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The contribution of general cognitive abilities and approximate number system to early mathematics

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Background. Math learning is a complex process that entails a wide range of cognitive abilities to be fulfilled. There is sufficient evidence that both general and specific cognitive skills assume a fundamental role, despite the absence of shared consensus about the relative extent of their involvement. Moreover, regarding general abilities, there is no agreement about the recruitment of the different memory components or of intelligence. In relation to specific factors, great debate subsists regarding the role of the approximate number system (ANS).

Aims. Starting from these considerations, we wanted to conduct a wide assessment of memory components and ANS, by controlling for the effects associated with intelligence and also exploring possible relationships between all precursors.

Sample and Method. To achieve this purpose, a sample of 157 children was tested at both beginning and end of their Grade 1. Both general (memory and intelligence) and specific (ANS) precursors were evaluated by a wide battery of tests and put in relation to concurrent and subsequent math skills. Memory was explored in passive and active aspects involving both verbal and visuo-spatial components.

Results. Path analysis results demonstrated that memory, and especially the more active processes, and intelligence were the strongest precursors in both assessment times. ANS had a milder role which lost significance by the end of the school year. Memory and ANS seemed to influence early mathematics almost independently.

Conclusion. Both general and specific precursors seemed to have a crucial role in early math competences, despite the lower involvement of ANS.

Approximately 5–8% of students (see Geary & Hoard, 2005) are affected by a mathematics learning disability (MLD). To prevent the severe manifestation of this condition, it is important to promote early detection of at-risk children. Towards this goal, several researchers focused on identifying which cognitive abilities are fundamental precursors of mathematics learning and that, when impaired, underlie MLD (e.g., De Smedt *et al.*, 2009; Passolunghi, Vercelloni, & Schadee, 2007).

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General precursors

There is sufficient evidence that mathematics learning is a complex process entailing a full spectrum of cognitive abilities that may be classified as either general or specific (see Passolunghi & Lanfranchi, 2012). While the former are shared across a wide range of learning processes and include memory and intelligence, the latter are related to the specific domain of mathematics.

Working memory (WM) involves the ability to mentally retain and manipulate different kind of information. There are several models of WM. The model we take as general reference is that of Baddeley (see Baddeley & Hitch, 1974), which postulates the presence of an active component of information retention that involves high-control processes and is indicated as *central executive*. Besides this component, two other ones, represented by the slave systems of *visuo-spatial sketchpad* and *phonological loop*, are instead mainly dedicated to a handling of the information that is typically passive, meaning that involves low-control processes without consistent information elaboration (see Cornoldi & Vecchi, 2003).

Some authors (see Bull, Espy, & Wiebe, 2008; Gathercole & Alloway, 2006; Passolunghi & Siegel, 2001; Swanson & Luxenberg, 2009), to better underline the distinction between more active or passive memory processes, prefer to use the term WM to refer only to central executive, while adopting the term short-term memory (STM) to indicate the slave systems. To better differentiate these two levels of information retention, also in the present work, WM and STM are treated as separated, even if interindependent, constructs, being our interest also the differentiation between these two levels of information processing.

Regarding the importance of memory in math learning, it is widely accepted that impairments at this level lead to detectable math difficulties. Memory has therefore a leading role in this process (Bull, Johnston, & Roy, 1999; De Smedt *et al.*, 2009; Geary, 1993; Mazzocco & Kover, 2007; Passolunghi, Cornoldi, & De Liberto, 1999; Passolunghi & Siegel, 2001, 2004; Swanson, 1993). However, agreement still lacks in relation to the recruitment of the different components. There is, in fact, general consensus on the importance of WM, despite some researchers reported a marginal role in children before second grade (e.g., Geary, Hoard, Nugent, & Byrd-Craven, 2008). More divergent views linger on the recruitment of STM. However behavioural and clinical data generally report a more reduced involvement of STM in comparison with that of WM (Geary, 1993).

Specific precursors

Regarding specific precursors, some of the pertaining abilities refer to the approximate number system (ANS), an innate system which allows the manipulation of quantities and magnitudes in an approximate way. A typical example of ability underlying ANS consists in approximately estimating computation results or in comparing two or more sets of elements to identify, without counting, which could be the most numerous.

Approximate number system capacities belong to a wider spectrum of abilities generally indicated with the term *number sense*. For the reason that a unique definition of number sense is still lacking (Gersten, Jordan, & Flojo, 2005), we selected to focus on the ANS component which is instead a core system robustly identified within it. More in detail, we considered the approximate skills pertaining to ANS from their non-symbolic aspect, thus assessing only the most basic and innate number sense aspect (therefore distinguishing this system from that including the symbolic number representation that is more typically exact).

The involvement of ANS in math learning is nevertheless very debated. Indeed, while some studies account for its significant role, both concurrent (e.g., Fuhs & McNeil, 2013; Gilmore, McCarthy, & Spelke, 2010; Libertus, Feigenson, & Halberda, 2011; Lonnemann, Linkersdörfer, Hasselhorn, & Lindberg, 2013) or also longitudinal (e.g., Halberda, Mazzocco, & Feigenson, 2008; Mazzocco, Feigenson, & Halberda, 2011a), many others do not (e.g., Holloway & Ansari, 2009; Sasanguie, De Smedt, Defever, & Reynvoet, 2012). Moreover, while some authors report deficits associated to ANS in children with or at risk for MLD (e.g., Mazzocco, Feigenson, & Halberda, 2011b; Piazza *et al.*, 2010), others highlighted impairments in making comparisons between quantities, but only when these quantities are represented by symbols and not when using non-symbolic, approximate numerosities (Iuculano, Tang, Hall, & Butterworth, 2008; Rousselle & Noël, 2007).

Previous works inspecting both general and specific precursors of math learning

Although numerous studies have explored the role of either general or specific precursors of math learning, fewer have simultaneously investigated both sets of abilities immediately prior to early formal schooling. Generally, the major part of the researches assessing both kinds of precursors limited their investigation to either memory, frequently explored with a limited number of tasks or analysed in only one of its components (e.g., Östergren & Träff, 2013), or specific skills. In relation to the latter, studies mainly investigated skills related to a more formal knowledge of numbers (e.g., Fuchs *et al.*, 2010; Mazzocco & Thompson, 2005; Passolunghi & Lanfranchi, 2012), with less attention to ANS.

In Cirino (2011), in spite of the large number of tasks employed to investigate the symbolic component, limited was the assessment of non-symbolic skills and math outcome (single-digit additions). Finally, the study of Xenidou-Dervou, De Smedt, van der Schoot, and van Lieshout (2013) was complete in terms of the evaluation of different aspects of memory and number sense, but it considered memory as a unique general precursor (without differentiating between WM and STM).

Current study

The aim of this research was to simultaneously evaluate the contribution of general and specific skills to children's early mathematics performance. More specifically, we wanted to conduct a wide assessment of active (WM) and passive (STM) memory components and of ANS, by controlling for the effects associated with intelligence and exploring possible relationship between all precursors. We specifically wanted to test the association between memory and ANS in young children evidenced in some studies (e.g., Xenidou-Dervou, van Lieshout, & van der Schoot, 2014; Xenidou-Dervou *et al.*, 2013), but not in others (e.g., Belacchi *et al.*, 2014).

Towards these goals, we administered a cognitive assessment at the beginning of Grade 1 (Time 1), a time that marks the onset of our participants' formal instruction (Italian formal education does not begin during kindergarten). Second, we investigated whether these variables could differently account for the variability in different levels of early mathematical skills. We finally conducted an exploratory analysis by inspecting the contribution of these precursors in math achievement at the end of Grade 1 (Time 2).

We hypothesized that both general and specific precursors would make unique contributions to concurrent and future levels of mathematics ability. We also expected the relative contribution and strength of these precursors to vary across different mathematic outcome measures and also in formal math assessed at the end of the grade. In spite of a greater significant involvement of memory, we expected also ANS to give a significant and distinctive contribution at least in early math performance.

Method

Participants

Participants were 157 first-grade children (80 males; mean age: 6 years, 3 months) recruited from seven classrooms across four primary schools in north-eastern Italy. Two children who were enrolled in the study were excluded because of a diagnosis of neurological conditions associated with learning difficulties, and five children were excluded due to limited Italian proficiency. Of the 157 children participating at Time 1 (early Grade 1), 134 (68 males) took part also at Time 2 (end of Grade 1). The 23 children who did not attend Time 2 were missing consent forms.

Procedure

Formal consent was obtained from the school headmaster and from the students' teachers and parents, in accordance with policies governed by our institutional review board. Once consent forms were obtained, students were individually tested at beginning of Grade 1 (Time 1), and again at the end of the school year (Time 2).

At Time 1, data collection was carried out for each child individually in three separate sessions lasting approximately 35 min each, with a brief break provided if requested. Testing occurred in a quiet room outside the classroom.

Measures collected at Time 1

Intelligence. Two subtests from the Italian edition of WISC-III (Wechsler, 1991; Italian edition, 2006) were administered as indicators of verbal and fluid intelligence, respectively (Sattler, 1992).

The *Vocabulary* subtest involves defining words presented orally, in order of increasing complexity. For this age group, up to 30 items are presented, each of which is scored according to the accuracy and thoroughness of the child's response. The maximum achievable score is 60 points.

The *Block Design* subtest involves producing a block construction to match a pictorial model shown by the experimenter. Up to 12 items are presented, and each is scored according to the accuracy and time needed to complete the construction within a predetermined time limit. The maximum score is 69 points.

Both subtests yield age-referenced scaled scores between 1 and 19, based on a mean of 10 and standard deviation of 3.

Short-term memory. *Forward word recall* (from Lanfranchi, Cornoldi, & Vianello, 2004). This task, tapping verbal STM, requires repeating an increasing number of common bi-syllabic words in the same order of presentation. The test is comprised of eight trials, two for each of the four levels of difficulty (two- to five-word spans). Correct reproductions are scored one point. The maximum score is eight points.

Forward digit recall (from WISC-III, Wechsler, 1991; Italian edition, 2006). In this task, which assesses verbal STM, children are required to repeat, following the order of presentation, an increasing number of digits. The test is composed by 16 trails, two for each of the eight levels of difficulty (two- to nine-digit spans). Correct recall is scored one point. The maximum score is 16 points.

Path recall (from Lanfranchi *et al.*, 2004). This task explores visuo-spatial STM and entails children observing the experimenter tracing pathways of increasing length on a grid (with the assistance of a toy frog) and then reproducing by themselves the traced pathway. The test is composed of eight trials, two for each of the four difficulty levels, which entail recalling a path of increasing length (two to four frog jumps within 3×3 and 4×4 grids). The correct recall is scored one point. The maximum score is eight points.

Working memory. *Backward word recall* (developed from Lanfranchi *et al.*, 2004). In this task, which explores verbal WM, children are asked to repeat an increasing number of common bi-syllabic words in the inverted order to that used by the experimenter in reading them. The task includes eight trials, two for each of the four increasing levels of difficulty (two- to five-word spans). Correct backward recall is scored one point. The maximum score is eight points.

Backward digit recall (from WISC-III, Wechsler, 1991; Italian edition, 2006). This task taps verbal WM and requires children to recall an increasing number of digits in the inverted order to that used by the experimenter. The test consisted of 14 trials, two for each of the seven levels of increasing difficulty (two- to eight-digit spans). One point is assigned for the correct recall. The maximum score is 14 points.

Verbal dual task (from Lanfranchi *et al.*, 2004). In this task, which explores verbal WM, children listen sequences of common bi-syllabic words. For each sequence, they have to recall the first pronounced word and further execute a simple task (tap the hand on the desk) when the experimenter pronounces the target word. The test is made up by eight trials, two for each of the four increasing levels of difficulty (two- to five-word spans). One point is assigned to each trial only if children both remember the first word of each sequence and perform the concomitant task. The maximum score is eight points.

Path dual task (from Lanfranchi *et al.*, 2004). In the present task, assessing visuo-spatial WM, the experimenter traces pathways on a 4×4 grid using a toy frog; for each pathway, children have to recall the first square to which the frog has jumped and carry out a concomitant task (tap the hand on the desk) when the frog jumps on the target square. The test is composed by eight trials, two for each of the four increasing levels of difficulty (two to five squares making the pathway). Correct responses, receiving one point, require both remembering the first square and realizing the concomitant task. The maximum score is eight points.

Approximate number system. Tasks tapping ANS were reproduced by following the indications given by the authors who originally developed them.

Magnitude comparison of intermixed quantities, hereinafter *Comparison-Intermixed* (adapted from Halberda *et al.*, 2008). This task requires children to rapidly judge which is the most numerous array of dots ('smiley faces' in our study). The two arrays consist in intermixed blue and yellow smiles of different sizes presented on a pc screen for 600 ms. The number of smiles per set varies from 3 to 15. Dots are controlled in size and total area. The proportion between the quantities being compared reflects the range proposed by Halberda *et al.* (2008): 1:2, 3:4, 5:6, 7:8 and their reciprocal (2:1, 4:3, 6:5, 8:7). Each of these eight proportions is presented five times in different numerosity combinations, giving a total of 40 trials. One point is given to each correct response, with a maximum score of 40 points.

Magnitude comparison of separate quantities, hereinafter *Comparison-Separate* (adapted from Piazza *et al.*, 2010). Also in this task, children are asked to rapidly judge, without counting, which is the most numerous array of dots. These are black dots included within two white discs presented simultaneously on either horizontal side of a white fixation cross for 1,000 ms. In each trial, one of the two discs contains the reference number of dots (16), while the other the target number of dots. In our version, numerosities vary from 8 to 24 (16 ± 8, 11 and 21 numerosities excluded, following Piazza *et al.*, 2010). The total number of trials is 56, four for each of the 14 possible target numerosities. Half of the trials are size controlled, and the remaining are area controlled. One point is assigned to each correct response, giving a maximum score of 56 points.

Approximate addition (adapted from Barth, La Mont, Lipton, & Spelke, 2005; Iuculano *et al.*, 2008). This task requires children to visually and approximately sum two arrays of blue dots and compare the sum with an array of red dots. In each trial, two arrays of blue dots appear in succession in the left side of the screen and are then hidden by the same black rectangular occluder. Thereafter, the array of red dots appears on the right side of the screen. After its appearance, each array of dots remains on the screen for 1,000 ms. The total number of dots per trial is between 8 and 25, with dot size varying only across trials as in Iuculano *et al.* (2008). The possible proportions between the total number of blue versus red dots are 4:5, 4:6, 4:7 and their reciprocals 5:4, 6:4, 7:4. The test consists of 24 trials, four for each of the six possible proportions. One point is given per correct response, with a maximum score of 24 points.

Early mathematical abilities. To measure early math skills, a translated version of Early Numeracy Test (ENT, by van Luit, van de Rijt, & Pennings, 1994), Form A, was administered. This test consists of 40 items belonging to the eight components in which the early mathematical abilities can be categorized and that have been defined by the authors as: Comparison, classification, correspondence, seriation, using counting words, structured counting, resultative counting, and general knowledge of numbers. The first four components include tasks requiring spontaneously developing quantitative abilities, while the remaining ones involve more knowledge-based skills (knowledge of numbers and performance of related tasks). More precisely, in previous studies (e.g., Aunio, Hautamäki, Sajaniemi, & van Luit, 2009), the first four ENT subscales were proven to belong to the same factor, named ENT-Relational, and the last four to a second factor, ENT-Counting.

No interruption criterion is applied. One point is assigned to each correct answer or correctly made task, with a maximum score of 40 points. A competence score (up to 100) has been derived from the test conversion tables, which weight the child's raw test score by his/her age. This is needed to control for the influence of age on early numeracy.

Measure collected at Time 2

At the end of Grade 1, math teachers rated their students' math abilities using a 5-point Likert-like scale corresponding to the following: 1 (*Insufficient*); 2 (*Sufficient*); 3 (*Fair*); 4 (*Good*); and 5 (*Very good*). These ratings roughly corresponded to the final evaluation (appearing in the report card) in mathematics and derived from the results achieved during all-year examinations.

Results

Data analysis

Main statistical analyses were conducted by means of the PAW Statistics 18 statistical package (IBM, New York, NY, USA). R package lavaan (free software) was instead used to draw the path analysis models, with the aim of evaluating the contribution of the measured precursors on math achievement. For model estimation, the maximum likelihood approach (Jöreskog & Sörbom, 1996) was selected. However, the inspection of variable distributions revealed cases in which the normality assumption was violated. Therefore, the Satorra–Bentler method (Satorra & Bentler, 1988) was applied to correct for asymmetry. Models were separately drawn for Time 1 and Time 2.

Preliminary analyses and results

Descriptive analyses in Table 1 report the scores obtained in all administered tasks measuring math skills and related precursors. Data show the range of variability and the asymmetry characterizing some of them.

T-tests revealed that children performed above chance (>50%) in each of the ANS tasks: Comparison-Intermixed, $M = 64.79\%$, $t(156) = 14.65$, $p < .001$, Comparison-Separate, $M = 67.23\%$, $t(156) = 30.23$, $p < .001$, and Approximate addition, $M = 65.79\%$, $t(156) = 17.69$, $p < .001$.

Correlation results are reported in Table 2. Significant correlations emerged between ENT achievement and Block design ($r = .51$, $p < .001$) and Vocabulary ($r = .32$, $p < .001$). Correlations of comparable strength were observed between ENT and Path dual task ($r = .35$, $p < .001$) and Backward digit recall ($r = .34$, $p < .001$). Regarding ANS tasks, mild significant correlations can be observed with the two magnitude comparison tasks (for both tasks $r = .20$, $p < .05$), whereas the link with Approximate addition did not attain statistical significance ($r = .14$, $p = .09$). ANS tasks were also differentially related to ENT factors and memory measures. Comparison-Intermixed was significantly related to ENT-Relational ($r = .23$, $p < .01$), and Comparison-Separate to ENT-Counting ($r = .21$, $p < .01$). Considering Approximate addition, it is possible to underline significant correlations with the WM tasks ($r = .25$, $p < .01$ with Backward word recall, $r = .20$, $p < .01$ with Backward digit recall, $r = .29$, $p < .001$ with Path dual task), not observed for the two magnitude comparison tasks. Fewer significant correlations can be noticed for teachers' ratings, which, however, resulted to be highly associated with ENT ($r = .61$, $p < .001$). For further details, please inspect Table 2.

Path model results

Time 1

Relations between math learning precursors and early math skills were assessed by means of path analyses. These models were defined using a theory-driven approach, thus basing on the fact that the selected constructs are theoretically robust and that the related tasks were proven to tap them well. As a consequence, standardized scores achieved in tasks pertaining to the same construct were collapsed to a single predictor variable. Composite

Table 1. Descriptive statistics of all variables

	Task	Min	Max	Mean	*SD*	Skewness	Kurtosis	Reliability
Math measures	ENT	36.00	91.00	68.45	10.09	−0.17	0.24	.94
	ENT-Relational	7.00	20.00	15.88	2.46	−0.77	0.56	.87
	ENT-Counting	2.00	20.00	12.61	4.11	−0.56	−0.16	.90
	Teachers' ratings	1.00	5.00	4.03	1.01	0.90	0.14	.96
Intelligence	Vocabulary	2.00	19.00	11.36	2.84	−0.39	0.81	.74
	Block design	3.00	18.00	11.19	2.98	−0.54	0.23	.80
Short-term memory	Forward word recall	3.00	8.00	5.77	0.96	−0.10	0.03	.88
	Forward digit recall	2.00	11.00	6.52	1.62	0.32	0.28	.87
	Path recall	3.00	8.00	6.24	1.06	−0.68	0.67	.70
Working memory	Backward word recall	0.00	6.00	2.65	1.06	0.54	0.85	.86
	Backward digit recall	0.00	6.00	2.50	1.09	0.70	1.54	.85
	Verbal dual task	0.00	8.00	4.66	1.75	−0.07	−0.72	.84
	Path dual task	0.00	8.00	4.68	1.99	−0.18	−0.51	.81
Approximate number system	Comparison-Intermixed	8.00	35.00	25.92	5.06	−0.71	1.04	.70
	Comparison-Separate	21.00	47.00	37.65	4.00	−0.73	1.73	.65
	Approximate addition	8.00	21.00	15.79	2.68	−0.25	−0.11	.62

Note. ENT, Early Numeracy Test; Min, minimum; Max, maximum; *SD*, standard deviation.

Table 2. Correlation matrix between all variables

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1. ENT	1.00															
2. ENT-Relational	.81***	1.00														
3. ENT-Counting	.93***	.57***	1.00													
4. Teachers' ratings	.61***	.53***	.58***	1.00												
5. Vocabulary	.32***	.28***	.28***	.25**	1.00											
6. Block design	.51***	.43***	.45***	.46***	.16*	1.00										
7. Forward word recall	.28***	.21**	.27***	.25**	.22**	.25***	1.00									
8. Forward digit recall	.32***	.26***	.31***	.24**	.13	.26***	.52***	1.00								
9. Path recall	.21**	.19*	.22**	.15	<.00	.16*	−.01	.07	1.00							
10. Backward word recall	.17*	.07	.19*	.06	.10	.20**	.14	.01	.06	1.00						
11. Backward digit recall	.34***	.18*	.34***	.14	.06	.26***	.33***	.16*	.10	.43***	1.00					
12. Verbal dual task	.29***	.28***	.25***	.17	.19*	.23**	.14	.18*	.15	.16*	.01	1.00				
13. Path dual task	.35***	.26***	.32***	.36***	.09	.30***	<.00	.02	.18*	.22**	.30***	.34***	1.00			
14. Comparison-Intermixed	.20*	.23**	.15	.06	.06	.10	.20**	.24**	−.01	.02	−.04	.07	−.03	1.00		
15. Comparison-Separate	.20*	.11	.21**	.14	.25***	.07	.14	−.02	−.03	.04	−.08	.05	<.00	.16*	1.00	
16. Approximate addition	.14	.05	.15	.16	.07	.22**	.16	.03	.03	.25**	.20**	.15	.29***	.07	.16*	1.00

Note. ENT, Early Numeracy Test.
$*p \leq .05$; $**p \leq .01$; $***p \leq .001$.

scores were therefore computed for each of them: Intelligence (Vocabulary and Block Design), STM (Forward word recall, Forward digit recall, and Path recall), WM (Backward word recall, Backward digit recall, Verbal dual task, and Path dual task), and ANS (Comparison-Intermixed, Comparison-Separate, and Approximate addition). Our intention was in fact that of evaluating the assessed constructs on their whole to inspect their global impact.

Model 1.1, which is reported in Figure 1a, is the final model we obtained for Time 1 and which was the most robust from both theoretical and statistical viewpoints. Model fit is indeed good ($\chi^2 = 0.13$, df = 2, $p = .94$; CFI = 1.00; NNFI = 1.09; RMSEA < .001; SRMR < .01).

Table 3a reports the statistical parameters of this model, which explained the 41% of ENT variance, TDC = .34. All exogenous variables significantly predicted ENT achievement, even if ANS contribution was milder than that of the other variables ($\beta = .12$, $p < .05$). The predominant role was assumed by the quote of intelligence acting directly ($\beta = .39$, $p < .001$), followed by WM ($\beta = .21$, $p < .001$) and STM ($\beta = .20$, $p < .01$). Regarding the relationships between precursors, a significant prediction of intelligence on STM ($\beta = .33$, $p < .001$), WM ($\beta = .27$, $p < .001$), and ANS ($\beta = .25$, $p < .01$) was observed. In this way, all these constructs were expected to act as mediator variables between intelligence and ENT.

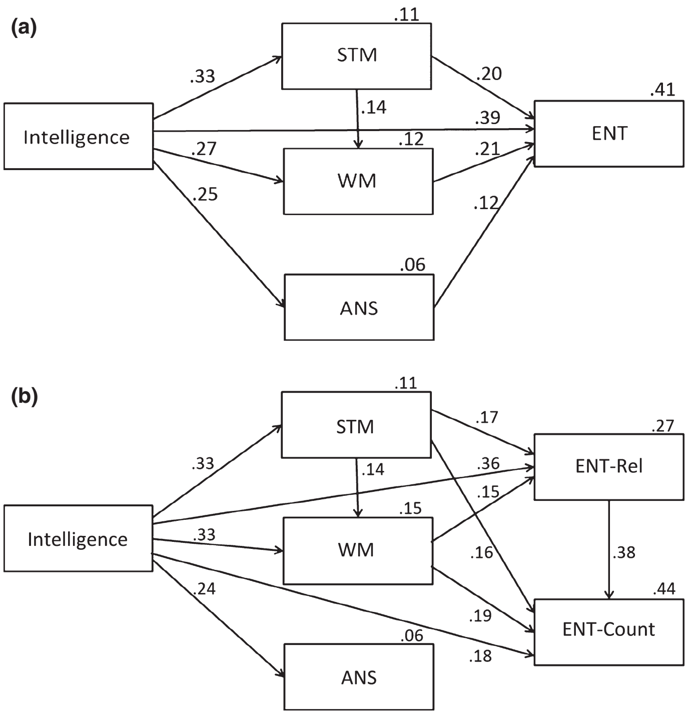

Figure 1. (a) Standardized solution of the relationships between predictor variables and whole Early Numeracy Test (ENT) performance assessed at Time 1. Note also the indirect role of intelligence and short-term memory on ENT performance. *$p \leq .05$; **$p \leq .01$; ***$p \leq .001$. (b) Standardized solution of the differential relationships between predictor variables and the two ENT factors (ENT-Relational and ENT-Counting) assessed at Time 1. Note the indirect influences of both intelligence and STM. *$p \leq .05$; **$p \leq .01$; ***$p \leq .001$. STM, short-term memory.

Table 3. Statistical parameters of path (a) Model 1.1 and (b) Model 1.2

Outcome variable	Predictor variable	β	*Z*-value	*p*	R^2
(a)					
STM	Intelligence	.33	4.66	<.001	.11
WM	Intelligence	.27	3.51	<.001	.12
	STM	.14	2.11	<.05	
ANS	Intelligence	.25	3.00	<.01	.06
ENT	Intelligence	.39	5.76	<.001	.41
	STM	.20	3.13	<.01	
	WM	.21	3.53	<.001	
	ANS	.12	2.00	<.05	
(b)					
STM	Intelligence	.33	4.66	<.001	.11
WM	Intelligence	.33	4.40	<.001	.15
	STM	.14	2.14	<.05	
ANS	Intelligence	.24	2.83	<.01	.06
ENT-Relational	Intelligence	.36	4.61	<.001	.27
	STM	.17	2.40	<.05	
	WM	.15	2.07	<.05	
ENT-Counting	Intelligence	.18	2.59	.01	.44
	STM	.16	2.89	<.01	
	WM	.19	3.16	<.01	
	ENT-Relational	.38	5.73	<.001	

Note. ANS, approximate number system; ENT, Early Numeracy Test; STM, short-term memory; WM, working memory.

Different early math skills domains. Concerning ENT test, our hypothesis was that children's achievement could be differentiated in relation to the type of tasks to be performed. Our hypothesis was also supported by the two-factor structure identified in Aunio *et al.* (2009). More precisely, the first four ENT subscales require basic and spontaneously developing capacities, contrary to the last four. Endorsed by this two-factor structure, we explored the predictive power of the investigated precursors also in relation to the different early math domains indicated, respectively, as ENT-Relational and ENT-Counting.

Model 1.2 (illustrated in Figure 1b) shows the relationships between the variables of interest and the two ENT factors, with performance on ENT-Relational expected to predict that of ENT-Counting. Also in this case, we reported the most robust model. Model fit indices are satisfactory ($\chi^2 = 5.07$, df = 4, $p = .28$; CFI = 0.99; NNFI = 0.98; RMSEA = .04; SRMR = .04) and precursors explained 27% of ENT-Relational variability and 44% of ENT-Counting variability, with overall TDC = .36 (for model parameters see Table 3b). The weight of the inspected constructs varied according to the ENT factor.

When considering ENT-Relational, the strongest path weight was that pertaining to the quote of intelligence acting directly ($\beta = .36$, $p < .001$), followed by STM ($\beta = .17$, $p < .05$) and WM ($\beta = .15$, $p < .05$). In relation to ENT-Counting, it can be observed the main and increased recruitment of WM ($\beta = .19$, $p < .01$), comparable to that of intelligence ($\beta = .18$, $p = .01$) and STM ($\beta = .16$, $p < .01$). ANS did not contribute significantly. Nevertheless, the main predictor of ENT-Counting was represented by

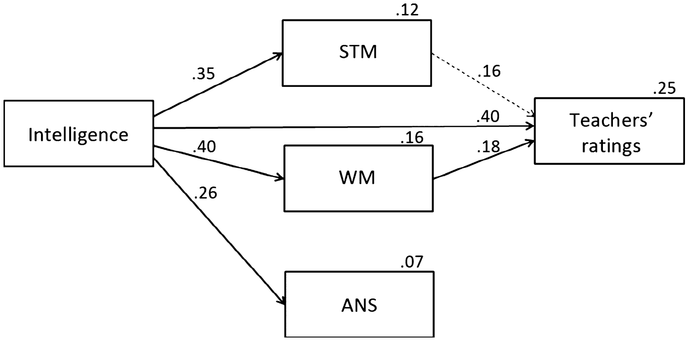

Figure 2. Standardized solution of the relationships between predictor variables assessed at Time 1 and teachers' ratings given at Time 2. Note that intelligence influences math performance also indirectly. $*p \le .05$; $**p \le .01$; $***p \le .001$. The dashed line indicates a relationship approaching significance.

ENT-Relational ($\beta = .38, p < .001$). Also in this case, the pattern of relationships between precursors found in Model 1.1 was met.

Time 2

Although our primary focus was the evaluation of the cognitive abilities in relation to early math competence, we also explored how well these indicators predicted teachers' ratings about children's math achievement at the end of Grade 1. Some authors included teachers' ratings as indicators of math achievement outcomes (e.g., Alloway *et al.*, 2005; Teisl, Mazzocco, & Myers, 2001), and this measure has been proven to significantly correlate ($r = .62$, see M. C. Passolunghi, unpublished data) with a variety of math tests. Nevertheless, we used teachers' ratings, which is not a standardized measure, only for an exploratory investigation. Consequently, the following results have to be treated with caution. For the same reason, we chose to define an independent model for Time 2. This choice has been also supported by the fact that teachers' ratings resulted to be predicted almost entirely by ENT performance (given the very high correlation between the two measures) and only indirectly by math precursors. This happened also when taking separately the performance in the two ENT factors. As our intention was to inspect the contribution of these precursors beyond the mediation of previous achievement, we did not insert ENT scores in this model.

We reported the final solution for the Time 2 model, termed Model 2, in Figure 2 and a summary of the related parameters in Table 4. The explained variance corresponded to 25%, TDC = .38. Fit indices are acceptable ($\chi^2 = 7.98$, df = 5, $p = .16$; CFI = 0.97; NNFI = 0.93; RMSEA = .07; SRMR = .05). With the exception of intelligence, precursors' predictive power was decreasing in comparison with Model 1.1 and that of ANS did not reach significance. Only intelligence indices ($\beta = .40$, $p < .001$) and WM ($\beta = .18$, $p < .05$) maintained quite strong relationships. The involvement of STM was only close to significance ($\beta = .16, p = .06$) but nearly comparable in strength to that of WM.

Discussion

The purpose of the current research project was to investigate the cognitive abilities acting as precursors of math learning, by observing their involvement in the acquisition of

Table 4. Statistical parameters of path Model 2

Outcome variable	Predictor variable	β	*Z*-value	*p*	R^2
STM	Intelligence	.35	4.62	<.001	.12
WM	Intelligence	.40	4.83	<.001	.16
Approximate number system	Intelligence	.26	2.84	<.01	.07
Teachers' ratings	Intelligence	.40	4.18	<.001	.25
	STM	.16	1.91	.06*	
	WM	.18	2.36	<.05	

Note. STM, short-term memory; WM, working memory.
*This link approached significance.

math-related skills at the beginning of schooling. As very few are the studies having investigated both general and specific precursors with regard to early math skills, we wanted to provide a global view of their involvement and possible interrelations. The indirect goal was the definition of the cognitive skills that can be deficient in MLD individuals, therefore identifying which of them can be monitored to precociously recognize the condition of risk. To achieve this aim, we selected to consider the effects of intelligence and ANS on their whole, treating them as unitary constructs, and those of memory by adopting the distinction only between active (WM) and passive (STM) processes (therefore without distinguishing between verbal and visuo-spatial components).

Our main hypothesis was that both general and specific abilities could have a significant involvement in this stage of development. This hypothesis was generally confirmed by path analysis results. More in detail, the fundamental role of memory was supported. WM resulted to be a strong precursor (e.g., Bull & Scerif, 2001; Gathercole, Brown, & Pickering, 2003; Gathercole & Pickering, 2000; Passolunghi & Lanfranchi, 2012; Xenidou-Dervou *et al.*, 2013), but also passive processes associated with STM were relevant (e.g., Bull *et al.*, 2008; Gathercole *et al.*, 2003). Our findings are therefore important in helping to shed light on the role of memory about which it has not been yet reached a unitary consensus among researchers (e.g., Landerl, Bevan, & Butterworth, 2004; for an opposite view). Nonetheless, at least in this stage of development, intelligence appeared to be the strongest precursor. In fact, it was observed to act on early math achievement both directly and indirectly, by influencing not only memory level (e.g., Colom, Rebollo, Palacios, Juan-Espinosa, & Kyllonen, 2004; Engle, Tuholski, Laughlin, & Conway, 1999; Kane, Hambrick, & Conway, 2005), but also that of ANS.

Another important outcome is represented by the specific precursors and particularly by ANS which, contrary to our expectations, manifested a rather small effect. The contribution of this component was however significant, in line with relevant literature results (e.g., Gilmore *et al.*, 2010; Halberda *et al.*, 2008; Mazzocco *et al.*, 2011a). Some authors instead argued that a significant contribution of ANS can be observed only giving that related performance requires capacities associated with WM and executive functions (e.g., Gilmore *et al.*, 2013; Soltész, Szűcs, & Szűcs, 2010). In this perspective, a significant relation between ANS and these general processes can be observed, and when controlling for them, ANS involvement on math learning loses significance. In our study, the ANS–memory relation did not reach significance, indicating that, on the whole, the two components are almost independent (see also Belacchi *et al.*, 2014; Mazzocco *et al.*, 2011a). Anyway, when considering the relation between individual tasks, it can be noticed that approximate addition, which was the most articulated and complex among the ANS tasks, was significantly related to all WM measures (besides to fluid intelligence), in line with Xenidou-Dervou *et al.* (2014). This finding suggests that, even within tasks pertaining to the same domain, the capacities required to perform them can be quite different and reflect the cognitive load they entail.

Predictive differences in relation to early math skills domains

A further aim of our research was to explore whether the investigated math precursors are differently recruited for different competences within early math tasks. With this purpose, we independently considered effects on ENT-Relational (more basic) and ENT-Counting (more complex). As hypothesized, differences across variables could be indirectly observed. For instance, intelligence explained the performance mainly on ENT-Counting than on ENT-Relational. The same trend could be highlighted in relation to WM, whereas the contribution of STM was almost equivalent across the two ENT factors, and greater to that of WM for ENT-Relational, but lower for ENT-Counting. This tendency can be explained by the fact that the acquisition of more complex early math abilities could require not simply the capacity of passively retaining new information, but also that of actively manipulating it. As task demands increase, WM is thought to progressively assume a higher involvement.

On the other hand, contrary to possible predictions, ANS skills were not related to either factor. A potential explanation is that ANS, comprehensive of even different tasks (as previously discussed), can have an effect susceptible to significance loss when partitioned among more outcome variables. In fact, the preliminary analyses conducted by considering relations with single ANS tasks indicated ENT-Relational to be related to the performance on Comparison-Intermixed quantities and ENT-Counting to that on Comparison-Separate. Again, only comparison tasks, and not approximate addition, as instead observed in kindergartners in Xenidou-Dervou *et al.* (2014), were the only predictors of ENT performance. These contradictory findings suggest that further investigations are needed to disentangle the role of overall ANS but also of pertaining subskills.

Time 2

The evaluation of math learning precursors involvement in the prediction of math achievement at the end of Grade 1 (Time 2) showed interesting results. From the inspection of path results, it could be noticed that the overall predictive values of the inspected predictors decreased in comparison with Time 1. Intelligence maintained a consistent involvement, followed by WM and STM. An important and crucial finding was that concerning ANS. In fact, at the end of the school year, its contribution was not only reduced, as supposed, but it did not even reach significance. This trend seems to be in line with those showing how ANS can lose its significant role when formal numerical abilities are acquired (e.g., Desoete, Ceulemans, De Weerdt, & Pieters, 2012), and in particular when it is controlled for learned symbolic skills, as indicated also in very recent works (Göbel, Watson, Lervåg, & Hulme, 2014; Lyons, Price, Vaessen, Blomert, & Ansari, 2014; van Marle, Chu, Li, & Geary, 2014).

Another possible explanation is that teachers' ratings can be influenced more by students' capacities reflecting higher memory and intelligence, without attributing much importance to the innate aspect of quantity manipulation. Actually, some studies have demonstrated ANS role to be significant also in older children (Inglis, Attridge, Batchelor, & Gilmore, 2011) and adults (Lourenco, Bonny, Fernandez, & Rao, 2012; Paulsen, Woldorff, & Brannon, 2010. See, however, Castronovo & Göbel, 2012 for opposite findings).

It is possible that only some ANS parameters can be significant predictors of formal math learning in older children. Accuracy performance is likely to display a ceiling effect for the used numerosities and ratios and therefore loses discriminative power. On the other hand, other parameters, such as reaction times, can instead be more informative as they can better differentiate children's performance. Hence, they can act as significant math predictors in upper grades (see Lonnemann *et al.*, 2013). The long-lasting predictive role of some ANS parameters can be observed also when controlling for symbolic aspects, suggesting that the latter do not completely mediate the relation between ANS and later math achievement, as evidenced in Fazio, Bailey, Thompson, and Siegler (2014). Having our study considered only accuracy as unique ANS parameter, future work is needed to shed light on the role of different aspects of ANS in math learning.

Finally, it can be pointed out that ANS has been proven to be only modestly hereditable, meaning that it is very likely to be subjected to developmental changes that are highly dependent to context and environment (e.g., Tosto *et al.*, 2014). This suggests that its developmental trend can be not linear and that external cues have an important role in determining its maturation. This evidence represents therefore an additional confounding factor.

Limitations and future directions

An important contribution of the present study has been, besides the confirmation of the major role of WM held in early mathematics, that of adding evidences in favour of that of STM and in trying to elucidate the role of ANS. Nonetheless, a limitation of the research concerns results pertaining to Time 2 evaluation, which should be corroborated by taking standardized tests to assess formal math learning. Moreover, our study did not include symbolic specific precursors, and, for this reason, it had not been possible to infer the role of ANS on math achievement while controlling for these skills. Future suggestions entail therefore the replication of the study by including a set of tasks tapping both non-symbolic and symbolic number sense skills. It could be interesting to longitudinally follow the development of both general and specific abilities to detect possible changes regarding their involvement in math learning in response to cognitive development and education (see Geary, 2011).

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