathematics but NC showed the strongest factor loading ($b = .94$, $p < .01$) on the given latent variable. Hence, IN and SH showed moderate and comparable effects ($b = .67$, $p < .01$; $b = .62$, $p < .01$, respectively) on the number-specific EFs latent variable. Both latent variables could also significantly and positively predict ($b = .76$, $p < .01$; $b = .77$, $p < .01$) the mathematics abilities factor as measured by NS and NO.

For the SEM model of the overall pooled children, MNL, DD, and DN exerted comparable and low-to-moderate effects ($b = -.41$, $p < .01$; $b = .67$, $p < .01$; $b = .71$, $p < .01$, respectively) on the domain-specific early mathematics but NC showed the strongest factor loading ($b = .97$, $p < .01$) on the given latent variable. Hence, IN and SH showed strong and comparable effects ($b = .79$, $p < .01$; $b = .74$, $p < .01$) on the number-specific EFs latent variable. Both latent variables could also significantly and positively predict ($b = .81$, $p < .01$; $b = .77$, $p < .01$) the mathematics abilities factor as measured by NS and NO.

In conclusion, it is noticeable from the SEM models that the relationships among the indicators (i.e., DD, DN, and NC) of the domain-specific early mathematics were strong and comparable for six-year-old children (informal schooling) but the NC was very strong and distinguishable for seven-year-old children (formal schooling). For six-year-old children, IN and SH abilities were comparable but these two abilities were stronger than those for seven-year-old children. Finally, the predictive power of the domain-specific early mathematics and the number-specific EFs were similar in prediction of the mathematics abilities across age and overall groups.

Discussion

The present study aimed to compare and examine the effects of the domain-specific early mathematics and the number-specific EFs on the mathematics abilities in a sample of six- and seven-year-old children. Analyses were first carried out to test the age group differences across DD, DN, NC, MNL, IN, SH, NS and NO, and to examine the relationships between two latent predictors (i.e., the domain specific early mathematics and the number-specific EFs) and the latent mathematics abilities in a sample of six- and seven-year-old children.

Based on the current findings, it is indicated that six- and seven-year-old children (informal schooling and formal schooling) were apparently evident on NC, NS, and NO differences. The finding in itself shows an integrative role of numerical development between numerical comparison, storage and manipulation abilities on mathematical achievement from preschool to primary school students (47). Further, the distinctive competency for NC, NO, and NS between two age groups suggests a numerical and developmental acquisitions from understanding precise magnitudes of nonsymbolic numbers, relating nonsymbolic to a foundation of symbolic numerical representations in six-year-olds (55), to expanding understanding the small symbolic numbers to larger whole numbers (i.e., single and double digits) in seven-year-olds (16).

Despite similarities between the DD and DN tests, these tests were used to examine the process of attributing numerical magnitude to nonsymbolic numbers in both age groups. Although the significant differences between the two age groups on both DD and DN were observed in **Table 2**, the effect sizes of both tests were somewhat small. It is plausible that ANS acuity, nonsymbolic and basic symbolic numerical knowledge fully reach the developmental milestone on numerical competence at younger ages (56). This is in line with previous findings that demonstrated the specific effects of ANS acuity and mapping precision between numeral notations and their corresponding magnitudes were dominant only in preschool children (57). In agreement with the literature, the performance on the MNL significantly differed between six- and seven-year-old children but the extent of discrepancy was small. However, the performance in the MNL task explained a relatively small amount of variance in the SEM model compared to the numerical comparison tasks.

There is still a lack of shared consensus on the relative extent of the involvement of domain-specific and general precursors in the development of mathematics abilities (48). The unique contribution of the present SEM findings is the differential associations between specific indicators of the domain-specific early mathematics and the number-specific EFs and the mathematics abilities from kindergarten through primary school. The important of subitizing, approximation, and comparison as indexed by DD and DN for mathematics abilities decreased as preschool children progressed through formal schooling. Nonetheless, the symbolic and exact understanding of numerical concepts as measured by NC and MNL were prioritized for the mathematics abilities with successive grades. Furthermore, the mathematics abilities were more dependent on both the domain-specific early mathematics (.67 vs .76) and the number-specific EFs (.69 vs .77) in older children. The mathematical problems will call upon a crucial process of detecting and assessing critical features of number sense (38) and involving maintenance, manipulation, and updating of information (58-60). A strong influence of both the domain-specific early mathematics and the number-specific EFs in older adults may reflect the increasingly demanding role of updating capacity with age (e.g., 46, 61-63).

Another main finding is that the relative importance of the domain-specific early mathematics and the number-specific EFs were similar in size in prediction of the mathematics abilities for six-year-old children. However, the number-specific EFs were a stronger predictor of the mathematics abilities than the domain-specific early mathematics for seven-year-old children. Indeed, in order to master mathematical competencies as measured by NS and NO tests, children are required to map and combine the different Arabic numerals and symbols onto the corresponding quantities and then compare with the target number of each item. Although the present study supports the previous findings that quantity representation or ability to map quantities and magnitudes with symbols was associated with the mathematics abilities (e.g., 1, 56, 64), our results highlight the stronger association among the domain-specific early mathematics, the EFs in a numerical context, and the mathematics abilities at the beginning of formal schooling. It is possible that the older children learn the school-taught mathematics, which provides them with the knowledge on symbol systems and procedural tools. Accordingly, in order to achieve mathematics calculations, the performances of EFs in a numerical context were improved in older children. In particular, the child needs to match the different number symbols and digits with the corresponding quantities, encode and store them into long-term memory (LTM) via the aid of working memory, and then monitor and replace the old numerical information (including strategy choices in simple and complex addition) with the incoming information during performing the mathematical tasks (48, 65).

Moreover, with a cumulative knowledge of symbol systems and strategy choices in older children, it may require a more efficient supporting system or the EFs to foster the acquisition of existing early mathematics abilities and arithmetical skills. In this view, apart from better knowledge on the domain-specific early mathematics, primary school children have to rely directly on the EF subcomponents to some extent. In this case, solving mathematical problems allows the child to select relevant information or strategies, inhibiting numerical information already processed but no longer relevant. And cognitive flexibility allows the child to switch from one strategy to another, transforming or substituting the no-longer relevant information with a new one (66-68). This view is in line with previous findings that highlighted central executive system or EFs as a main component in activation and retrieval of mathematical facts in LTM (46, 69) and that the strength between the EF functions and LTM may be stronger for older children, compared to preschoolers (70).

Nonetheless, this study also possesses a number of noteworthy limitations. Given the strong link between working memory and IQ, although no children with LD and ADHD were found, the present study lacks a control over children's IQ scores. Accordingly, a cautious interpretation of the finding must be considered. Moreover, the weak correlation among MNL and other variables in the same construct may stem from the issue of the test format and the scoring method. Finally, the current study did not compare the relative effects of the domain-specific early mathematics, the number-specific EFs, and the general EFs on mathematics abilities. The present findings provide a strong motivation to delineate these factors.

Conclusion

The present study yielded two key findings. First, seven-year-old children outperformed six-year-old children over all measures of the domain-specific early mathematics and the number-specific EFs, especially, for more sophisticated numerical knowledge and EF subcomponents, namely symbolic numerical magnitude representations as indexes by NC and MNL tests, and the numerical inhibitory and shifting abilities as measured by the IN and SH tests. Second,

both the domain-specific early mathematics and the number-specific EFs were comparable and significant predictors of the mathematics abilities for six- and seven-year-old children, but the domain-specific early mathematics and the number-specific EFs were apparently dominant in relation to the mathematics abilities for seven-year-old children.

Abbreviations

ADHD: Attention Deficit Hyperactivity Disorder

AGFI: Adjusted GFI

ANS: Approximate Number System

CFI: Comparative Fit Index

DD: Dot-Dot comparison

DN: Dot-Number comparison

EFs: Executive Functions

GFI: Goodness of Fit Index

IN: Numerical Stroop test

LD: Learning Difficulties

LTM: Long-Term Memory

MANOVA: Multivariate Analysis of Variance

MNL: Mental Number Line

NC: Number Comparison test

NO: Numerical Operation test

NS: Number Sets test

PAE: Percent Absolute Error

RMSEA: Root Mean Square Error of Approximation

SEM: Structural Equation Modeling

SH: Numerical shifting test

SYMP: Symbolic Magnitude Processing

Declarations

Ethics approval and consent to participate

The current study was reviewed and approved by the Burapha University Institutional Review Board (BUU-IRB 6200/01533). Written informed consent for study participation was obtained from all participant's parent/guardian. The current investigation was conducted in line with Good Clinical Practices and the Declaration of Helsinki Ethical Principles.

Consent for publication

Not applicable.

Competing interests

None.

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Authors' contributions

PW and RCK contributed to the first draft of the manuscript. PW and RCK designed the methodology and created the models. PW conducted the formal analysis. PW and RCK reviewed and approved the final manuscript.

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Availability of data and materials

The datasets used and analyzed during the present study are available from the corresponding author on reasonable request.

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Tables

Table 1. The constructs, tests, test length, and time spent.

Constructs		Tests (Acronym)	Number of items	Time spent (Minutes)
The domain-specific early mathematics	Dot-Dot comparison	Dot-Dot comparison test (DD)	30	2.5
	Dot-Number comparison	Dot-Number comparison test (DN)	30	2.5
	Number comparison	Number comparison test (NC)	60 (Single)	2
		(Single & Double digits)	60 (Double)	3
Analogous Magnitude representation	Mental number line: Percent Absolute Error (MNL)	10	5	
The number-specific EFs	Inhibition	Numerical Stroop test (IN)	30 (Single)	2
		(Single & Double digits)	30 (Double)	3
	Shifting	Numerical shifting test (SH)	35	3
Mathematics abilities		Number sets test (NS)	16 (5 set)	2
			16 (9 set)	3
		Numerical operation test (NO)	20	5

Table 2. Descriptive statistics for variables indicating the domain-specific early mathematics, the number-specific EFs and the mathematics abilities among six-and seven-year-old children ($n_{6yrs} = 238 / n_{7yrs} = 267 / N_{overall} = 505$) and age group differences.

Variable	Min-Max		Mean (SD)			<i>a</i>			Skewness			Kurtosis			Group differences (6 vs. 7 years old)		
	6 yrs	7 yrs	6 yrs	7 yrs	All	6 yrs	7 yrs	All	6 yrs	7 yrs	All	6 yrs	7 yrs	All	<i>F(df)</i>	<i>p</i>	Part <i>h</i> ²
The domain-specific early mathematics																	
DD	0-30	0-30	18.84 (10.12)	25.24 (6.87)	22.23 (9.13)	.97	.95	.97	-0.49	-1.71	-1.05	-1.15	2.52	-0.11	70.49(1)	<.01	0.12
DN	0-30	0-30	17.36 (9.68)	23.23 (9.13)	20.46 (9.83)	.96	.97	.97	-0.28	-1.26	-0.71	-1.13	0.39	-0.80	49.16(1)	<.01	0.09
NC	0-120	0-120	49.61 (34.60)	83.44 (30.93)	67.50 (36.79)	.99	.99	.99	0.49	-0.71	-0.16	-0.65	-0.18	-1.10	134.62(1)	<.01	0.22
MNL	1.5-55	0-44.6	19.37 (8.21)	15.96 (8.38)	17.57 (8.46)	.76	.67	.72	1.03	0.66	0.76	2.59	0.67	1.51	21.25(1)	<.01	0.04
The number-specific EFs																	
IN	0-60	0-60	39.34 (17.21)	51.30 (12.94)	45.66 (16.23)	.97	.97	.97	-0.79	-2.16	-1.29	-0.38	4.55	0.78	78.91(1)	<.01	0.14
SH	0-35	0-35	17.52 (9.82)	23.92 (8.85)	20.90 (9.84)	.95	.94	.95	-0.17	-1.12	-0.60	-0.95	0.86	-0.56	59.38(1)	<.01	0.11
Mathematics abilities																	
NS	0-31	0-32	4.42 (6.27)	13.98 (9.39)	9.48 (9.37)	.94	.94	.94	-0.11†	0.08	0.74	-0.96†	-1.18	-0.72	176.49(1)	<.01	0.26
NO	0-20	0-20	2.46 (4.02)	7.61 (6.23)	5.18 (5.89)	.93	.94	.95	1.44†	0.42	1.07	1.09†	-1.10	-0.14	118.35(1)	<.01	0.19

Note †Transformed values by logarithm (NS_{original}=2.03_{skewness} & 4.25_{kurtosis} and NO_{original}=2.65_{skewness} & 6.83_{kurtosis} for six-year-old children).

Table 3. The correlation coefficients among variables representing the domain-specific early mathematics, the number-specific EFs, and the mathematics abilities for the overall pooled children (N = 505).

Variable	DD	DN	NC	MNL	IN	SH	NS	NO
The domain-specific early mathematics								
DD								
DN	.61**							
NC	.66**	.70**						
MNL	-.26**	-.30**	-.40**					
The number-specific EF								
IN	.64**	.58**	.70**	-.31**				
SH	.47**	.50**	.59**	-.24**	.58**			
Mathematics ability								
NS	.45**	.48**	.64**	-.43**	.50**	.48**		
NO	.42**	.40**	.60**	-.44**	.44**	.39**	.61**	

Note ***p*<.001.

DD = Dot-Dot comparison test; DN = Dot-Number comparison test; NC = Number comparison test (Single & Double digits); MNL = Mental number line: Percent Absolute Error; IN = Numerical Stroop test (Single & Double digits); SH = Numerical shifting test; NS = Number sets test (5 & 9 sets); NO = Numerical operation test.

Table 4. The correlation coefficients among variables representing the domain-specific early mathematics, the number-specific EFs, and the mathematics abilities for the overall pooled children for six- (lower diagonal) and seven- (upper diagonal) year-old children (ns = 238 and 267).

Variable	DD	DN	NC	MNL	IN	SH	NS	NO
The domain-specific early mathematics								
DD		.35**	.47**	-.20**	.49**	.25**	.34**	.29**
DN	.74**		.63**	-.22**	.37**	.44**	.37**	.28**
NC	.68**	.69**		-.35**	.63**	.50**	.54**	.51**
MNL	-.22**	-.29**	-.36**		-.30**	-.20**	-.44**	-.44**
The number-specific EF								
IN	.65**	.66**	.65**	-.23**		.42**	.40**	.35**
SH	.51**	.45**	.55**	-.18**	.61**		.36**	.29**
Mathematics ability								
NS	.44**	.49**	.51**	-.30**	.44**	.49**		.43**
NO	.43**	.44**	.51**	-.31**	.39**	.34**	.49**	

Note ** $p < .001$.

Figures

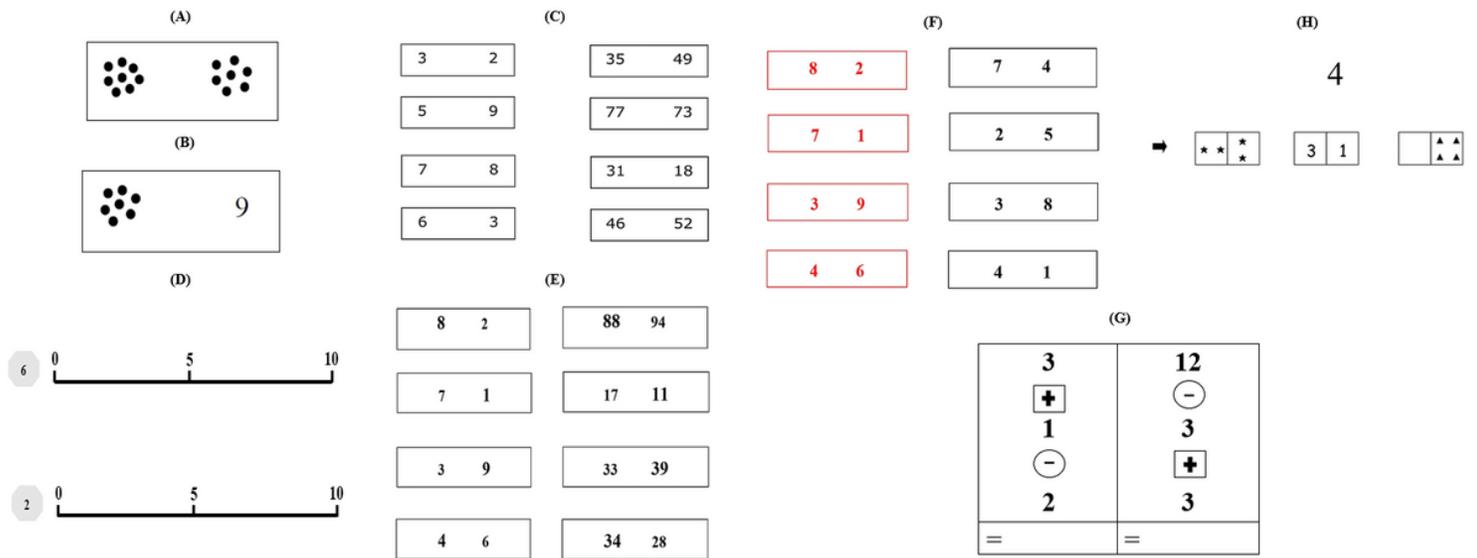


Figure 1

Screenshots of the tests in the current study: A) The Dot-Dot comparison test; B) The Dot-Number comparison test; C) The Number comparison test; D) The Mental Number Line; E) The Numerical Stroop test; F) The Numerical Shifting test; H) The Number Sets test; G) The Numerical Operation test.

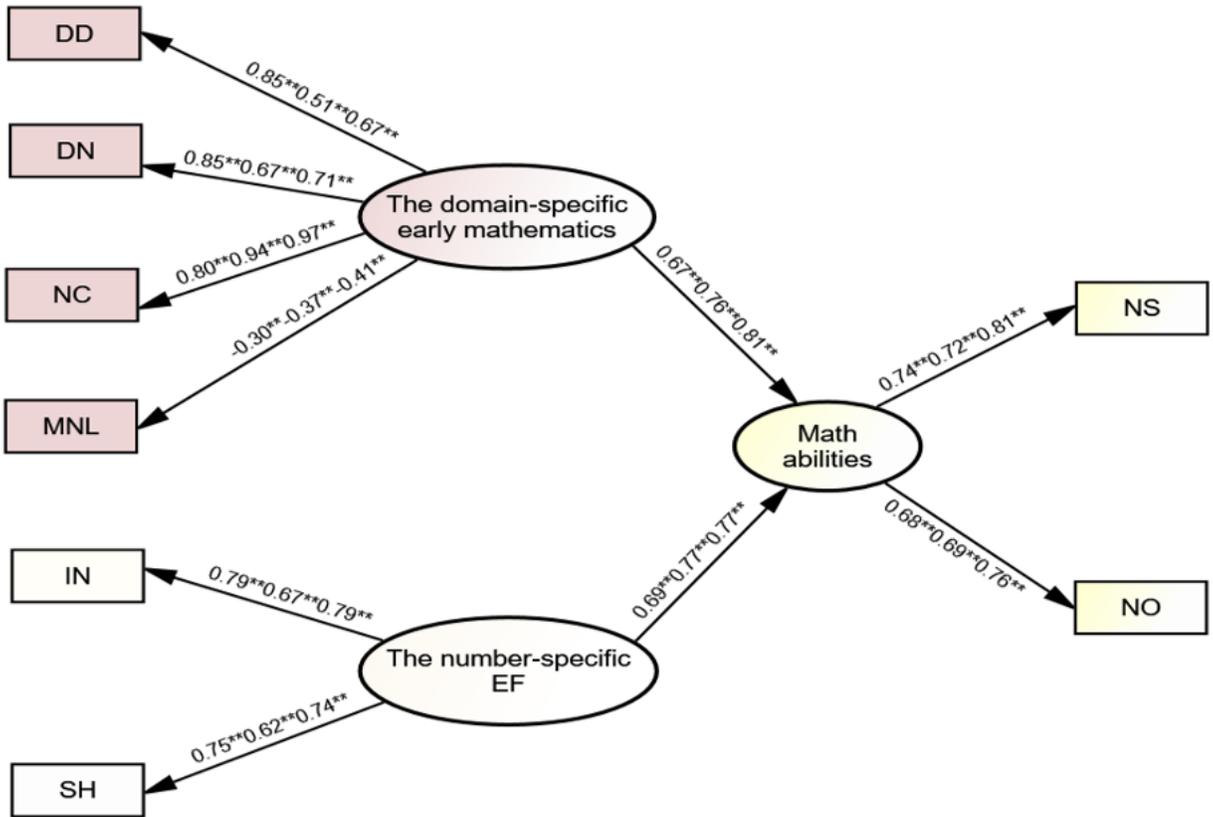


Figure 2

The relationships among the domain-specific early mathematics, the number-specific EF, and the mathematics abilities for six- and seven-year-old children. Separate parameters of different age groups (six-year-old/ seven-year-old/six-and-seven-year-old) and standardized coefficients (β s) are reported. Note $**p < .01$.