Journal of Experimental Child Psychology 178 (2019) 104–120

Contents lists available at ScienceDirect

Journal of Experimental Child Psychology

journal homepage: www.elsevier.com/locate/jecp

What predicts mathematics achievement? Developmental change in 5- and 7-year-old children

Fanny Gimbert [a], Valérie Camos [b], Edouard Gentaz [a,c], Karine Mazens [a,*]

[a] University of Grenoble Alpes, CNRS, LPNC, 38000 Grenoble, France
[b] Department of Psychology, Fribourg Center for Cognition, University of Fribourg, 1700 Fribourg, Switzerland
[c] Sensorimotor, Affective and Social Development Unit, University of Geneva, 1211 Geneva, Switzerland

A R T I C L E I N F O

Article history:
Received 11 May 2017
Revised 6 July 2018

Keywords:
Approximate number system
Number line estimation
Working memory
Mathematics achievement
Child development
Mathematical Learning

A B S T R A C T

Many changes occur in general and specific cognitive abilities in children between 5 and 7 years of age, the period coinciding with entrance into formal schooling. The current study focused on the relative contributions of approximate number system (ANS) acuity, mapping precision between numeral symbols and their corresponding magnitude (mapping precision) and working memory (WM) capacity to mathematics achievement in 5- and 7-year-olds. Children's performance was examined in different tasks: nonsymbolic number comparison, number line estimation, working memory, mathematics achievement, and vocabulary. This latter task was used to determine whether predictors were general or specific to mathematics achievement. The results showed that ANS acuity was a significant specific predictor of mathematics achievement only in 5-year-olds, mapping precision was a significant specific predictor at the two ages, and WM was a significant general predictor only in 7-year-olds. These findings suggest that a general cognitive ability, especially WM, becomes a stronger predictor of mathematics achievement after entrance into formal schooling, whereas ANS acuity, a specific cognitive ability, loses predictive power. Moreover, mediation analyses showed that mapping precision was a partial mediator of the relation between ANS acuity and mathematics achievement in 5-year-olds but not in 7-year-olds. Conversely, in 7-year-olds but not in 5-year-olds, WM fully mediated the relation between ANS acuity and mathematics achievement. These results showed that between 5 and 7 years of

* Corresponding author.
E-mail address: karine.mazens@univ-grenoble-alpes.fr (K. Mazens).

https://doi.org/10.1016/j.jecp.2018.09.013

age, the period of transition into formal mathematical learning, important changes occurred in the relative weights of different predictors of mathematics achievement.

Introduction

The cognitive foundations of children's mathematical learning constitute a current and fruitful topic in numerical cognition. Many studies have been interested in identifying math-specific cognitive precursors for mathematics achievement at an early age (Chu, vanMarle, & Geary, 2015; Cragg & Gilmore, 2014; Dehaene, 1997; LeFevre et al., 2010; Sasanguie, De Smedt, Defever, & Reynvoet, 2012). Among these predictors, the importance of the ability to mentally represent and manipulate approximate magnitude is particularly debated. This primitive ability to make approximate numerical judgments, shared by humans and nonhuman animals, relies on a common nonverbal system to represent quantities called the approximate number system (ANS). Another ability, the mapping between numeral symbols and their corresponding magnitude (mapping precision), has also been proposed to predict mathematics achievement (e.g., De Smedt, Verschaffel, & Ghesquière, 2009; Siegler & Booth, 2004). Finally, working memory (WM) capacity is well known to be a robust predictor of mathematics achievement (for meta-analyses, see Friso-van den Bos, van der Ven, Kroesbergen, & van Luit, 2013; Peng, Namkung, Barnes, & Sun, 2016). Although ANS acuity, mapping precision, and WM have been considered relevant predictors of mathematics achievement in recent theoretical and empirical models (Geary, 2013; Wong, Ho, & Tang, 2016), no study has directly examined their respective weights on mathematics achievement at different ages during childhood. Indeed, previous research studying these three abilities and mathematics achievement has mostly been conducted with one age group (Xenidou-Dervou, De Smedt, van der Schoot, & van Lieshout, 2013) or with a longitudinal design (Wong et al., 2016; Xenidou-Dervou, Molenaar, Ansari, van der Schoot, & van Lieshout, 2017). The specific approach of the current study relies on the fact that we assessed developmental changes with entrance into formal schooling in the respective weights of these three cognitive abilities on mathematics performance. Because we used the same tasks to measure the different abilities at two different ages, 5 and 7 years, any differences observed between these ages can be attributed to developmental differences and not methodological differences.

The role of ANS acuity

ANS acuity is the degree of precision with which one quantity can be discriminated from another. To measure it, most studies have used the nonsymbolic large number comparison task. In this task, participants are presented with two distinct sets of dots on a screen and are asked to find the largest set (e.g., Dietrich, Huber, & Nuerk, 2015). A major feature of the ANS is that it follows Weber's law—that is, the discriminability of two quantities depends on their ratio rather than on their absolute numerical difference (Moyer & Landauer, 1967). Some authors argue that the ANS could serve as a foundation for mathematical skills development (Dehaene, 2001; Feigenson, Dehaene, & Spelke, 2004). If the sensitivity to approximate quantities serves as a foundation for mathematical skills, individual differences in ANS acuity should affect their acquisition. Results from correlational studies have supported this view, showing a positive relation between ANS acuity and mathematics performance, but at the same time other studies have failed to find such a significant relation (for reviews, see De Smedt, Noël, Gilmore, & Ansari, 2013; Feigenson, Libertus, & Halberda, 2013; and Nath & Szűcs, 2016).

Three recent meta-analyses have attempted to resolve this discrepancy and confirmed a modest but significant relation ($r \sim .20$) between performance in ANS tasks and mathematics achievement (Chen & Li, 2014; Fazio, Bailey, Thompson, & Siegler, 2014; Schneider et al., 2016). They have also shown that the discrepancies in the literature about the relation between ANS acuity and mathematics achievement can be explained by different factors such as the age of the participants and the scoring procedure. According to Fazio et al.'s (2014) meta-analysis, the link between ANS acuity and mathematics achievement is stronger before children begin formal mathematics instruction ($r = .40$) than after (i.e., 6-year-olds, $r = .17$). However, according to Chen and Li (2014), this correlation is similar in children under 12 years old (3–12 years, $r = .25$) and adults over 17 years old ($r = .22$). Moreover, in Schneider et al.'s (2016) meta-analysis, the relation between magnitude comparison (i.e., including nonsymbolic number comparison and symbolic number comparison performance) and mathematics achievement was weakly moderated by age. Schneider et al. (2016) also showed that the relation between magnitude comparison and mathematics achievement depended on the task used to assess mathematical competence. This last result is in line with Libertus, Feigenson, and Halberda (2013), who found that 3- to 7-year-olds' ANS acuity correlated with their informal mathematics abilities (e.g., counting objects, informal verbal calculation problems) but not with their formal mathematics abilities (e.g., numeral literacy, mastery of number facts, written calculation skills).

These findings suggest that the measures used to assess ANS acuity and mathematics achievement must be carefully chosen to study the relation between these two abilities. Moreover, as highlighted by Schneider et al. (2016), methodological differences between studies are often confounded with an age effect. To our knowledge, the development of the relation between ANS acuity and mathematics achievement before and after entrance into formal schooling has never been examined in the same cross-sectional study with the same methodological choices applied for different age groups.

The role of mapping precision between number symbols and magnitude

Mapping between number symbols and magnitude refers to the ability to associate symbolic numbers (i.e., number words and Arabic numerals) and their corresponding magnitudes. Its precision is commonly measured with estimation tasks (e.g., Barth, Starr, & Sullivan, 2009; Libertus, Odic, Feigenson, & Halberda, 2016; Lipton & Spelke, 2005; Wong et al., 2016). In estimation tasks, participants need to either produce an analogical representation of quantity from a symbolic number or the opposite. In children, the number line estimation task proposed by Siegler and Opfer (2003) has been extensively used in many studies at different ages (e.g., Booth & Siegler, 2006; Geary, 2011; Wong et al., 2016). In this task, children are presented with symbolic numbers and are asked to estimate their locations on a horizontal bounded line (e.g., 0–10, 0–100, 0–1000). To place the position of a symbolic number on this line, children need to rely on their nonsymbolic quantity representation. Mapping skills are more developed when children are able to estimate the number position accurately. The 0–100 version of this task has been used in children before and after entrance into formal schooling, and children's performance in this task was shown to correlate with mathematics achievement (e.g., Sasanguie, Göbel, Moll, Smets, & Reynvoet, 2013; Siegler & Booth, 2004; Xenidou-Dervou, van der Schoot, & van Lieshout, 2015).

However, developmental changes with entrance into formal schooling do not appear clearly in the relationship between mapping precision and mathematics achievement. Siegler and Booth (2004) found correlations between accuracy (i.e., percentage absolute error) in the number line estimation task (0–100 version) and mathematics achievement that did not significantly differ between kindergarten children and second graders ($r = -.45$ and $r = -.37$, respectively, $z = -0.29$, $p = .39$). With other age groups—first, second, and third graders—Sasanguie et al. (2013) did not observe an important developmental difference in the relation between these two measures. These results and the few developmental data in 5- and 7-year-olds do not allow for a prediction of a potential change on the relationship between mapping precision and mathematics achievement.

The role of WM capacity

WM refers to the domain-general cognitive capacity in charge of maintaining "goal-relevant information in mind while processing other information" (Geary, 2013, p. 24). WM capacity is known to predict school achievement (e.g., Gathercole, Pickering, Knight, & Stegmann, 2004) and to be especially related to mathematics achievement (for reviews, see Barrouillet, 2018; Cragg & Gilmore, 2014; and Raghubar, Barnes, & Hecht, 2010). Recent meta-analyses (Friso-van den Bos et al., 2013; Peng et al.,

2016) have shown that the relation between WM and mathematics achievement depends on age, WM domains (in children but not in adults), and types of mathematics skills.

Assessing WM capacity in young children could be challenging. Indeed, two limits stand out. First, WM capacity is usually measured through verbal short-term memory tasks (e.g., forward recall tasks) or visuospatial short-term memory tasks (e.g., Corsi blocks). As highlighted by Cowan (2017), short-term storage is sometimes defined as "the passive (i.e., non-attention-based, non-strategic) component of WM" (p. 1158). Tasks involving holding and manipulating information, such as the backward digit span (e.g., Bull, Espy, & Wiebe, 2008; Wong et al., 2016; Xenidou-Dervou et al., 2015), the backward word recall (e.g., Xenidou-Dervou, De Smedt, van der Schoot, & van Lieshout, 2013), and the counting span (e.g., Rasmussen & Bisanz, 2005), are more rarely used in kindergarten children. Second, these tasks, frequently used in primary school children, could be inappropriate in kindergarten children. For example, using the backward digit span task, Bull et al. (2008) observed that many 4- and 5-year-olds were unable to recall two items in reverse order, severely limiting variability on this task (many data were missing for this task). This limit can partly explain the few developmental data in young children.

Few studies provide data on the relation between WM and mathematics achievement before and after entrance into formal schooling. Using the backward digit span task, Passolunghi and Lanfranchi (2012) showed that WM capacities measured at 5 years of age were significantly correlated to numerical competencies measured 6 months later ($r = .43$) but not significantly correlated to mathematics achievement measured at 6 years 6 months of age ($r = .12$). Because the numerical competencies and mathematical achievement measures did not involve the same skills, the correlations observed before and after entrance into formal schooling are difficult to compare. Also using the backward digit span task, Rasmussen and Bisanz (2005) showed that WM was more strongly related to verbal addition problem performance in 6-year-olds ($r = .48$, $p < .01$) than in 5-year-olds ($r = .35$, *ns*). In the same study, different results were obtained when using the counting span task: the relation between WM and verbal addition problems was weaker in 6-year-olds ($r = .08$, *ns*) than in 5-year-olds ($r = .59$, $p < .01$). These discrepant results observed between studies can be explained by the different measures chosen.

It is important to highlight another significant limitation when studying the relationship between WM and mathematics achievement—the use of numbers as stimuli. Indeed, the backward digit span and counting span tasks involve knowledge of symbolic numbers and require their manipulation. Familiarity with symbolic numbers and higher capacities in number manipulation could explain a large part of the relation observed between WM and mathematics achievement. Finally, it has been shown in adults and children that time-constrained WM tasks are better predictors of fluid intelligence or school achievement than more traditional WM span tasks (Lépine, Barrouillet, & Camos, 2005; Lucidi, Loaiza, Camos, & Barrouillet, 2014).

To overstep all the aforementioned limits in assessing WM capacity and examine its relationship with mathematics achievement in kindergarten children, we chose a highly sensitive time-constrained task involving holding and manipulating information, which involves no number or mathematical processes. Therefore, in the current study, we adapted the computer-paced WM task proposed by Camos and Barrouillet (2011; see Method for more details).

Mediators between ANS acuity and mathematics achievement

One theoretical developmental hypothesis is that young children first rely on the ANS to scaffold their early learning of symbolic numbers. When they learn symbolic numbers (between 2–3 years old and 7–8 years old), they build and strengthen the link between the ANS and symbolic numbers (i.e., mapping precision). Later, once the link between the ANS and symbolic numbers is well established, ANS acuity is less of an influence on mathematics achievement (Geary, 2013). Considering this theory, the link between ANS acuity and mathematics achievement may be mediated by mapping precision when children begin to learn symbolic numbers, and the mediating role of mapping precision may decline across development.

Few studies have directly tested the idea that mapping precision could be a mediator between ANS acuity and mathematics achievement, and no study has compared this mediation effect at different ages. In a study with 10-year-old children, the mapping factor was not found to mediate the relationship between ANS acuity and mathematics achievement (Fazio et al., 2014). Indeed, in that study, ANS acuity and performance in a number line estimation task were unrelated to each other and had independent effects on mathematics achievement. However, in children between 5 and 7 years old, Libertus et al. (2016) found that the variability of estimated responses mediated the link between ANS acuity and mathematics achievement, but accuracy did not. Moreover, in a longitudinal study, Wong et al. (2016) observed the following relationship: ANS acuity at 6 years of age was related to mapping precision at 6 years 5 months of age, which in turn was related to exact symbolic arithmetic performance at 7 years of age. The mapping precision factor was found to fully mediate the effect of ANS on mathematics. However, that study did not allow for a consideration of the development of this mediating relationship. Developmental data are necessary to study the evolution of this relationship with age.

Another hypothesis is that the correlation between ANS acuity and mathematics achievement could be explained by domain-general cognitive abilities, especially executive functions. When executive functions are considered in studies, they are commonly used as control factors (e.g., Fuhs & McNeil, 2013; Gilmore et al., 2013), but very few authors have investigated their potential role of mediation. In a recent experiment in 12-year-old children, Price and Wilkey (2017) showed that executive functions such as inhibitory control and WM (a visuospatial measure of WM) mediate the relationship between nonsymbolic number comparison and mathematics achievement. To our knowledge, no study has investigated this mediation relationship across development.

The current study

This study aimed to better understand how specific and general cognitive capacities are related to mathematics performance before and after entrance into formal schooling. This age period was chosen because, on entrance into elementary school, children begin formal mathematics instruction, focusing on the explicit learning of symbolic numbers and basic arithmetic. This learning may affect the respective weights of the different predictors involved in mathematics achievement. This study focused on three relevant predictors of mathematics achievement: ANS acuity, mapping precision (domain-specific capacities), and WM (domain-general capacity). Two theoretical aims were pursued: (a) to investigate developmental differences in the relationships between each of these predictors and mathematics achievement and (b) to examine whether mapping precision and WM each mediate the relation between ANS acuity and mathematics achievement at the two contrasted ages.

To do so, 5- and 7-year-old children's performance was examined in a nonsymbolic number comparison task (Halberda, Mazzocco, & Feigenson, 2008), a number line estimation task (Siegler & Opfer, 2003), a WM task (Camos & Barrouillet, 2011), and a mathematics achievement task. Moreover, a vocabulary task was used to determine whether each of these predictors was a general predictor of academic achievement or a specific predictor of mathematics achievement.

For the first aim, the predictive weight of ANS acuity on mathematics achievement was expected to be stronger in 5-year-olds than in 7-year-olds (Fazio et al., 2014). No developmental difference was expected for the predictive weight of mapping precision on mathematics achievement (Siegler & Booth, 2004). Concerning WM, an interpretation suggested by Inglis, Attridge, Batchelor, and Gilmore (2011) to explain why the relationship between ANS acuity and mathematics achievement was stronger in children than in adults was tested in the current study. These authors proposed that "once children have reached a certain sophistication with numerical concepts, other factors (WM capacity, strategy choice, teaching effectiveness, etc.) may come to dominate individual differences in mathematical performance, leading to a decline in the relationship with ANS acuity" (p. 1228). This hypothesis suggests that the strength of the association between ANS acuity and mathematics achievement declines with age while the strength of the association between WM and mathematics achievement increases. If this interpretation is correct, contrary to what is observed with ANS acuity, WM capacity should be a stronger predictor of mathematics achievement in 7-year-olds than in 5-year-olds. Our study should provide data to directly test this hypothesis. Concerning the specificity or generality of the predictors studied, we supposed that ANS acuity, mapping precision, and WM should predict mathematics achievement in 5- and 7-year-olds. However, only WM, not ANS acuity or mapping precision, should predict vocabulary scores at the two ages because WM generally predicts global school achievement (e.g., Gathercole et al., 2004).

For the second aim, we supposed that mapping precision should mediate the relation between ANS acuity and mathematics achievement at 5 years of age and that this mediating relationship should be weaker at 7 years of age. This assumption relies on Geary's (2013) theory that the more children advance in formal mathematical learning, the less ANS is involved. Then, mapping precision should be a more important mediator between ANS acuity and mathematics achievement when children are at the beginning of learning symbolic numbers than afterward. Concerning WM, given the current state of research, no hypothesis could be advanced about the development of this mediating relationship.

Method

Participants

A total of 148 children participated in the study: 73 kindergartners (age range = 5 years 2 months to 6 years 2 months, mean = 5 years 8 months; 43 girls) and 75 second graders (age range = 7 years 2 months to 8 years 4 months; mean = 7 years 8 months; 41 girls). They were recruited from four schools in Grenoble (France) and the surrounding area and came from families with middle or high socioeconomic status.

Tasks and materials

Nonsymbolic number comparison

Using the Panamath software (Halberda et al., 2008), children were presented with two arrays of spatially separated blue and yellow dots on a 15.6-inch screen (resolution = 1024 $\times$ 1280 pixels, refresh rate = 40 Hz). The two arrays were simultaneously presented on a blue (left side) or yellow (right side) frame, such that the horizontal visual angle was 19° and the vertical visual angle was 15°. All dot arrays ranged from 5 to 15 dots, and five ratio bins were used: 1.2, 1.5, 1.8, 2.2, and 2.8. On half of the trials (i.e., 30 trials) the cumulative surface area of the two arrays of dots to be compared was equal, and on the other half of the trials the average size of the individual dots in each array was equal. As a consequence, the size of the dots decreased with increasing numerosity in the first set, when surface areas were controlled, and the total surface area increased with increasing numerosity in the second set, when the size of the dots was controlled. The side of presentation of the larger array was counterbalanced across trials. Arrays were heterogeneous in size, the default radius of the dots was 36 pixels, and the maximum variability in size between the dots was ±20%. The dots appeared for 1800 ms, followed by a visual mask and then by a blank screen that remained until the child gave a verbal response (e.g., "blue"). Studies in preschoolers used display times varying from 1200 to 2533 ms (Chu et al., 2015; Halberda & Feigenson, 2008). In our experiment, after a pilot test with a display time of 1200 ms, we finally chose to increase the presentation time to 1800 ms because young children reported that they did not have enough time to see the stimulus arrays on screen. In the current study, the child sat approximately 40 cm from the screen and was asked to indicate whether more of the dots were blue or yellow. The experimenter pressed a key on the keyboard to record the answer and triggered the presentation of the next trial after verifying that the child was looking at the screen. After four practice trials involving arrays that differed by a 2.8 ratio and accuracy feedback, 60 test trials were presented as commonly reported in the literature (Libertus, Feigenson, & Halberda, 2011, 2013), with 12 trials for each ratio. Trials were presented in a random fixed order. To measure ANS acuity, we used accuracy measures, and not Weber fractions or response times, because of the better reliability of accuracy (Dietrich et al., 2015; Inglis & Gilmore, 2014).

Number line estimation

Children were presented with 20 sheets of paper, 1 sheet at a time. A 25-cm line appeared on each sheet with the number 0 printed just below the left end and the number 100 printed just below the right end. Children were asked to put a single mark on each line to indicate the location of a number. No feedback was given to participants regarding the accuracy of their marks. The number to be placed was printed above the middle of the line, read by the experimenter, and was different on each sheet. The 20 numbers presented were 4, 6, 8, 12, 17, 21, 25, 29, 33, 39, 43, 48, 52, 57, 61, 72, 79, 84, 90, and 96. The order of the sheets was randomized separately for each child. One practice trial with another number (i.e., 3) was used. The accuracy of children's number line estimates was measured by calculating the percentage absolute error (PAE): PAE = [|Estimate − Actual Number|/Scale of Estimates] × 100. For example, if a child marked the location of 4 on a 0–100 number line at the position that corresponded to 8, the PAE would be 4%: [|8 − 4|/100] × 100.

Working memory

The WM task was adapted from the color-naming span task proposed by Camos and Barrouillet (2011) for young children. This computer-paced complex span task was time constrained and consisted of a series of one to five animal images to be remembered. Each animal was orally stated by the experimenter and repeated by the children. Then, it was followed by a processing period during which children named the color of two successively presented smileys. Stimuli were presented using the E-Prime application (Schneider, Eschman, & Zuccolotto, 2002). Each picture, animal or colored smiley, was presented for 2 s, with a 1-s interstimulus interval (Fig. 1). The smileys were 6.5 cm in diameter and colored yellow, blue, or red. The animal pictures came from a set of standardized pictures (Cannard et al., 2006), named *Banque de données d'images informatisées* (BD2I), and were chosen because they would be familiar to 5-year-old children. The oral pronunciation of these pictures consisted in three to five phonemes. Four trials were presented for each length (total = 20). At the end of each trial, a question mark appeared on-screen to prompt children to recall aloud the name of the animals presented in any order. The experimental session was preceded by a practice session in which children were familiarized with the colored stimuli by being asked to name the color of three series of two smileys and then receiving feedback. Then, they performed two practice trials with one animal and two trials with two animals. After the practice session, the 5-year-olds started with the one-animal series, whereas the 7-year-olds directly started with the two-animal series (if they could not recall the two animals, the experimenter presented the one-animal series). The WM task stopped when children failed in three successive trials of the same length. WM scores consisted of the total number of trials in which children correctly recalled all the animals (maximum score = 20).

Mathematics achievement

This test consisted of three subtasks: exact symbolic addition, exact symbolic subtraction, and numerical verbal problems. Each subtask presented trials in increasing order of difficulty, and the testing stopped after three successive errors for a subtask. The 5- and 7-year-old children performed the same three subtasks, but the first trial in each subtask was advanced for the 7-year-olds to minimize boredom due to the long testing time. If a 7-year-old child failed in the first three trials, the experimenter presented the 5-year-olds' first trials. In these tasks, children were not allowed to write and should mentally solve and verbally respond to each problem. To ensure children's understanding of the task, children performed one practice trial with feedback before each subtask. The mathematics achievement score is the total correct responses obtained in these three subtasks (maximum score = 34).

In exact symbolic addition, children were asked to solve 12 addition problems presented on cards and read by the experimenter (2 + 2, 0 + 8, 6 + 3, 3 + 5, 7 + 7, 20 + 30, 32 + 14, 15 + 17, 24 + 18, 37 + 45, 123 + 75, and 246 + 150). They were given approximately 15 s to respond, but this information was not revealed to them. When children exceeded the time limit, the experimenter proposed to go on with the next trial. The 7-year-old children began at the fifth trial.

In exact symbolic subtraction, the procedure was the same as in the exact symbolic addition subtask except that children were asked to solve 12 subtraction problems presented on cards and read by the experimenter (4–2, 5–3, 6–6, 4–0, 9–5, 16–4, 40–20, 27–6, 36–16, 44–23, 135–23, and 320–12).

In numerical verbal problems, children were asked to solve 10 problems read by the experimenter (e.g., "Denis has 3 marbles. He gets 2 more. How many marbles would he have then?"). On half of the

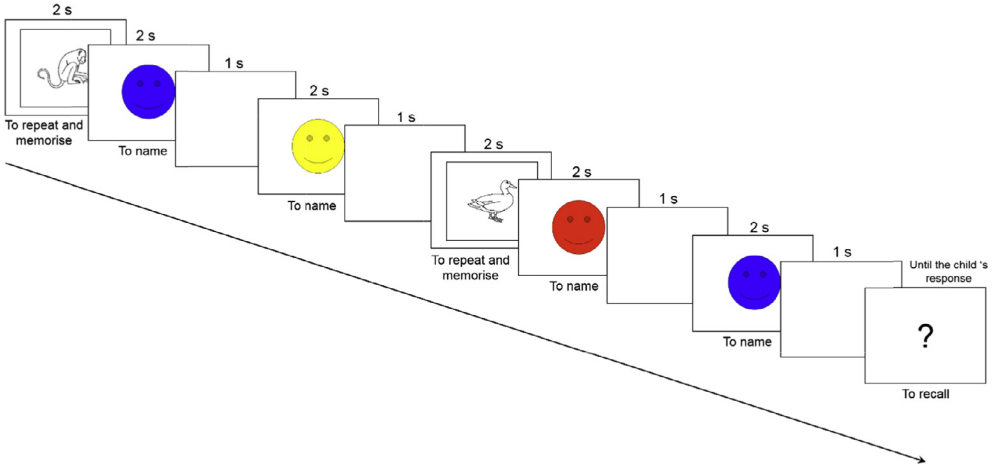

Fig. 1. Illustration of a two-animal trial in the color-naming span task (adapted from Camos & Barrouillet, 2011).

problems, addition was involved, and on the other half, subtraction was involved. The 7-year-old children began at the third trial.

Vocabulary

Receptive vocabulary was assessed through the *Échelle de vocabulaire en images* (EVIP), Form B, the French adaptation of the Peabody Picture Vocabulary Test (Dunn, Dunn, & Theriault-Whalen, 1993). Children were asked to choose the correct picture among four possibilities, corresponding to the word stated by the experimenter. This task was stopped when children made six errors on eight successive trials (maximum score = 160). The raw scores were used as a measure.

Procedure

Children were individually tested in a separate room at school in two 30-min sessions. All the children first performed the number line estimation task, followed by the WM task and the vocabulary task, in the first session. In the second session, the first task was the mathematics test, followed by the nonsymbolic comparison task. Two nonsymbolic comparison tasks were administered in the second session: a visual one and a haptic one (see Gimbert, Gentaz, Camos, & Mazens (2016) for details on the haptic task). In this study, we only described and analyzed the visual nonsymbolic comparison task. Symbolic number knowledge was also assessed at the end of the second session, but data were not reported due to the ceiling effect in children's performance.

Results

In each task, scores less or greater than 3 standard deviations from the participants' mean scores were removed from the analyses. Moreover, data from 1 child were not available due to a failure to complete the nonsymbolic number comparison task. Overall, 0.9% of the data (three scores) were excluded from the 5-year-old group, and 0.7% of the data (two scores) were excluded from the 7-year-old group. Descriptive results for each measure and final age samples are presented in the online supplementary material.

Our Results section consists of three distinct parts. In the first part, we focused on the relationships between the different measures and the mathematics achievement score by examining and comparing the correlation matrices at the two ages. In the second part, hierarchical regression analyses were performed to test whether each predictor was domain specific or domain general. More important, these analyses made it possible to examine the weight of each predictor of mathematics achievement in the two age groups. In the third part, mediation models were run to test whether mapping ability and WM each mediated the relation between ANS acuity and mathematics achievement.

Correlation analyses

We conducted correlation analyses among nonsymbolic number comparison accuracy, PAE in number line estimation, WM score (i.e., the three supposed predictors of mathematics achievement), age in months, vocabulary scores, and mathematics achievement scores (Table 1). We compared the correlations observed between the three predictors and mathematics achievement at the two ages. Nonsymbolic number comparison accuracy was significantly correlated with mathematics scores in 5-year-old children ($r = .34$) but not in 7-year-old children ($r = .21$). Fisher's r-to-z transformation revealed that there was no significant difference between these two correlations ($z = 0.83$, $p = .20$). PAE in number line estimation was related to mathematics scores at the two ages (5-year-olds: $r = -.62$; 7-year-olds: $r = -.49$), with no significant difference between ages ($z = 1.12$, $p = .13$). WM scores were correlated with mathematics at the two ages (5-year-olds: $r = .31$; 7-year-olds: $r = .52$), and the difference between ages was marginally significant ($z = 1.52$, $p = .06$).

Hierarchical regression analyses

For each age, to determine the main predictors of mathematics achievement, a hierarchical regression analysis was conducted, with mathematics achievement scores as a dependent variable and age in months, WM score, nonsymbolic number comparison accuracy, and PAE in number line estimation as predictors. To control for the age effect on mathematics achievement, age in months was entered in the model in Step 1. As a general cognitive factor, WM was entered in Step 2, and the two specific factors—nonsymbolic number comparison and number line estimation—were added in Step 3 (Table 2).[1]

In 5-year-olds, WM entered in Step 2 significantly predicted additional variance (9%), $F_{\text{for } R^2 \text{ change}} = 7.56$, $p = .008$. The two specific predictors entered in Step 3 together significantly predicted additional variance (29%), $F_{\text{for } R^2 \text{ change}} = 15.48$, $p < .001$. The whole model (i.e., Step 3) in total accounted for 46% of the variance in mathematics achievement ($p < .001$). Nonsymbolic number comparison accuracy and PAE in number line estimation were significant predictors, whereas WM score was not.

In 7-year-olds, WM entered in Step 2 significantly predicted additional variance (31.5%), $F_{\text{for } R^2 \text{ change}} = 31.76$, $p < .001$. The two specific predictors entered in Step 2 together significantly predicted additional variance (14%), $F_{\text{for } R^2 \text{ change}} = 18.82$, $p < .001$. The whole model (Step 3) in total accounted for 46% of the variance in mathematics achievement ($p < .001$). PAE in number line estimation and WM score were significant predictors, whereas nonsymbolic number comparison accuracy was not.

For each age, to determine whether the predictors were specific to mathematics achievement, a second hierarchical regression analysis was conducted with the same predictors and steps but with vocabulary score as a dependent variable (Table 2). In 5-year-olds, WM entered in Step 2 significantly predicted additional variance (8%), $F_{\text{for } R^2 \text{ change}} = 6.03$, $p = .02$, but not the two specific predictors entered in Step 3 (2%), $F_{\text{for } R^2 \text{ change}} = 0.86$, $p = .43$. The whole model in total accounted for 17% of the variance in vocabulary ($p = .01$), and no predictor was a significant predictor. In 7-year-olds, WM entered in Step 2 significantly predicted additional variance (6.9%), $F_{\text{for } R^2 \text{ change}} = 5.01$, $p = .03$, but not the two specific predictors entered in Step 3 (near 0%), $F_{\text{for } R^2 \text{ change}} = 0.20$, $p = .82$. The whole model explained 7% of the variance in vocabulary score ($p = .27$), and no predictor was a significant predictor.

[1] To control for the effect of general abilities and age at the same time on mathematics achievement in a third hierarchical regression analysis (one for each age group), vocabulary score and age in months were entered together in Step 1, WM was entered in Step 2, the two specific factors—nonsymbolic number comparison and number line estimation—were added in Step 3, and mathematics achievement score was the dependent variable (Table B in online supplementary material). Including vocabulary score in Step 1 did not change the significance of the results.

Table 1
Correlations (Bravais–Pearson's *r*) between performance in the different tasks and age in months in 5- and 7-year-olds.

	1	2	3	4	5
(A) 5-year-olds					
1. Age in months					
2. Vocabulary	.26*				
3. Nonsymbolic number comparison	.01	.08			
4. PAE in number line estimation	−.08	−.29*	−.24*		
5. Working memory	.11	.27*	.24*	−.32**	
6. Mathematics achievement	.25*	.34***	.34***	−.62****	.31**
(B) 7-year-olds					
1. Age in months					
2. Vocabulary	.01				
3. Nonsymbolic number comparison	.07	.05			
4. PAE in number line estimation	−.01	−.13	−.04		
5. Working memory	−.08	.25*	.30**	−.25*	
6. Mathematics achievement	.10	.38***	.21	−.49****	.52****

* $p < .05$.
** $p < .01$.
*** $p < .005$.
**** $p < .001$.

These results showed that in 5-year-olds, ANS acuity and mapping precision were significant specific predictors of mathematics achievement, whereas in 7-year-olds, only mapping precision appeared as a significant specific predictor. In 5-year-olds, the relative weight of WM on mathematics achievement was not significant, whereas in 7-year-olds, WM was the more powerful predictor. At the two ages, the predictive power of WM on vocabulary was not negligible and approached significance ($p = .08$ and $p = .06$ for 5- and 7-year-olds, respectively).

Mediation analyses

The mediation models were tested using the PROCESS macro for SPSS (Preacher & Hayes, 2008, Model 4). Confidence intervals of 95% for the mediation model were obtained using 5000 bootstrap samples. These analyses were run with age in months and vocabulary scores entered as covariates in order to control for the effect of general abilities and age while evaluating the potential mediation effects. In 5-year-olds, the total effect of ANS acuity on mathematics performance (Path c in Fig. 2A) was significant ($\beta_c = .33$, $SE = .11$, $p = .004$) after controlling for covariates, whereas this was not the case in 7-year-olds ($\beta_c = .38$, $SE = .20$, $p = .07$). Analyses were performed by entering as mediator first mapping precision and second working memory.

Mapping precision as a mediator

In 5-year-olds, the overall model, including both ANS acuity and mapping precision as predictors and both age and vocabulary as covariates, explained 47% of the variance in mathematics. The effect of ANS acuity on mapping performance was just above the significance threshold (Path a; $\beta_a = -.27$, $SE = .14$, $p = .06$), and the effect of mapping abilities on mathematics performance was significant (Path b; $\beta_b = -.43$, $SE = .08$, $p < .001$), showing that children with higher mapping abilities tended to have a more acute ANS and to perform better in mathematics. The direct effect of ANS acuity on math performance (Path c′) was statistically significant ($\beta_{c'} = .21$, $SE = .10$, $p = .03$). The confidence interval (CI) for the indirect effect (Path ab) was entirely above zero ($\beta_{ab} = .12$, 95% CI [.004, .27]), indicating that the relation between ANS acuity and mathematics performance was partially mediated by mapping precision in 5-year-olds (Fig. 2A).

In 7-year-olds, the overall model, including both ANS acuity and mapping precision as predictors and both age and vocabulary as covariates, explained 36% of the variance in mathematics. The effect of ANS acuity on mapping performance was not significant (Path a; $\beta_a = -.03$, $SE = .11$, $p = .79$), and the effect of mapping abilities on mathematics performance was significant (Path b; $\beta_c = -.87$, $SE = .19$,

Table 2
Hierarchical regression analyses predicting mathematics or vocabulary achievement, entering age in months in Step 1, working memory in Step 2, and nonsymbolic comparison and number line estimation in Step 3.

(A) 5-year-olds (n = 70)

	Mathematics				Vocabulary			
Variable	β	t	p	R^2	β	t	p	R^2
Model Step 1				.08				.07
Age in months	.28	2.38	.02		.27	2.30	.02	
Model Step 2				.17				.15
Age in months	.25	2.25	.03		.25	2.17	.03	
Working memory	.31	2.75	.008		.28	2.46	.02	
	$F_{\text{for } R^2 \text{ change}}$ = 7.56, p = .008				$F_{\text{for } R^2 \text{ change}}$ = 6.03, p = .02			
Model Step 3				.46				.17
Age in months	.22	2.34	.02		.23	2.04	.046	
Working memory	.07	0.70	.49		.22	1.79	.08	
Nonsymbolic comparison	.19	2.04	.046		−.02	−0.14	.89	
Number line estimation	−.51	−5.14	< .001		−.16	−1.31	.20	
	$F_{\text{for } R^2 \text{ change}}$ = 17.58, p < .001				$F_{\text{for } R^2 \text{ change}}$ = 0.86, p = .43			

(B) 7-year-olds (n = 73)

	Mathematics				Vocabulary			
Variables	β	t	p	R^2	β	t	p	R^2
Model Step 1				.005				.001
Age in months	.07	0.59	.56		−.03	−0.21	.83	
Model Step 2				.32				.07
Age in months	.11	1.14	.26		.005	−0.04	.97	
Working memory	.56	5.64	<.001		.26	2.24	.03	
	$F_{\text{for } R^2 \text{ change}}$ = 31.76, p < .001				$F_{\text{for } R^2 \text{ change}}$ = 5.01, p = .03			
Model Step 3				.46				.07
Age in months	.09	1.04	.30		−.005	−0.04	.97	
Working memory	.44	4.49	< .001		.25	1.95	.06	
Nonsymbolic comparison	.07	0.77	.44		−.02	−0.85	.85	
Number line estimation	−.38	−4.16	< .001		−.07	−0.59	.56	
	$F_{\text{for } R^2 \text{ change}}$ = 8.81, p < .001				$F_{\text{for } R^2 \text{ change}}$ = 0.20, p = .82			

(A): *Note.* Multicollinearity: Tolerance is between .83 and .98.
(B): *Note.* Multicollinearity: Tolerance is between .85 and .93.

p < .001), showing that children with higher mapping abilities performed better in mathematics. The direct effect of ANS acuity on math performance (Path c′) failed to reach significance ($\beta_{c'}$ = .35, SE = .18, p = .05). The confidence interval for the indirect effect (Path ab) included zero (β_{ab} = .03, 95% CI [−.16, .19]), indicating no mediation effect of mapping precision on the relation between ANS acuity and mathematics performance in 7-year-olds (Fig. 2B).

Working memory as a mediator

In 5-year-olds, the overall model, including both ANS acuity and WM capacity as predictors and both age and vocabulary as covariates, explained 27% of the variance in mathematics. The direct effect of ANS acuity on mathematics performance (Path c′) was significant ($\beta_{c'}$ = .28, SE = .11, p = .01). The confidence interval for the indirect effect (Path ab) included zero (β_{ab} = .04, 95% CI [−.007, .19]), indicating no mediation effect of WM capacity on the relation between ANS acuity and mathematics performance (Fig. 2C).

In 7-year-olds, the overall model, including both ANS acuity and WM capacity as predictors and both age and vocabulary as covariates, explained 35% of the variance in mathematics. The direct effect of ANS acuity on mathematics performance (Path c′) was not significant ($\beta_{c'}$ = .11, SE = .19, p = .56). The

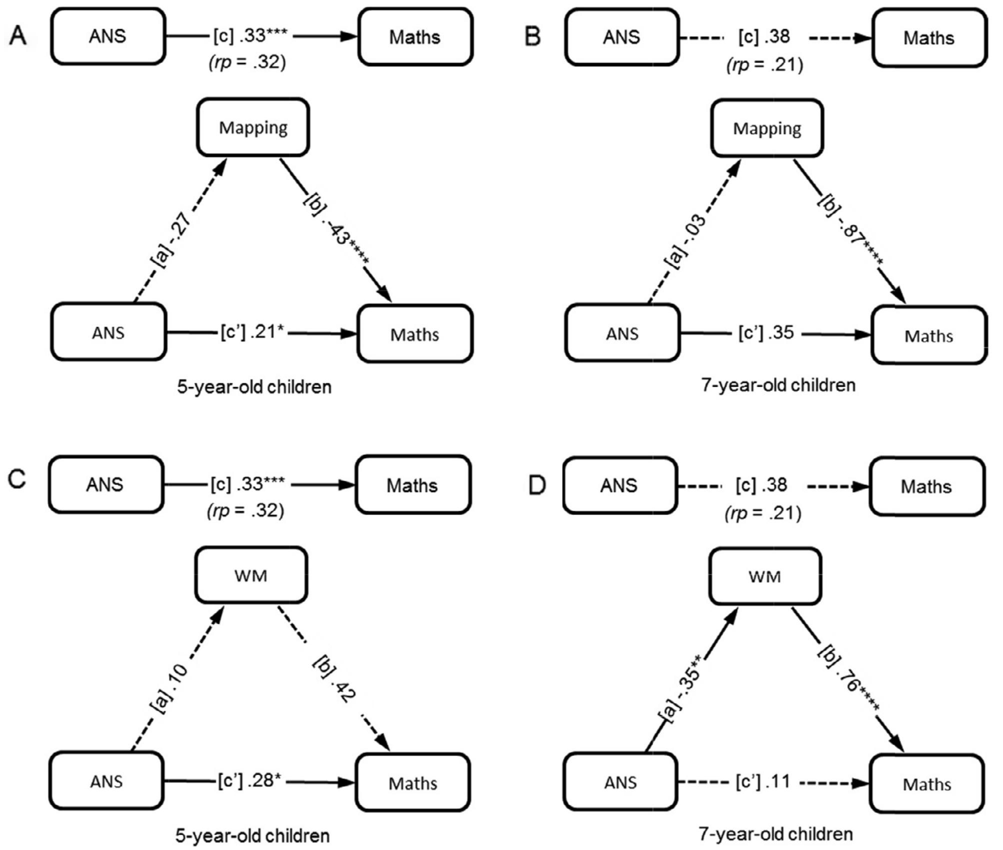

Fig. 2. Unstandardized coefficients of the mediation models observed in 5-year-old children (A, C) and in 7-year-old children (B, D), controlling for age in months and vocabulary scores. [ab], indirect effect of approximate number system (ANS) acuity on mathematics achievement (Maths); [c′], direct effect of ANS on Maths; [c], overall effect of ANS on Maths; Mapping, mapping precision; WM, working memory capacity; *rp*, standardized coefficient. $^{*}p < .05$, $^{**}p < .01$, $^{***}p < .005$, $^{****}p < .001$.

confidence interval for the indirect effect (Path ab) was entirely above zero (β_{ab} = .26, 95% CI [.07, .57]). These results indicate that the relation between ANS acuity and mathematics performance was entirely mediated by WM capacity at this age (Fig. 2D).

Discussion

The current study examined how three relevant cognitive abilities relate to mathematics performance before and after entrance into formal schooling. These three cognitive abilities—ANS acuity, mapping precision, and WM capacity—were assessed using the same tasks at 5 and 7 years of age. The main findings showed that the predictive relative weight of ANS acuity on mathematics achievement decreased after children entered into formal schooling, whereas the predictive relative weight of WM on mathematics achievement increased. Mapping precision was a main predictor of mathematics achievement at the two ages. This study also examined the involvement of potential mediators in the relation between ANS acuity and mathematics achievement. Mapping precision was found to be a partial mediator in 5-year-old children, and WM was found to be a full mediator in 7-year-old children.

Concerning the relation between ANS acuity and mathematics achievement, correlational results suggested that this link was significant in children before they entered into formal mathematics instruction ($r = .34$, $p < .005$) but not after ($r = .21$, *ns*). Even though the difference between these two correlation coefficients was not significant, results from hierarchical regression analyses showed that ANS acuity was a significant specific predictor of mathematics achievement in 5-year-olds but not in 7-year-olds. Because we used exactly the same tasks in both age groups, the difference observed in our results should be due to differences in age and not to methodological differences. Our findings are entirely consistent with Fazio et al.'s (2014) meta-analysis showing that the correlation between ANS acuity and mathematics achievement is stronger before 6 years of age ($r = .40$) than after ($r = .17$). This developmental difference was also observed by Xenidou-Dervou et al. (2017) in a longitudinal study. In that study, 7-year-olds' mathematics achievement was predicted by ANS acuity when it was measured in 5-year-olds but not when it was measured in 7-year-olds. This could suggest that having high ANS abilities at 5 years could facilitate the start of formal mathematics education, which would then be maintained in the following years.

Concerning the relation between mapping precision and mathematics achievement, results showed that mapping precision was a main specific predictor of mathematics achievement, as was previously highlighted by some authors (e.g., Sasanguie et al., 2013; Siegler & Booth, 2004; Wong et al., 2016; Xenidou-Dervou et al., 2015). No developmental difference was shown from correlational analyses (5-year-olds: $r = .62$; 7-year-olds: $r = .49$) or from hierarchical regressions. Being able to precisely associate symbolic numbers with their analogical magnitude appears to play a key role in the symbolic number learnings before and after entrance into formal mathematics instruction.

Regarding the relation between WM and mathematics achievement, although the difference between the correlations observed in 5- and 7-year-olds ($r = .31$ and $r = .52$, respectively) failed to reach significance, a developmental change clearly appeared in the hierarchical regression analysis. WM was not a significant predictor in 5-year-olds, but it was in 7-year-olds. These results represent a step forward in our comprehension of the relation between WM and mathematics achievement. Indeed, the period between 5 and 7 years of age coincides with an important change in WM functioning that could explain our results. Younger children tend not to implement any maintenance strategy (such as subvocal rehearsal or attentional refreshing) to keep information active in WM, whereas older children do (e.g., Camos & Barrouillet, 2011; Hitch, Halliday, Schaafstal, & Heffernan, 1991). Thus, our findings suggest that the role of WM in mathematics achievement could rely on this ability to maintain relevant information by implementing some maintenance strategy. Moreover, because our task did not rely on symbolic numbers, we can affirm that the relationship observed between WM and mathematics achievement was not supported by children's familiarity with symbolic numbers.

Overall, these results show that ANS acuity was a significant predictor only at 5 years of age, and its relation with mathematics achievement was weak. Moreover, mapping precision was an important predictor of mathematics achievement at the two ages, whereas WM was an important predictor at 7 years. In other words, even though ANS acuity could influence mathematics achievement in 5-year-olds, its impact will be limited in comparison with mapping precision at 5 years or mapping precision and WM at 7 years.

To better understand the relation between ANS acuity and mathematics achievement, mediation analyses were performed including mapping precision or WM as a mediator at the two ages. Mapping precision was the first mediator considered. Results showed that mapping precision was a partial mediator of the relation between ANS acuity and mathematics performance in 5-year-old children, but this mediation relationship was not observed in 7-year-old children. At this age, the nonsignificant and very weak relation observed between ANS acuity and mathematics achievement can explain the absence of a mediating relationship between ANS acuity and mathematics scores. This absence was also observed by Fazio et al. (2014) in 10-year-old children, but not exactly for the same reason. Indeed, contrary to our results, Fazio et al. found a significant relation between ANS acuity and mathematics achievement. This difference could be explained by the age difference (i.e., 7-year-olds vs. 10-year-olds), the scoring procedure (i.e., accuracy vs. a composite score including Weber fraction and response time), or the different tasks used to assess mathematics achievement (i.e., arithmetic vs. general mathematics achievement). Three other studies showed that mapping performance mediated the relation between ANS acuity and mathematics achievement. Libertus et al. (2016) and Wong et al. (2016) showed a total mediation relationship, contrary to our findings. They differed on some points from our experiment—the design of the study, the children's age, and the tasks used to assess the different abilities—and these could explain the discrepant results. Recently, Jang and Cho's (2018) findings pointed out that the mediating role of mapping depends on the domain of mathematics and age. In our study, WM was the second mediator considered. Results showed that WM fully mediated the relationship between ANS acuity and mathematics achievement in 7-year-olds but not in 5-year-olds. Price and Wilkey (2017) found results in 12-year-olds that were similar to what we found in 7-year-olds. Together, all these results support the idea that a change occurs with entrance into formal schooling.

In addition to mapping precision and WM, other mediators have been proposed to explain the link between ANS acuity and mathematics achievement. Among them, the following have been shown to be mediators between ANS acuity and arithmetic performance: number-specific factors (for a review, see Libertus, 2015), counting skills and understanding of cardinality in 3- to 5-year-old children (vanMarle, Chu, Li, & Geary, 2014), and understanding of ordinality in adults (Lyons & Beilock, 2011). Moreover, nonsymbolic approximate addition performance has been shown to mediate the relation between ANS acuity and exact calculation in 10-year-old children (Pinheiro-Chagas et al., 2014). Concerning domain-general factors, as previously mentioned, the implication of inhibitory control yielded mixed results (Fuhs & McNeil, 2013; Gilmore et al., 2013; Keller & Libertus, 2015). Another possible explanation, suggested by Libertus et al. (2016) but not demonstrated yet, is self-confidence. Indeed, two recent studies have provided evidence that confidence could influence performance in numerical tasks (Odic, Hock, & Halberda, 2014; Wang, Odic, Halberda, & Feigenson, 2016). Being able to precisely compare nonsymbolic numbers, to precisely associate symbolic numbers with their quantities, and to be aware of these abilities could make children more self-confident when engaging in mathematics tasks. All the mediators mentioned can play different or complementary roles depending on the age of the children. More developmental studies are required to better understand their involvement.

When studying the predictive weights of different abilities on mathematics achievement, an important issue concerns the tasks chosen to assess these abilities. For example, concerning mathematics achievement, ANS acuity was shown to correlate with informal but not with formal mathematics abilities (Libertus et al., 2013). Moreover, studies have shown that using different methods to construct nonsymbolic stimuli directly affected the measure of ANS acuity (e.g., Clayton, Gilmore, & Inglis, 2015; Smets, Sasanguie, Szücs, & Reynvoet, 2015). Using different measures to index ANS acuity, such as Weber fraction and accuracy, leads to methodological discrepancies between studies and makes it difficult to compare results. To limit this difficulty, one possibility is to systematically use accuracy instead of Weber fraction given that accuracy has a better reliability (Inglis & Gilmore, 2014). One limitation of our study is that we used only one measure for each ability considered. Although our findings need to be replicated with different tasks to strengthen them, they are consistent with Geary's (2013) theoretical model. Indeed, the developmental changes observed in our findings suggest that the more children advance in mathematical learning, the less they rely on their ANS and the more they rely on other abilities. In the same vein, Inglis et al. (2011) supposed that the relationship between the ANS and mathematics declines as participants gain mathematical experience because other factors, such as WM capacity, may come to dominate individual differences in mathematics performance. Our findings suggest that WM is a more powerful predictor of mathematics achievement in 7-year-olds than in 5-year-olds, and this clearly supports Inglis et al.'s (2011) hypothesis. Only one of our results modulates Geary's (2013) theoretical model. Indeed, in Geary's model, attentional control is necessary when children learn to associate symbolic numbers with their magnitude (i.e., mapping ability) but not when they apprehend quantity with the ANS. In our study, there is a relation between the ANS and WM even if the correlations are weak (5-year-olds: $r = .24$; 7-year-olds: $r = .30$). This suggests that attentional control has a moderate role in nonsymbolic number comparison tasks. Our mediation analyses on potential developmental changes shed light on the two hypotheses presented to explain the relationship between ANS acuity and mathematics achievement. Indeed, in 5-year-olds this relationship is mediated by mapping precision, which supports the "mapping hypothesis," whereas in 7-year-olds this relationship is mediated by WM, which supports the domain-general cognitive abilities hypothesis.

A final point to highlight is that we cannot rule out another possibility to interpret the partial mediation observed in 5-year-olds. Indeed, school instruction in mathematics could improve the precision of mapping and result in better ANS acuity. The effect of education on ANS acuity was suggested in research based on the comparison between populations with and without access to mathematics education (Nys et al., 2013; Piazza, Pica, Izard, Spelke, & Dehaene, 2013). Authors of these studies argued that bidirectional relations between ANS acuity and mathematics achievement are possible. To provide support for the causality of the relation between ANS acuity and mathematics achievement, ANS training studies have been performed to observe whether training has an impact on scores in mathematics achievement. However, methodological issues make it difficult to obtain a clear conclusion (for a review, see Szűcs & Myers, 2017).

To conclude, our study, using identical tasks in two different age groups, shows significant changes in the relative weight of different predictors of mathematics achievement at the point of entrance into formal schooling. More specifically, between 5 and 7 years of age, the predictive relative weight of ANS acuity decreases while the predictive relative weight of WM increases. At both 5 and 7 years, mapping precision is a main predictor. Moreover, in 5-year-olds but not in 7-year-olds, mapping precision partially mediates the relation between ANS acuity and mathematics achievement. Conversely, in 7-year-olds but not in 5-year-olds, WM fully mediates the relation between ANS acuity and mathematics achievement. To extend these findings and to better understand how these predictors affect mathematical learning, carefully designed training studies should be carried out.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jecp.2018.09.013.

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