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Now You See It, Now You Don't – Cognitive Skills and Their Contributions to Mathematics Across Early Development

RESEARCH ARTICLE

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ABSTRACT

A broad variety of domain-specific (e.g., non-symbolic magnitude comparison and arithmetic) and domain-general (e.g., spatial skills and inhibition) skills have been identified as precursors to mathematics achievement. However, due to the increasing complexity of mathematics education with age and the associated increase in cognitive demands, it can be assumed that a divergent set of skills is predictive of mathematics achievement at different ages. This cross-sectional study in children aged 3, 5, and 7 years aims at identifying the differential contribution of domain-specific and domain-general contributors to mathematics and delineating their developmental dynamics. Our results reveal a consistent role for non-symbolic magnitude comparison across all age groups, non-symbolic arithmetic starting from the age of 5 years and visuospatial memory only in 5-year-olds. These findings support the notion that mathematics cannot be conceived as a unitary cognitive skill and provide a fine-grained analysis of the cognitive requirements of mathematical skills at different ages. On a more general note, they are in line with the idea that the ANS provides a critical scaffold for the development of mathematical skills but challenge the view that all ANS measures tap into the same underlying process.

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INTRODUCTION

It has been well established that a broad variety of domain-specific (e.g., magnitude comparison and arithmetic) and domain-general (e.g., spatial skills, inhibition) skills play an important role in the development of mathematics (for a review see De Smedt, 2022). Individual differences in these cognitive precursors have regularly been shown to associate with later mathematics outcome (e.g., Geary et al., 2017; Passolunghi & Lanfranchi, 2012). Nevertheless, mathematics performance reflects a complex construct comprised of various numerical processes, rapidly progressing throughout a child's development. Therefore, early cognitive skills predicting mathematics performance are likely to reflect two key factors, maturation, and the level of education in mathematics. Many researchers have aimed at suggesting the mechanics behind the way domain-specific and domain-general skills relate to mathematics, often without taking into account both the rapid changes within these cognitive precursors as well as the constantly evolving curriculum of mathematics (for a review see Cragg & Gilmore, 2014). Domain-specific and domain-general skills continuously grow throughout the development of a child, however, even skills that are highly related to each other do not always develop at the same rate or start developing at the same age (Best & Miller, 2010). Therefore, the way in which domain-specific and domain-general skills relate to mathematics, will at least in part depend on their stage of development. Furthermore, while mathematics achievement is often measured with standardised all-encompassing mathematics measures (Cragg & Gilmore, 2014), each age group has a distinctive educational curriculum determining the mathematics they practice and learn to understand at that point in their development. This is not thoroughly investigated in the literature, where several domain-specific and domain-general skills are often pitted against each other across ages as precursors of standardised all-encompassing mathematics performance. This renders it difficult to draw conclusions on the way individual differences in domain-specific and domain-general skills underlie mathematics development.

This study aims to test the hypothesised predictors per age range, according to the mathematics curriculum that is reflected at a specific educational level. In doing so, this study will add empirical support to previously suggested mechanisms concerning domain-specific and domain-general contributions to mathematics.

DOMAIN-SPECIFIC PRECURSORS OF MATHEMATICS

Humans possess the ability to represent and manipulate non-symbolic magnitudes, an innate ability that they share with other species (Dehaene, 2011). This ability is often said to be represented in the Approximate Number System (ANS), which has some common neural underpinnings with the symbolic mathematics system in children (Schwartz et al., 2021). The precision of the ANS (i.e., ANS acuity) increases with age (Halberda & Feigenson, 2008) and differs between individuals (Halberda et al., 2008). ANS acuity is often measured by means of a magnitude comparison task (e.g., "which of two sets of dots is more numerous?"). The ANS acuity measured through a magnitude comparison task has been found to correlate with symbolic mathematics performance both concurrently and longitudinally across different ages and is often described as the evolutionary foundation of mathematics (Dehaene, 2011; Halberda et al., 2008; Halberda & Feigenson, 2008). It has been suggested that symbolic numbers acquire their meaning through a mapping process that associates approximate magnitude representations encoded in the ANS with abstract numerical symbols. Nevertheless, some alternative accounts to the ANS model in relation to symbolic number processing have been suggested. In his Discrete Semantic System (DSS) model, Krajcsi and colleagues (2016) propose that hallmark effects in numerical cognition such as the distance and size effect in number comparison tasks emerge from the frequency of the symbols rather than by the ratios of their values. In addition, the symbol-symbol association account (Reynvoet & Sasanguie, 2016) proposes that acquisition of meaning for symbolic numbers initially involves associating exact representations of small numerical quantities with their corresponding symbols. Subsequently, children combine this with the extension of the count list knowledge which leads to the creation of an "independent and exact symbolic system based on order relations between symbols (p. 1; Reynvoet & Sasanguie, 2016)." Furthermore, not all studies have replicated a correlation between ANS acuity and mathematics achievement (e.g., Castronovo & Göbel, 2012; Iuculano et al., 2008; Vanbinst et al., 2012). More recently, research found that the nature of the correlation between the ANS and mathematics achievement might change with age, mathematics experience, and the development of other important cognitive precursors of mathematics (Coolen et al., 2022). Indeed, the ANS has been found to be more correlated to informal mathematics achievement and at the start of mathematics learning (Coolen et al., 2022; Libertus et al., 2013). It has therefore been suggested that the importance of domain-general skills gradually increases when mathematical concepts become more complex with the beginning of formal schooling (e.g., Gimbert et al., 2019). Nevertheless, non-symbolic approximate numerical representations may provide a foundation to arithmetical manipulations in both children and adults (Barth et al., 2006). ANS acuity improved after training on approximate arithmetic and this training in turn further improved symbolic arithmetic in children (Park et al., 2016) and adults (Park & Brannon, 2013). Training on a magnitude comparison task, however, did not yield the same far transfer improvements (Park & Brannon, 2014). This suggests that while approximate arithmetic could be causally related to symbolic arithmetic, this is not necessarily the case for the magnitude comparison task, which is expected to play a bigger role in emerging informal mathematics skills (Libertus et al., 2013). Moreover, some research suggests that tasks measuring non-symbolic magnitude comparisons and non-symbolic arithmetic are in part separable as they show poor construct validity and both tasks might be measuring different ANS-related skills (Coolen et al., 2022; Gilmore et al., 2011). Indeed, non-symbolic magnitude comparison is expected to be more predictive of early mathematical development for which the acquisition of number concepts is central, while non-symbolic arithmetic is expected to be more predictive of symbolic arithmetic skill acquisition.

DOMAIN-GENERAL PRECURSORS OF MATHEMATICS

The current literature has made it abundantly clear that a focus only on domain-specific skills to understand the development of mathematics is not sufficient. A broad variety of domain-general skills such as working memory (De Smedt et al., 2009), spatial skills (Atit et al., 2021) and inhibition (Allan et al., 2014) have been found to contribute to mathematics development. When specific domain-general skills come into play likely depends on the developmental rate of those skills as well as the child's developmental level of mathematics. Hence, when and the way in which different domain-general skills are associated with mathematics needs to be further disentangled.

Spatial skills

Spatial skills have been found to be a strong unique precursor of mathematics across different ages (Xie et al., 2019). Several accounts for the association between spatial skills and mathematics exist, although they are not necessarily mutually exclusive. One reason why spatial and numerical processes are related is that they rely on overlapping neural areas. Indeed, according to the neuronal recycling hypothesis (Dehaene & Cohen, 2007), parietal brain areas that support spatial processing could be used to process numerical information (Knops, 2018; Knops, Thirion, et al., 2009). This might explain the close association between numbers and space (Knops, 2018). This association is present from birth for non-symbolic quantities and progressively transfers to symbolic quantity information during childhood and persists in adulthood (Fischer & Shaki, 2014; McCrink & de Hevia, 2018). For example, the SNARC (Spatial-Numerical Associations of Response Codes) effect describes that people associate small numbers (e.g., 1, 2, 3) with a left side of space and larger numbers (e.g., 7, 8, 9) with the right side of space (Wood et al., 2008). This has been taken as empirical support that people represent numbers on a Mental Number Line. Moreover, in arithmetic, a spatial bias is also present. The Operational Momentum effect refers to a spatial bias to the right for additions and to the left for subtractions (Knops, Viarouge, et al., 2009). These biases suggest that numbers are represented spatially in the form of a Mental Number Line and with numbers being the building blocks of mathematics, this can in part explain the association found between spatial skills and mathematics.

Another account for the relation between spatial skills and mathematics is that spatial skills are a precursor of cognitively more demanding skills such as working memory (Hawes & Ansari, 2020). According to the Baddeley model of working memory, our working memory is split up into three subcomponents comprised of the visuospatial sketchpad, the phonological loop, and the central executive. The central executive controls the visuospatial sketchpad and the phonological loop, which are responsible for storing respectively visuospatial and verbal information (Baddeley & Hitch, 1994). In this respect, visuospatial skills, in particular visuospatial short-term memory reflecting the role of the visuospatial sketchpad, can be hypothesised to relate to mathematics because of its involvement as a working memory component. Indeed, visuospatial working memory is essential in even simple mathematical tasks such as number comparison or simple calculations, to retain numerical information in the memory and manipulate it (Coolen & Castronovo, 2023; De Smedt et al., 2009). Relatedly, the temporal order of working memory content – even verbally mediated content such as a list of words – tends to be represented in space (Abrahamse et al., 2016), which has led to the idea that all serial working memory content is spatially represented on a 'mental white board' (Guida et al., 2020). Nevertheless, spatial skills are a broad construct that describes capacities to generate, maintain, recall, and manipulate visuospatial information (Hawes & Ansari, 2020). A variety of spatial skills reflected in this definition have been identified as precursors of mathematics, but a thorough understanding pertaining to the function of unique skills remains suggestive (Hawes et al., 2022). However, various spatial skills have been shown to correlate strongly and load unto one factor representing spatial skills in children aged 5 to 13 years (Mix et al., 2016). Still, some spatial tasks have been shown to be more strongly related to mathematics and are better suited for training purposes to associate to improvements in mathematics (Hawes et al., 2022). One such spatial skill is visuospatial memory, reflecting maintaining and processing visual and spatial information when it is no longer present to construct integrated representations of one's environment (Judd & Klingberg, 2021). Visuospatial memory has mostly been suggested to play a role when rapidly acquiring new number skills in early mathematical development, such as counting and associating small quantities to abstract numerical concepts (i.e., Arabic digits) (Holmes & Adams, 2006). Furthermore, as children start to do simple calculations, learning happens in a very visual way, for example with the use of objects or fingers (Boaler et al., 2016). The association between visuospatial memory and mathematics has been found to decrease with age, as children gradually step back from using their mental representations of numerosities and rely more on abstract verbal representations in mathematics (Coolen & Castronovo, 2023; De Smedt et al., 2009; Holmes et al., 2008). Indeed, not only verbal working memory but also verbal skills such as phonological reasoning has been associated to mathematics (e.g., Peng et al., 2020). In adults, the solving of both mental multiplication and subtraction problems were comparably impaired by concurrent dual-task interference from visuo-spatial and verbal working memory tasks, suggesting that mental arithmetic relies on both verbal and visuo-spatial codes (Cavdaroglu & Knops, 2016). Spatial attention has received less interest in the past research on spatial skills and mathematics and has not always been found to associate with mathematics (Ashkenazi & Silverman, 2017; Gold et al., 2013; but see Raghubar et al., 2015). Nevertheless, the presence of some spatial biases in numerical processing (i.e., SNARC effect, Operational Momentum effect) could directly reflect spatial attentional shifts. For example, attentional re-orienting in adults has been shown to correlate to the OM effect (Katz et al., 2017). Furthermore, previous research successfully predicted whether adults engaged in additions or subtractions based on the neural activation during attentional shifts to respectively right or left (Knops, Thirion, et al., 2009). These findings illustrate a potential role for spatial attention in mathematics and in particular in arithmetic. In this study, we thus aim to test the role for spatial attention and visuospatial memory in the development of mathematics. It should be noted that other spatial skills such as spatial visualisation and mental rotation have been associated to the development of mathematics (Hawes & Ansari, 2020), which will not be tested in the current study. Even though spatial skills have been identified as a consistent and unique precursor of mathematics, other domain-general skills are likely to contribute distinctly to the development of mathematics.

Inhibition

Inhibitory control refers to a cognitive mechanism to suppress irrelevant stimuli, responses, or processes. Inhibition is not a unitary construct and has often been split between response inhibition (i.e., suppression of prepotent motor responses) and interference control (i.e., suppression of distracting information) (Rey-Mermet et al., 2018). Research has mostly looked at the association between interference control and mathematics and has found significant correlations (Gilmore et al., 2015). Indeed, the classroom is filled with distractors and academic achievement appears to be associated with interference control (Lee & Lee, 2019). More specifically to mathematics, interference control can be useful in a variety of mathematical tasks. For example, to inhibit inappropriate or slower strategies (e.g., addition instead of subtraction; finger counting instead of arithmetical fact retrieval), inhibit prepotent responses such as during arithmetic fact retrieval (e.g., 3 × 3 = 6) or inhibit irrelevant information in mathematical problem-solving questions (Bull & Lee, 2014). Thus, arithmetic facts and problem-solving would appear to be particularly vulnerable to interference (De Visscher & Noël, 2014). Nevertheless, inconsistencies exist in the literature investigating the link between inhibition and mathematics (Lee & Lee, 2019). These inconsistencies can be a result of 1) choice of inhibition type, 2) choice of mathematics tasks and age-related differences (i.e., reflecting their mathematics knowledge) (Lee & Lee, 2019). These factors will be taken into consideration in this study wherever possible. Going beyond previous studies, the role of inhibition will be tested in 3 different age groups and for different subtests of mathematics to explore in more detail whether inhibition is linked to specific maths subtasks in particular. We did not include multiple inhibition measures in this study. Rather, we opted for assessing the interference control facet of inhibition instead of response suppression to align with the literature describing a more likely role for interference control in maths (Lee & Lee, 2019).

MATHEMATICS DEVELOPMENT

Mathematics is a complex and multi-dimensional construct comprised of a large number of different, but related skills. Previous literature on individual differences in mathematics achievement focus only on one particular mathematical skills such as arithmetic or they use standardised mathematics achievement measures encompassing various numerical skills, which renders interpretations difficult (Cragg & Gilmore, 2014). The numerical skills reflected in mathematics are highly dependent on the age of the child and what the corresponding mathematical curriculum looks like. Since this study will focus on the start of maths education in preschool (*Programme d'enseignement de l'école maternelle*, 2019) and primary school (*Programmes et horaires à l'école élémentaire*, 2019), the French curriculum at three key stages will be discussed. Children in the first year of preschool in France (*Petite sections*, 3 years) do not have a mathematical curriculum, but they get introduced to pre-mathematical activities through play. This is meant to enable children to understand and use numbers, recognise shapes and organise collections of objects according to different criteria or properties (e.g., shape, size, length, mass, colour). They begin to learn concepts such as smaller than, larger than, more or less than and play spatial construction games (e.g., building towers, cube puzzles) to enable the observation of 3-dimensional space. At the end of French preschool (*Grande section*, 5 years), children acquire the sequence of numbers up to 20-30 and learn how to use them. They generally perceive that numbers are used to represent quantities and can identify positions such as first, second, third. At this age, children discover operations (adding, subtracting, removing, sharing) even if operation techniques are not yet on the agenda. Solving simple operation problems, allows for an entry into the world of calculations. In the second year of French primary school (*CE1*, 7 years) children manipulate numbers up to 1000 through counting, ordering, comparing, and writing. They consolidate the basics of arithmetic by memorising the addition and subtraction tables from 1 to 9 and the multiplication tables with multiplications by 2, 3, 4 and 5. Furthermore, they learn to add and subtract numbers in columns, so that they understand the value of digits according to their place (unit-decade-hundred). Children are regularly confronted with mathematical problem solving to consolidate their numerical knowledge.

Taken together, the differences in mathematics between the start of preschool, the end of preschool and the second year of primary school are huge and the increasing complexity of mathematics education over time is associated with an increase in cognitive demand. It can therefore be assumed that a divergent set of skills is predictive of mathematics at different ages.

HYPOTHESIS

With this theoretically guided study we aim to get a better grasp of the unique domain-specific and domain-general contributions tested in this study in the development of mathematics (tested in this study with the following subtests from the Tedi-math: cohort 1 – counting, counting pictures, number identification, and number comparison; cohort 2 – number comparison, number transcoding, ordering, and simple arithmetic; cohort 3 – number transcoding up to 3-digits, ordering and arithmetic up to 2-digits).

Petite Section – Since the pre-mathematical activities in the classroom involve spatial skills in the form of pattern construction and 3D constructions, we expect that visuospatial skills will be important from the first year of preschool at the age of 3 years. Furthermore, as children start to manipulate quantities and learn the meaning for "more than" and "less than", children are able to perform a magnitude comparison task, which measures ANS acuity. Indeed, the ANS has previously been demonstrated to predict mathematics particularly at the start of mathematics education (Libertus et al., 2013), thus we expect the magnitude comparison performance to associate to mathematics at the start of preschool.

Grande Section – 5-year-olds typically understand the counting sequence and can represent Arabic numbers on a mental number line (Gunderson et al., 2012). They can use this mental number line when learning simple additions and subtractions, which are represented by respectively right (up) or left (down) shifts along the number line (Knops, Thirion, et al., 2009). For this reason, we would expect a role for spatial attention starting from the final year in preschool. Related, the underlying capacities required (e.g., understanding place-value) and the strategies used (e.g., counting up and down on fingers) for counting, understanding the order sequence and simple calculations rely on spatial underpinnings (Liu & Zhang, 2022). We would expect visuospatial skills to still play a role in mathematics at the end of preschool.

There is a potential role for inhibition at the age of 5 years, depending on the mathematics competencies of the child. Indeed, children are slowly introduced to strategies to solve mathematics problems in a quicker way (e.g., memorising addition tables rather than counting up and down from a number), urging children to inhibit less adapted strategies (Bull & Scerif, 2001). Nevertheless, not all children at this age are explicitly taught new strategies as this is not formally part of the curriculum yet.

In terms of domain-specific skills, children are slowly introduced to manipulate numerical information (e.g., simple calculations) rather than just discriminating more and less than. Therefore, we hypothesise that while the association between magnitude comparison and mathematics will slowly decrease starting the age of 5 year, the task of addition magnitudes, resembling the newly learning skills of adding small Arabic digits, will increase its association to mathematics.

CE1 – Visuospatial skills have been suggested to be involved in the acquisition of new mathematical skills, but to a lesser extent once those skills have been mastered (Andersson, 2008). Indeed, there seems to be a shift at the age of 6-7 years where verbal memory (in the form of arithmetic memory retrievals) becomes more important to mathematics than visuospatial memory (Coolen & Castronovo, 2023; De Smedt et al., 2009). Thus, visuospatial skills tend to be less important to mathematics as primary school progresses (Coolen & Castronovo, 2023; McKenzie et al., 2003), hence why we expect that visuospatial skills are less associated to mathematics in 7-year-olds compared to the younger age groups. For the same reason we would expect that spatial attention is less important in 7-year-olds, as arithmetical facts are retrieved from the verbal memory rather than calculated through shifts up or down the mental number line. Nevertheless, the literature on spatial skills is somewhat inconsistent in this view, with studies testing the association between spatial skills (e.g., spatial visualisation) and maths showing a stronger relation in higher-level mathematics. It is therefore important to note that only spatial attention and visuospatial memory will be tested in this study, but results are not generalisable towards other spatial skills such as spatial visualisation.

There is a likely role for inhibition, as slower and less adaptive strategies to solve mathematical problems need to be inhibited and replaced by the learned memorisations and operation tables.

In terms of domain-specific skills, we expect that magnitude comparison skills, previously demonstrated to be important at the start of mathematics education rather than later (Libertus et al., 2013), is no longer associated to mathematics, while approximate magnitude addition skills, reflecting the manipulation of quantities could act as an error-check during symbolic arithmetic operations to discard responses that seem far from the expected outcome (Feigenson et al., 2013; Lourenco et al., 2012).

For the reasons outlined above, we expect a divergent set of skills to relate to mathematics at the different ages, see Figure 1.

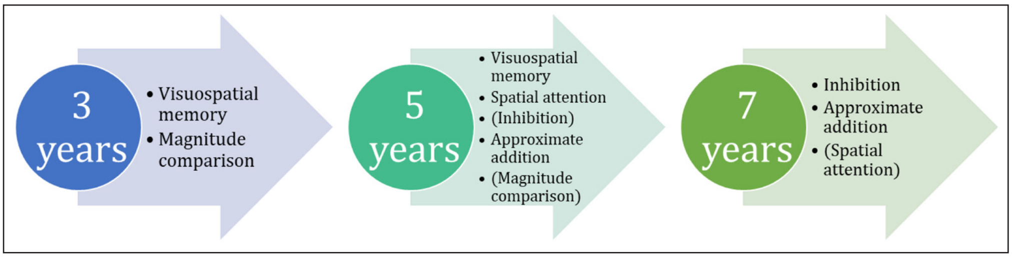

Figure 1 The expected set of domain-general and domain-specific skills per age range, representing the first year of preschool (Petite Section, 3 years), the third and last year of preschool (Grande Section, 5 years) and the second year of primary school (CE1, 7 years).

METHOD

PARTICIPANTS

482 children aged 3 to 7 years took part in this study (246 females, 236 males, M_{age} = 67.06 months, SD_{age} = 18.83 months). Descriptive statistics of the children per age group (*Petit section* (first year of preschool): 3–4 years (N = 159); *Grande section* (third and final year of preschool): 5-6 years (N = 174); *CE1* (second year of primary school): 7–8 years (N = 157)) are presented in Table 1. The children had been recruited from 10 schools in and around Paris as part of a longitudinal study on domain-general and domain-specific contributions to mathematics development. The participants were recruited across two years due to COVID-19 school closures in the first year of testing. Due to the unexpected school interruption during COVID-19 lockdown periods, the year in which participants were tested was added as a random effect in the analysis. The study aimed at a sample size of a minimum of 100 participants per cohort which was obtained. Power analysis with alpha = 0.05, power = 0.8, showed that 34 participants were needed per cohort for a moderate to large effect size with 6 predictors in a regression analysis, which was obtained in this study. Of the 482 participants, 8 participants (5 from cohort 1 and 3 from cohort 2) were excluded prior to data analysis, due to not understanding the instructions because of language barriers. An information sheet and consent form were handed to the parents and children were asked orally whether they wanted to take part in the study. Children, parents, and schools had the option to opt out from the study at any time. Parents from participating children were asked to complete a questionnaire on their level of education (1: primary education completed, 2: secondary education completed, 3: university education completed, 4: PhD completed). Returned responses showed that parent/guardian A had an average of 2.77 and parent/guardian B had an average of 2.73. The study received ethical approval from the Ethics Committee of the Université de Paris Cité (Comité D'Etique de la Recherche U-Paris): 2020-10-KNOPS. This work was supported by the Agence Nationale de la Recherche (ANR-18-CE28-0003). The anonymised data that support the findings of this study and the analysis script have been made available on OSF and can be accessed at https://osf.io/pe3uc/.

PROCEDURE

Children were tested individually in a quiet area on the school premises. Children from cohort 1 were tested in 3 sessions of on average 20 minutes each and children from cohort 2 and 3 were tested in 2 sessions of on average 30-40 minutes each. The order of the task was kept identical for all children within one cohort to ensure a similar experience for all participants.

MATERIAL

Mathematics achievement

Children's mathematics achievement was measured using the Tedi-math (Test for Diagnostic Assessment of Mathematical Disabilities; Grégoire et al., 2003), which allows for an overall composite score of mathematics achievement, as well as specific scores of mathematics subtests. This test covers five numerical and mathematical facets: 1) counting, 2) knowledge of the numerical system, 3) logical operations, 4) estimating number size, and 5) computational abilities. Per cohort, tasks that are adapted at their age range and that were included in their curriculum were included in the measure. Cohort 1 took part in counting, recognising numbers (Arabic and verbal) and comparing numbers (Arabic and verbal). Cohort 2 children took part in comparing numbers, reading and writing numbers, ordering, and simple additions and subtractions. Finally, Cohort 3 children took part in reading and writing up to 3-digit numbers, ordering, up to 2-digit additions and subtractions, and multiplications. Every subtest was transformed to a percentage and the mean percentage of the subtests was used as mathematics performance measure.

Domain-specific skills

Non-symbolic magnitude comparison

To measure ANS acuity, the Panamath Software by Halberda et al. (2008) was used. The perceptual controls chosen were the default settings which were adapted at the different age ranges (cohort 1: 3 years, cohort 2: 5 years, cohort 3: 7 years) by using the default settings for the respective age. This was necessary to avoid ceiling effects as the age differences between the cohorts were too big. In this task, two arrays of spatially separated red and blue dots were simultaneously presented on a laptop screen. Children were instructed to decide whether there were more red or blue dots. The dots were presented in a frame of their colour for 2533ms for cohort 1, 2128ms for cohort 2 and 1789ms for cohort 3, followed by the empty frames until the child gave a response by pressing a red-dot (the key 'f' on a Azerty keyboard) or a blue-dot (the key 'j' on a Azerty keyboard). The number of dots ranged from 5 to 21 dots and the ratios between the two quantities to be compared varied from 1.2 to 1.5 based on the default parameters of the Panamath software for the respective ages. Due to the longer display time and to limit the duration of the task, the number of trials was less in cohort 1. All participants had 2 practice trials and 56 experimental trials for cohort 1 and 72 experimental trials for cohort 2 and 3. In addition, cohort 1 children had 6 practice trials on paper to explain the instructions and to verify whether instructions and the meaning of 'more' were understood. Instructions were repeated when participants made at least one error. Half of the trials had a cumulative surface area that was congruent with the number of dots and half was incongruent. Within each frame the dot sizes varied randomly with an average of 36 pixels and variations up to 20%. The correct answer was presented on the left and right side of the screen with equal probability (50%). The mean accuracy was used as measure as this was previously shown to be the most reliable measure in children (Inglis & Gilmore, 2014).

Non-symbolic magnitude addition

This computerised non-symbolic magnitude Addition task was created on PsychoPy 3. In this task two dot arrays appeared sequentially on the left side of a laptop screen and disappeared sequentially behind a grey occluder. The child was told that a first group of dots fell into the box and that the second group joins the first group in the box. The child was then shown a third dot array on the right side of the screen and was instructed to press one key ('ctrl' key) on the same side as the occluder if they thought that there were more dots in the box or to press another key ('menu' key) on the same side as the third array of dots if they thought there were more dots next to the box. The task consisted of 48 experimental trials with 4 practice trials. First and second operands were sampled with equal probability from the sets {8, 9, 18, 14} and {5, 6, 6, 10}. Outcomes were matched across operations and were either 14 or 24. The response alternatives were varied as a function of their ratio with the correct outcome. Response alternatives were {5, 7, 11, 18, 28, 42}. Non-numerical features of the stimuli were balanced such that the sum of the overall occupied area (sum of pixels), density, the convex hull, or the diameter (individual dot size) could not be systematically used as a cue to solve the task. That means, that the sum of these features of the operands (e.g., convex hull operand 1 + convex hull operand 2) were equally often congruent with the numerical larger/smaller relation between operands sum/difference and response alternative. For example, if the response alternative for the problem 10 + 14 was 72 (i.e., numerically larger), the non-numerical features were either congruent (larger) or incongruent (smaller) with equal probability (i.e., 50%).

The mean accuracy of all trials was used as a measure to remain consistent with the non-symbolic magnitude comparison task.

Domain-general skills

Visuospatial short-term memory

To assess visuospatial short-term working memory, a computerised version of the Corsi block tapping task was used on the experiment builder PEBL2 (Mueller & Piper, 2014), a free psychology software for creating experiments. Nine blue squared appear on screen in a pseudorandom pattern. At a frequency of 1Hz, one of the squares changed colour to yellow until a button "ready" appears at the bottom. The child's task is to remember and reproduce the flashed sequence by touching the squares on the screen in the same order. The length of the flashed sequences increases in difficulty, starting with two flashed squares up to nine flashed squares. Every length is presented two times with a different order to the sequence and the experiment ends with two incorrect responses on the same length. The score for this task (i.e., block span) corresponds to the highest sequence length achieved with at least one correct response.

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Spatial attention

The spatial attention tasks used in this study differed for cohort 1, due to the age difference. A Posner task (Posner, 1980) on tablet created on PsychoPy3 was used to assess spatial skills in cohort 1. A mouse looking to the left (1/3 of the trials), the right (1/3 of the trials) or straight (1/3 of the trials) appeared in the centre of the screen. Subsequently, a cheese appeared either on the right or the left of the mouse. The child was instructed to press as quickly as possible on the cheese. While they were instructed to press as quickly as possible, there was no maximum time limit. The trial was congruent if the cheese appeared on the same side as the mouse was looking (24 trials), incongruent if the cheese was on the opposite side of the direction that the mouse was looking (12 trials) and neutral if the mouse was looking straight ahead (12 trials). The number of congruent trials was twice the number of incongruent trials to create a prepotent response, which had to be inhibited in the incongruent trials. The presence of a congruency effect will be verified in the RT of the tasks before using the RT as measure. No accuracy data is available as the trial was ended when the cheese was pressed, hence resulting in 100% accuracy for all children.

For cohorts 2 and 3, a child-friendly version of the Attentional Networking Task (ANT) was adapted to measure spatial attention (Rueda et al., 2004). Each trial started with a fixation cross in the middle of the screen with a random variable duration between 600ms and 1200ms. After this, an asterisk appeared in 2/3 of the trials above (1/3 of the trials) or below (1/3 of the trials) the fixation point for 100ms. No cue was displayed in the remaining trials. Subsequently, either one yellow fish or a horizontal line of 5 yellow fish was presented above or below the fixation point. Fish that were presented in the same location as the asterisk cue were compatible trials, while fish presented on the opposite location as the asterisk cue were incompatible trials. Fish flanking the one in the middle could be either congruent (50% of the trials, pointing in the same direction as the one in the middle) or incongruent (pointing in the opposite side as the one in the middle). Participants were instructed to press the fish on the keyboard (key ‘q’ for left and key ‘m’ for right on an Azerty keyboard) that was swimming in the same direction as the fish in the middle. The child had 2500ms to respond after which the fish disappeared. The yellow fish were presented on a cyan background. There were 7 practice trials and 54 experimental trials. To check the validity of the task, the compatibility effect between compatible and incompatible trials was calculated in both the RT and accuracy. If both measures presented a compatibility effect, a combined measures would be used, including reaction times (RT) and error rate (ER, 1- accuracy): RT(1+2ER), following Goffin and Ansari (2016) and Lyons et al. (2014).

Inhibition

The inhibition task used in this study differed between cohort 1 and the other cohort due to the age difference. The cancellation task from the WPPSI was used for children from cohort 1. The cancellation task consists of 2 pages in A3-format with multiple drawings (targets and non-targets). The child is instructed to highlight all drawings of things that people can put on them. Although typically used as an attention task, the cancellation task requires children to indicate targets and thus also to inhibit non-targets (Brucki & Nitrini, 2008). This is in line with interference control as inhibition type. The number of correctly highlighted targets minus the number of the incorrectly highlighted items was used as measure.

For cohorts 2 and 3, the Bivalent Shape Task (BST) on the experiment builder PEBL2 was used to assess interference control (Mueller & Esposito, 2014). The participant is instructed to determine whether a shape in the middle of the screen is a circle or a square. If the target is a circle, the participant needs to press a key on the left with a red circle on it. If the target is a square, the participant needs to press the key on the right with a blue square on it. To remind the participant which side to press, a red circle is displayed under the target on the left and a blue square is displayed under the target on the right. The target shape in the middle of the screen is presented either in red, blue or white, creating congruent (i.e., red circle, blue square), incongruent (i.e., blue circle, red square) and neutral (i.e., white shapes) trials. To check the validity of the BST, the congruency effect between congruent and incongruent trials was analysed in both the RT and accuracy. If both measures presented a compatibility effect, a combined measures would be used (RT(1+2ER)).

RESULTS

ANALYSIS PLAN

The main analysis consisted of three mixed effect regression models, using the 'nlme' package in R (R Core Team, 2021; RStudio Team, 2020) to explore the variance in overall mathematics scores accounted for by each cognitive skill at different education levels (i.e., per cohort). Per cohort, in the first step age, gender, and SES (i.e., education level of parent A and education level of parent B separately) were entered as fixed predictors of overall maths scores, while school and year of testing were entered as random effect. Note that R-square per regression model will not be reported due to the complexity of the mixed-effect model including two random effect, because the random effect capturing variation at the group-level is not directly quantified by R-square and interpretations would be challenging or misleading (Harrison et al., 2018). In a second step all domain-specific and domain-general skills were added as fixed predictors: NSadd (mean accuracy), Panamath (mean accuracy), distractor inhibiton (i.e., Cancellation (accuracy) or BST (RT(1+2ER)), depending on cohort), ANT (RT), and Corsi Block (block span). In a third step, 2-way interaction were added to the model to explore the interactions between domain-general and domain-specific skills (NSadd*BST; NSadd*ANT; NSadd*Corsi; Panamath*BST; Panamath*ANT; Panamath*Corsi). Non-significant interactions within all models were excluded from the final model description.

A second set of mixed regressions were conducted to examine domain-general and domain-specific factors related to each subtest of mathematics per cohort. Note that while the symbolic magnitude comparison subtest was tested in cohort 3, this was not included in the composite maths score for cohort 3, as this is not part of the curriculum for 7-year-olds. This subtest will be included in the separate regressions per subtest to enable comparisons between cohorts of this measure.

PRELIMINARY ANALYSES

Missing data and outliers

A total of 8.28% of the data was missing (Cohort 1: 11.11%; Cohort 2: 5.78%; Cohort 3: 8.28%). The missing data was explored for reasons, which included COVID-19 school closures before finishing all tests (e.g., cancellation, Posner, Panamath and BST), computer failure or interruptions by school-related activities such as break period. The patterns for missing data were explored and a Little's test to assess whether data was missing at random was carried out on each cohort separately. We found that missing data were missing at random, cohort 1: $\chi^2 = 22.4$, df = 20, $p = .32$; cohort 2: $\chi^2 = 21.2$, df = 21, $p = .449$; cohort 3: $\chi^2 = 38.4$, df = 26, $p = .056$. Cohort 3 was explored further due to a p-value close to significance, and missing data patterns were due to COVID-19 school closures (16 participants did not complete the final two tests, BST and Panamath). To retain a maximum of the sample size and because the reason for missing values were judged to be missing at random, the missing values were imputed using the 'mice' package in R (v3.13.0; van Buuren & Groothuis-Oudshoorn, 2011) with 10 imputations following the rule of thumb that the number of imputations should be similar to the percentage of incomplete cases (White, Royston, & Wood, 2011). Results from regression analyses were combined across the 10 imputed datasets and the combined results are presented. Outliers that were 2 SD from the task mean were explored but not deleted because they were judged as reflecting the true variability in classrooms.

Task validity

To assess the validity of the ANT/Posner task and the BST task, the presence of a congruency and/or compatibility effect was examined. Therefore, ANOVAs with congruency and cohort as factors and an interaction term were conducted to compare congruent to incongruent trials and cohort on mean reaction times (RT) and accuracy for the BST and to compare compatible to incompatible trials and cohort on mean RT and accuracy for the ANT. A paired-samples t-tests was conducted to compare the mean reaction times (RT) and accuracy of congruent and incongruent trials for the Posner task.

There was a significant main effect of cohort on the BST RT, $F(1,582) = 142.14$, $p < .001$, with cohort 3 having lower RT and thus higher performance on the BST task than cohort 2 and a significant main effect of congruency with quicker mean RT of congruent trials (M = 911.88, SD = 153.25) compared to incongruent trials (M = 938.83, SD = 168.53) on the BST task, $F(1,582) = 5.09$, $p = .024$. The interaction was not significant, indicating a congruency effect in RT of the BST in both cohorts, $F(1,582) = 0.94$, $p = .334$. There was also a significant main effect of cohort on the BST accuracy, $F(1,582) = 22.25$, $p < .001$, with cohort 3 scoring more accurate compared to cohort 2, and a significant main effect of congruency, with the mean accuracy of the congruent trials (M = 0.90, SD = 0.09) being significantly higher than the incongruent trials (M = 0.87, SD = 0.1) in the BST task, $F(1,582) = 14.04$, $p < .001$. Again, the interaction between cohort and congruency (accuracy) was not significant, indicating a congruency effect in accuracy on the BST in both cohorts, $F(1,582) = 2.37$, $p = .124$. Since the congruency effect was confirmed for both the RT and the accuracy of the BST, a combined measure of accuracy and RT was used, where the performance was RT(1+2 Error Rate) following Lyons et al. (2014) and Goffin and Ansari (2016).

To examine the presence of a congruency effect in the Posner task, a paired sample t-tests was conducted on the RT of congruent vs. incongruent trials. The accuracy was not useful as the target remained displayed until a correct response, resulting in 100% accuracy for all participants. There was no significant differences between the mean RT of the congruent trials (M = 0.90, SD = 0.09) and the incongruent trials (M = 0.90, SD = 0.09), $t(109) = 0.39$, $p = .65$, indicating that the Posner task was not successful and cannot be used as a valid spatial attention task. This task will be excluded from future analyses.

Finally, the presence of a compatibility effect in the ANT will be examined in RT and accuracy. ANOVA demonstrated that there was a significant main effect of cohort on the ANT RT, $F(1,636) = 183.14$, $p < .001$, with cohort 3 having lower RT scores than cohort 2, and a significant main effect of compatibility on the ANT RT with the mean RT of compatible trials (M = 1066.23, SD = 161.13) being significantly faster than the incompatible trials (M = 1107.57, SD = 150.52), $F(1,636) = 14.48$, $p < .001$. There was no significant interaction between cohort and compatibility, indicating a compatibility effect in both cohorts, $F(1,636) = 2.25$, $p = .134$. There was a significant main effect of cohort on the accuracy of the ANT, $F(1,636) = 116.43$, $p < .001$, with cohort 3 outperforming cohort 2. However, there was no significant difference between the mean accuracy of compatible trials (M = 0.84, SD = 0.15) and incompatible trials (M = 0.85, SD = 0.15) in the ANT, $F(1,636) = 0.22$, $p = .642$. There was no significant interaction between cohort and compatibility on the ANT accuracy, $F(1,636) = 0.10$, $p = .760$. Due to the insignificant compatibility effect in the accuracy of ANT, the accuracy measure will not be used in the analyses and the difference in RT between incompatible and compatible trials will be used as ANT measure.

Descriptive and correlation analyses

Table 1 displays all tasks' mean, standard deviation and range per cohort. Correlational matrices for all tasks per cohort are displayed in supplementary material in Tables A1, A2, and A3.

Table 1 Descriptive statistics for all tasks and demographic information per cohort.

	COHORT 1 (N = 154; 75 MALES)			COHORT 2 (N = 171; 74 MALES)			COHORT 3 (N = 157; 87 MALES)		
	M	SD	RANGE	M	SD	RANGE	M	SD	RANGE
Age (months)	43.89	3.57	37–50	66.97	3.58	58–74	89.73	4.65	77–108
Tedi-math	0.33	0.14	0.13–0.85	0.55	0.24	0.10–1	0.82	0.16	0.13–1
Panamath	72.44	15.12	37.7–98.2	77.75	10.41	34.4–100	84.76	8.77	59.2–98.6
NS addition	0.64	0.12	0.39–0.89	0.74	0.11	0.28–0.96	0.82	0.08	0.50–0.98
Cancel/BST	18.06	9.66	0–41	42.29	127.07	–530–392	18.24	89.81	–223–388
Posner/ANT	–	–	–	25.75	117.63	–463–412	58.37	83.87	–186–267
Corsi	1.97	0.78	1–4	3.5	0.94	1–6	4.24	0.97	1–8
Education 1	2.86	0.56	1–4	2.69	0.76	1–4	2.77	0.71	1–4
Education 2	2.80	0.58	1–4	2.69	0.72	1–4	2.69	0.70	1–4

REGRESSION ANALYSES

The basic models including age, education_parent1, education_parent2, and gender per cohort showed that age was the only significant variable in cohort 1, B = .015 (SE = .003, $p < .001$). Cohort 2 had age, B = .012 (SE = .005, $p = .012$) and education of parent 2, B = .076 (SE = .038, $p = .048$) as significant variables. For cohort 3, the basic model showed age, B = .008 (SE = .003, $p = .003$), and education of parent 1, B = .069 (SE = .021, $p = .002$) as significant variables. Therefore, age, education_parent1 and education_parent2 were included in the following models together with domain-general and domain-specific skills.

Cohort 1: regression coefficients for the model including all domain-general and domain-specific measures and their significant interactions for cohort 1 are displayed in Table 2. The only significant factor related to mathematics performance in cohort 1 for the pooled results is the mean accuracy of Panamath, B = .002 (SE = .001, $p = .001$).

No interaction between domain-general and domain-specific skills are significant, $p > .059$.

Table 2 Summary of regression analysis for variables related to mathematics in Cohort 1.

PREDICTORS	B	SE	t	p
Age (months)	.005	.003	1.49	.139
Edu_1 (SES)	.029	.022	1.27	.208
Edu_2 (SES)	–.002	.020	–0.08	.936
Panamath (magnitude comparison)	.003	.001	3.26	.001
NS addition (magnitude addition)	.180	.103	1.74	.084
Cancellation (inhibition)	.002	.002	1.64	.111
Corsi (visuospatial memory)	.022	.015	1.49	.139

Cohort 2: Table 3 demonstrates the regression coefficients for the mixed model including all domain-general and domain-specific measures related to mathematics performance. Significant variables related to mathematics performance in cohort 2 are Corsi block tapping task, B = .081 (SE = .019, $p < .001$), mean accuracy of the Panamath task, B = .004 (SE = .002, $p = .022$), and mean accuracy of NSadd, B = .369 (SE= .160, $p = .023$).

No interactions between domain-general and domain-specific skills are significantly related to mathematics in cohort 2, $p > .307$.

Table 3 Summary of regression analysis for variables related to mathematics in cohort 2.

PREDICTORS	B	SE	t	p
Age (months)	.003	.005	0.72	.471
Edu_1 (SES)	.022	.032	0.69	.489
Edu_2 (SES)	.057	.036	1.59	.117
Panamath (magnitude comparison)	.004	.002	2.31	.022
NS addition (magnitude addition)	.369	.160	2.30	.023
BST (inhibition)	.000	.000	0.91	.365
ANT (spatial attention)	–.000	.000	–0.16	.869
Corsi (visuospatial memory)	.081	.019	4.33	<.001

Cohort 3: Table 4 displays the regression coefficients for the model including all domain-specific and domain-general variables and their significant interactions related to mathematics performance in cohort 3. The significant variables related to mathematics performance are the mean accuracy of Panamath, B = .004 (SE = .001, $p = .002$), and the mean accuracy of NSadd, B = .370 (SE = .141, $p =.010$).

No interaction between domain-general and domain-specific skills related to mathematics are significant, $p > .304$.

PREDICTORS	B	SE	t	p
Age (months)	.005	.002	1.89	.061
Edu_1 (SES)	.043	.021	2.04	.045
Edu_2 (SES)	.044	.023	1.94	.059
Panamath (magnitude comparison)	.004	.001	3.18	.002
NS addition (magnitude addition)	.370	.141	2.63	.010
BST (inhibition)	–.000	.000	–1.05	.298
ANT (spatial attention)	.000	.000	1.32	.190
Corsi (visuospatial memory)	.016	.011	1.39	.166

Table 4 Summary of regression analysis for variables related to mathematics in cohort 3.

Per cohort, separate mixed effect regressions with the same control variables for consistency (age, SES_1, SES_2 as fixed effects and school and year of testing as random effects) were carried out for each maths subtest (i.e., cohort 1: counting, counting pictures, number identification; cohort 1, 2, and 3: number comparison; cohort 2 and 3: number transcoding, ordering, arithmetic). Subtests that are the same for multiple cohorts can increase in difficulty (i.e., number comparison, number transcoding and arithmetic). The arithmetic subtest in cohort 2 consists of simple (e.g., single digits or no carry-over) additions and subtractions. The arithmetic subtest in cohort 3 consist of additions and subtractions (including 2-digit and carry-over problems) and single digit multiplications. Figure 2 illustrates the significant cognitive variables related to different maths subtest per cohort after Holm-Bonferroni corrections for multiple comparisons. Table A4 in supplementary material illustrates the regression coefficients of all regressions with Holm-Bonferroni correction. Table A5 in supplementary material illustrates the regression coefficients without Holm-Bonferroni correction for informative purposes, but should not be interpreted.

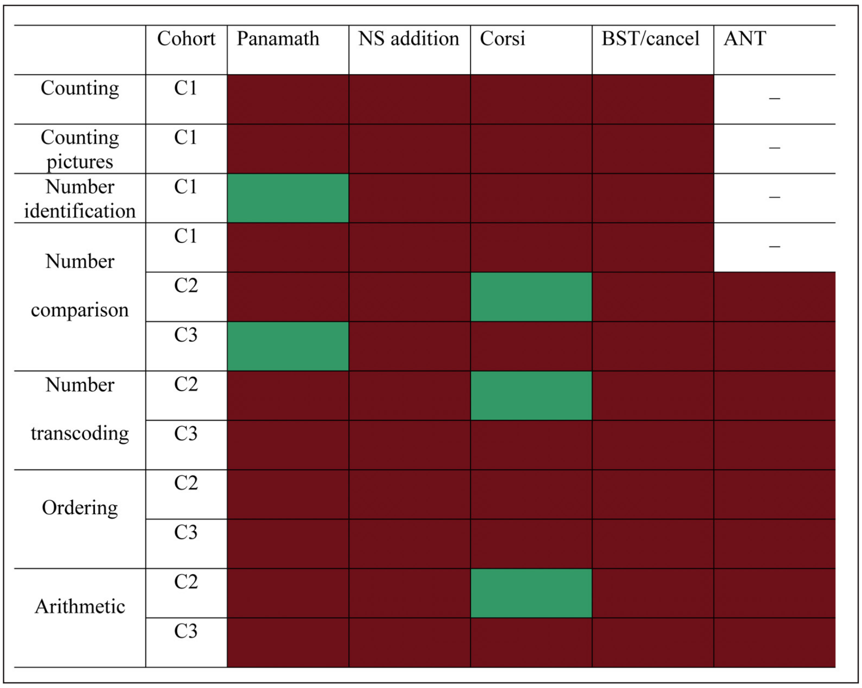

Figure 2 Display of Holm-Bonferroni corrected significant (green) and non-significant (red hatched) variables related to separate maths subtests per cohort.

DISCUSSION

The overall aim of this study was to identify unique domain-specific and domain-general contributions and their interactions in the development of mathematics taking into account the maths activities performed in the classroom at different ages, 3 years, 5 years and 7 years. Overall non-symbolic magnitude skills appear important in the development of mathematics in all three cohorts. Visuospatial memory seems mostly important at the age of 5 years and no significant role was found for inhibition and spatial attention throughout the development of mathematics in the ages 3, 5, or 7 years (see Figure 3). A slightly more divergent view between cohorts appears when exploring the relations between cognitive skills and separate mathematics subtests.

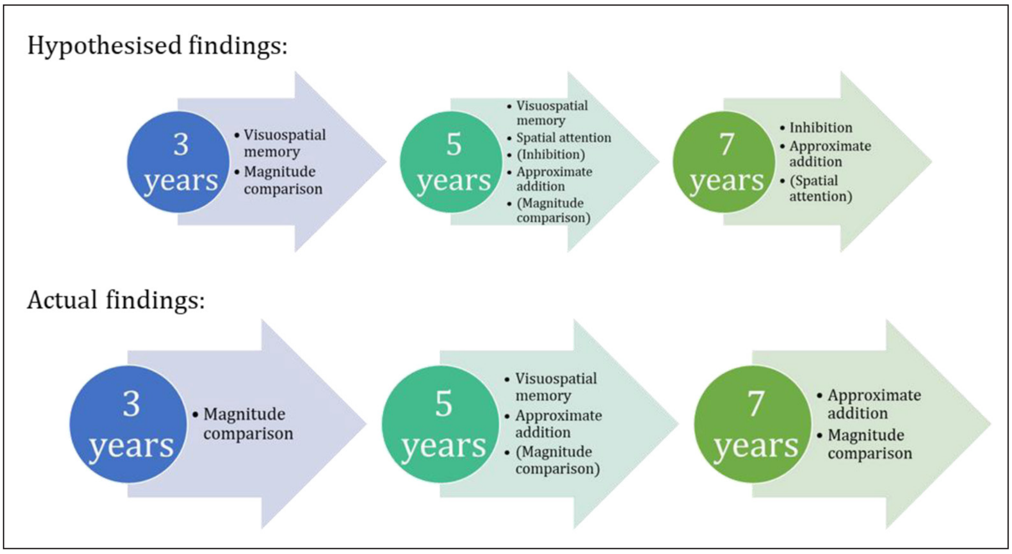

Figure 3 Comparison of the set of hypothesised significant skills to the set of actual significant domain-general and domain-specific skills per age range related to overall mathematics score, representing the first year of preschool (Petite Section, 3 years), the third and last year of preschool (Grande Section, 5 years) and the second year of primary school (CE1, 7 years).

COHORT 1 (3-YEAR-OLDS)

The first cohort corresponds to 3-year-old-children in the first year of preschool in France. At this age, children start to learn the meaning of numbers and their corresponding cardinal value as well as having pre-mathematics activities such as pattern constructions and block building. For this reason, visuospatial memory and magnitude comparison skills were hypothesised as important variables in relation to mathematics skills at this age. Nevertheless, only magnitude comparison skills were significantly related to mathematics skills. This is likely due to the items included in the mathematics task, which do not directly reflect spatial components of mathematics (e.g., pattern constructions, recognising shapes). Although fostering spatial skills through patterns and block building in preschool have been suggested to be important for later mathematics (Wijns et al., 2020), this is possibly a link that is not yet formed in the first year of preschool. Note that other spatial skills not taken into account in this study, such as spatial visualisation may be positively associated with math performance at that age. Indeed, it has been suggested that spatial visualisation may help to construct a relation between space and numbers in early development (Hawes & Ansari, 2020). Here, only number identification was related to non-symbolic magnitude comparison skills.

COHORT 2 (5-YEAR-OLDS)

The second cohort corresponds to 5-year-old-children in the third and last year of preschool in France. Children at this age are expected to understand the basics of numbers (e.g., Arabic digits, cardinal knowledge), know the counting sequence and start to learn how to manipulate Arabic numbers in simple calculations (e.g., 2 + 3). As expected, magnitude comparison, non-symbolic addition and visuospatial short-term memory were related to mathematics achievement. A more nuanced view was found when examining the different mathematics subtests, where the most important cognitive skill was visuospatial short-term memory in three subtests (i.e., Number comparisons, Number transcoding, and arithmetic) and no role for the domain-specific measures (i.e., non-symbolic addition task, magnitude comparison task). Indeed, previous literature is in line with visuospatial short-term memory playing an important role in learning mathematics at the age of 5 years (Coolen & Castronovo, 2023), which can reflect visuospatial strategies to solve mathematical problems used at this age such as finger counting.

Contradictory to our hypotheses, inhibition and spatial attention did not significantly relate to mathematics. The role of inhibition in mathematics performance at the age of 5 years was unclear, as some new strategies to solve mathematical problems (e.g., memory retrieval for simple calculations) are already introduced at this age, which might require inhibition of older strategies, although new strategies might not yet be adopted by most children. Indeed, as shown by the results for cohort 2, at the end of preschool, children use visuospatial strategies in mathematics performance and might not yet use other more verbal strategies.

Spatial attention had been hypothesised to play a role when children use their numerical representations on the mental number line when calculating additions and subtractions (Gunderson et al., 2012). Nevertheless, this was not reflected in the results. van Galen and

Reitsma (2008) argue that while magnitude-spatial associations might be present from a young age, the automatic activation of a spatial representation of Arabic numbers does not emerge until the age of 9 years. In addition, Pinheiro-Chagas et al. (2018) demonstrated that the Operational Momentum (i.e., the tendency to overestimate addition outcomes and underestimate subtraction outcomes), a bias thought to originate from the spatial-numerical link was present in 9-year-olds and resembled the bias as found in adults, while it was not yet present in 8-year-old children.

COHORT 3 (7-YEAR-OLDS)

The third cohort corresponds to 7-year-old-children in the second year of formal primary education in France. At the age of 7 years, French pupils learn to manipulate up to 3-digit numbers and are instructed to memorise addition, subtraction, and multiplication tables rather than using slower more visuospatial strategies (e.g., finger counting). Therefore, visuospatial short-term memory and spatial attention had been hypothesised to be less important in this cohort, as verbal skills, which was not measured in this study, were likely to become more important. Inhibition was hypothesised to play a role as a new strategy of verbal memorisation of calculations had to replace previous visual strategies that had to be inhibited. Furthermore, as non-symbolic additions might act as an error-check during symbolic arithmetic operations (Feigenson et al., 2013; Lourenco et al., 2012), this skill was expected to play a role, but not magnitude comparison, which has been shown to play a smaller role with age (Coolen et al., 2022).

Contradictory to what we hypothesised, only domain-specific skills (both magnitude comparison and non-symbolic addition) were significantly related to mathematics at the age of 7 years. Nevertheless, visuospatial short-term memory was significantly related to the subtest arithmetic in this cohort. On the other hand, the magnitude comparison measure was significantly related to the subtest number comparison (not included in the overall mathematics score for cohort 3). Indeed, visuospatial skills have been suggested to be involved in the acquisition of new mathematical skills (in this cohort arithmetic problems such as multiplications), but to a lesser extent once mathematical skills have been mastered (Andersson, 2008). Thus, the role of visuospatial short-term memory only in arithmetic is not surprising. Furthermore, as verbal skills were not included in this study, a shift from visuospatial skills to verbal skills could not be tested, despite the role that verbal skills likely play throughout the development of maths (e.g., Peng et al., 2020). The significant role for both domain-specific skills (i.e., magnitude comparison and non-symbolic addition) simultaneously reflects previous research highlighting that while both measures represent non-symbolic magnitude skills, they are somewhat separable in underlying capacities (Coolen et al., 2022; Gilmore et al., 2011). Inhibition had been hypothesised as playing a significant role in mathematics performance in 7-year-old-children, which was not confirmed in the results. In Lee and Lee (2019), the authors reviewed recurring inconsistent and weak links between inhibition and mathematics in previous developmental research and argue that inconsistencies could originate from one of four reasons (a. age-related, b. measurement issues, c. the sensitivity of the inhibition task, d. the amount of inhibition in mathematics tasks). Due to the inclusion of different age groups and different mathematical subtests, it is likely that the lack of a role for inhibition in mathematics performance in the current study originates from the choice of inhibition task and how it might match (or mismatch) with the mathematical tasks chosen. Inhibition is likely to play a role in different arithmetic problem solving contexts. Most prominently, the selection of the correct result of a given multiplication problem from long-term memory involves the inhibition of incorrect, table-related results (e.g., Verguts & Fias, 2005). Furthermore, inhibition is likely to be involved in suppressing inappropriate strategies or irrelevant information such as information from a context problem that is irrelevant to the problem itself. During other multi-step arithmetic problem solving strategies, inhibition may serve to filter intermediate results or prevent the intrusion of incorrect numerical associations. Against this background, the lack of correlation in the investigated age groups may be due to the lack of these factors in the tested performance measures. The lack of correlation in the current study may be due to the limited strategy repertoire and lack of irrelevant context information in the tested mathematical abilities. According to these considerations, inhibition should become more important with increasing complexity of the mathematical operations. The current finding echoes previous reports of lowered correlation between inhibition and tests of specific mathematical abilities compared to the correlation between inhibition and general mathematical achievement tests (i.e., curricular tests; Friso-van den Bos, van der Ven, Kroesbergen, & van Luit, 2013). Results for cohort 3 should be interpreted with caution due to ceiling effects in some of the mathematics subtests, in particular in ordering and number transcoding, which might lead to inaccurate predictions.

ROLE OF THE ANS IN DEVELOPMENT

The ability to discriminate two sets of objects on the basis of their cardinality represented the only predictor that was significantly related to mathematical skills in all age groups. This is remarkable since the domain-specific components that contributed to the overall math-score diverge to a large degree between age groups and children in cohort 3 approached ceiling performance for a number of constituting aspects of math skills. Despite these limiting factors, higher ANS acuity was associated with higher math performance. This is in line with previous findings (Pinheiro-Chagas et al., 2014) and the idea that the ANS represents a domain-specific factor that provides a scaffold for the development of symbolic mathematical skills throughout development. In analysing in more detail which mathematical capacity is associated with the ANS acuity, the current study goes beyond previous studies. We found that ANS acuity is significantly associated with number-related capacities (number comparison, number identification) rather than arithmetic or ordinality. This could be equally interpreted as evidence for either the idea that the ANS provides a scaffold for the acquisition of the cardinal principle or the idea that it facilitates the mapping of number words onto the ANS (Szkudlarek & Brannon, 2017). Note that there is a discussion in the current literature as to whether or not inhibition is partially driving the correlation between ANS acuity and maths performance (Fuhs & McNeil, 2013; Gilmore et al., 2013; but see Keller & Libertus, 2015; Pinheiro-Chagas et al., 2014). It is suggested that inhibition helps children to inhibit irrelevant information in a magnitude comparison task such as visual features (dots size, convex hull, density, etc) to better extract the numerical information. Indeed, Gilmore et al. (2013) found that only the incongruent trials from a magnitude comparison task related to maths achievement, while these trials require the inhibition of salient visual features and congruent trials do not. In addition, they found that the magnitude comparison task was no longer significantly related to maths when controlling for inhibition skills. In the current study, both inhibition and magnitude comparison were taken into account, hence controlling for inhibition in the association between magnitude comparison and mathematics. Since the inhibition measure was not significantly related to mathematics and no interaction was found between inhibition and magnitude comparison, the results of this study support the interpretation that inhibition does not drive the association between ANS acuity and maths performance. Nevertheless, keeping in mind the inconsistent results in the literature regarding the association between inhibition tasks and mathematics and a possible mismatch in the inhibition task chosen in this study, the current findings cannot rule out a potential influence of inhibition partially accounting for the link between ANS acuity ad maths performance.

INTERACTIONS

As a secondary aim in this study, potential interactions between domain-general and domain-specific skills in relation to mathematics performance were explored. The expected interactions between domain-general and domain-specific skills were not found in this study. This is likely due to the cross-sectional design of the study, which does not allow to explore interactions between cohorts. Future longitudinal data will enable us to explore potential shifts between domain-general and domain-specific skills across development.

CONCLUSION

In sum, we hypothesised that domain-general and domain-specific skills related to mathematics skills would differ depending on the ages, reflecting the mathematics skills learned at that age. Although the findings do not fully overlap with the hypotheses, differences in unique contributions to mathematics per age range can be found. The magnitude comparison task reflecting ANS acuity is the only task that plays a consistently significant role in mathematics performance across all three cohorts, although less when exploring its role in separate mathematics subtests. Approximate addition skills, which represent a somewhat separable skill to magnitude comparison as demonstrated by the findings in this study and previous literature (Coolen et al., 2022; Gilmore et al., 2011) and the fact that they shared between 3% and 23%

of variance in our samples, only starts to play a role in mathematics from the age of 5 years. On the other hand, visuospatial memory plays an important role in mathematics and across most subtests, at the age of 5 years. This is in line with previous research demonstrating an important role for visuospatial memory in 5-year-olds, followed by a shift from visuospatial to verbal memory starting the age of 6 years (Coolen & Castronovo, 2023; De Smedt et al., 2009), reflecting the strategies used in mathematics tasks (e.g., visual finger counting or arithmetic retrieval from the verbal memory).

DATA ACCESSIBILITY STATEMENT

The pseudonymous data that support the findings of this study and the analysis script have been made available on OSF and can be accessed at https://osf.io/pe3uc/

ADDITIONAL FILE

The additional file for this article can be found as follows:

- **Supplementary material.** Tables A1 to A5. DOI: https://doi.org/10.5334/joc.309.s1

ETHICS AND CONSENT

The study received ethical approval from the Ethics Committee of the Université de Paris Cité (Comité D'Etique de la Recherche U-Paris): 2020-10-KNOPS. An information sheet was provided to the parents and a signed informed consent form was required to let their child participate in this study, with the option to withdraw from the study at any time.

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COMPETING INTERESTS

The authors have no competing interests to declare.

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