Early numerical abilities and cognitive skills in kindergarten children

Maria Chiara Passolunghi [a,*], Silvia Lanfranchi [b], Gianmarco Altoè [b],
Nadia Sollazzo [a]

[a] *Department of Life Sciences, "Gaetano Kanizsa" Psychology Unit, University of Trieste, 34128 Trieste, Italy*
[b] *Department of Developmental and Socialization Psychology, University of Padova, 35131 Padova, Italy*

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ABSTRACT

In this study, a unitary path analysis model was developed to investigate the relationship between cognitive variables (derived from published studies) and early numerical abilities in children attending the last year of kindergarten. We tested 100 children starting their last year of kindergarten on the following cognitive abilities: intelligence, phonological abilities, counting, verbal and visuospatial short-term memory and working memory, processing speed, and early numerical abilities. The same children were tested again on early numerical abilities at the end of the same year. The children's early numerical abilities at the beginning of the final year of kindergarten were found to be directly related to their verbal intelligence, phonological abilities, processing speed, and working memory and to be indirectly related to their nonverbal intelligence. Early numerical abilities at the end of the same year are directly related not only to early numerical abilities assessed at the beginning of the year but also to working memory and phonological abilities as well as have an indirect relationship with verbal and nonverbal intelligence. Overall, our results showed that both general and specific abilities are related to early mathematic learning in kindergarten-age children.

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[*] Corresponding author.
E-mail address: passolu@units.it (M.C. Passolunghi).

Introduction

Achieving a good level of mathematical ability is important to success at school and attainment in the activities of everyday life. Investigating the abilities linked to math learning, therefore, is important both from a theoretical standpoint, to clarify the cognitive abilities related to successful math learning, and from a social and educational point of view, with a view to the early identification of individuals at risk for mathematical learning disability and to the development of appropriate enhancement training for them.

Although a shared definition is still lacking, the core skills that predict children's performance in mathematics have been referred to using the general term *early numeracy abilities.* They include skills such as counting ability, one-to-one correspondence, quantity comparison, and representing numerical magnitudes in the form of a mental number line (Gersten, Jordan, & Flojo, 2005; Jordan, Kaplan, Ramineni, & Locuniak, 2009; Van de Rijt & Van Luit, 1999). A number of studies on kindergarten children found a relationship between early numerical abilities and later mathematical skills (e.g., Aunio & Niemivirta, 2010; Jordan, Kaplan, Oláh, & Locuniak, 2006; Jordan et al., 2009). For example, Mazzocco and Thompson (2005) found that mathematical learning disability in third grade could be accurately predicted from difficulty with certain mathematics tasks in kindergarten, including reading numerals, applying counting principles, number line concepts, and mental additions. Koponen, Aunola, Ahonen, and Nurmi (2007) showed that procedural calculation skills in fourth grade were predicted by individual differences in children's early numerical abilities assessed in kindergarten. Investigating the impact of early numerical abilities on mathematical achievement in the first grade of primary school, Jordan, Kaplan, Locuniak, and Ramineni (2007) found that the former accounted for 66% of the variance in the latter.

Only a few studies have considered the role of both general cognitive skills and more specific abilities, such as early numerical abilities, in predicting later mathematical achievement in primary school. Geary (2011) found that early numerical abilities, processing speed, and visuospatial working memory predicted mathematical achievement from first grade to fifth grade. Hassinger-Das, Jordan, Glutting, Irwin, and Dyson (2014) found that attention problems and executive functioning were unique predictors of mathematical achievement in first-grade children with weak early numerical abilities at the end of kindergarten. Östergren and Träff (2013) found that both early number knowledge and verbal working memory affected kindergarten and first-grade arithmetical ability. Locuniak and Jordan (2008) reported that early numerical abilities in kindergarten contributed a significant amount of the variance in calculation fluency in second-graders over and above the influence of more general predictors (age, reading, memory, and verbal and spatial cognition).

However, no studies have been conducted to date to develop a comprehensive model that includes general cognitive variables such as working memory, processing speed, phonological ability, intelligence, and early numerical abilities in children attending their last year of kindergarten. In the current study, therefore, we aimed to produce a unitary path analysis model capable of identifying the relationship between these variables. We also aimed to analyze the autoregressive effects of the numerical abilities identified at the beginning of the school year on the numerical abilities measured at the end of the same year. Thus, our model concerns both the concurrent and predictive roles of cognitive variables in influencing early numerical abilities. The following sections briefly explain the rationale underlying the variables considered in the study and our specific study hypotheses.

Working memory and short-term memory

Working memory can be seen as a short-term "working space" for temporarily retaining information while the individual is involved in other tasks. Baddeley and Hitch (1974) described working memory as a three-way system comprising a central executive and two slave systems. The central executive can be seen as a limited-capacity processor responsible for attentional control over actions and for processing and coordinating the two slave systems called the phonological loop (for retaining linguistic information) and the visuospatial sketchpad (for retaining visuospatial information). The distinctions between the central executive system and specific memory storage systems (i.e., the phonological loop and the visuospatial sketchpad) in some ways parallel the distinctions between working memory and short-term memory. The term *working memory* refers to a processing resource of limited capacity involved in preserving information while simultaneously processing the same or other information (Baddeley & Logie, 1999).

Experimental tasks assessing working memory and the influence of the central executive component typically involve storage, processing, and effortful mental activity (Kail & Hall, 2001; Miyake & Shah, 1999). In contrast, short-term memory typically involves situations where participants passively retain small amounts of material and minimal resources from long-term memory are activated to perform the task. Short-term memory tasks involve participants reproducing items in the order they were presented immediately after their presentation, and no cognitive processing is required (digit or word span forward tasks).

Most of the literature indicates that working memory is related to a variety of numerical and mathematical abilities underlying the solution of both simple addition and subtraction problems and complex arithmetical problems (e.g., De Smedt, Verschaffel, & Ghesquière, 2009; Passolunghi, Cornoldi, & Di Liberto, 1999). This view is supported by the finding that children who are weak in mathematics also have problems with working memory (Hitch & McAuley, 1991; Passolunghi & Pazzaglia, 2005; Passolunghi & Siegel, 2004; Siegel & Ryan, 1989) or with both visuospatial short-term memory (STM) and working memory (e.g., Passolunghi & Mammarella, 2010; Siegel & Ryan, 1989; Szucs, Devine, Soltesz, Nobes, & Gabriel, 2013), whereas they have no particular problems in verbal STM tasks (McLean & Hitch, 1999; Passolunghi, 2006). Verbal STM could influence mathematical performance differently (see Bull, Espy, & Wiebe, 2008; Passolunghi & Cornoldi, 2008; Passolunghi, Mammarella, & Altoè, 2008) depending on an individual's age and the demands of the mathematical task presented. For example, verbal STM appears to be involved in counting (Logie & Baddeley, 1987) and has a major role when calculation involves temporarily storing information but not carrying over or borrowing operations (Fuerst & Hitch, 2000).

Based on the results of studies on children of primary school and kindergarten age, our hypothesis was that short-term memory and especially working memory are related to early mathematical learning.

Processing speed

Processing speed can be considered as the efficiency and rapidity with which simple cognitive tasks are performed (see Case, 1985). For example, processing speed can determine how quickly numbers are recited, objects are counted, and problems are solved. Processing speed also affects the efficiency of working memory and short-term memory; the more quickly these systems work, the more information is processed before decay. However, processing speed and short-term/working memory are two separate systems (e.g., Kail, 2007). Bull and Johnston (1997) found processing speed to be the best predictor of arithmetical competence in 7-year-olds. D'Amico and Passolunghi (2009) found that fourth-graders with arithmetic learning disability performed poorly in terms of the speed with which they activated numerical and non-numerical information from long-term memory. In a group of third-graders, Fuchs and colleagues (2006) found processing speed to be a significant predictor of arithmetical ability assessed using a task that involved addition and subtraction number facts (see also Swanson & Kim, 2007). Based on these results, our initial model consequently included a measure of processing speed to explore the hypothesis of a direct link between processing speed and early numerical abilities in kindergarten children.

Phonological abilities

Several studies have highlighted the role of phonological awareness in subsequent mathematical achievement. Phonological processing may influence the development of mathematical computation skills because speech sound processes are used to solve problems in this academic domain (Bull & Johnston, 1997; Szucs, Devine, Soltesz, Nobes, & Gabriel, 2014). Leather and Henry (1994) identified phonological awareness as the main predictor of arithmetical ability in 7-year-olds and argued that some phonological manipulations require arithmetical processes (cf. Fuchs et al., 2006; Hecht, Torgesen, Wagner, & Rashotte, 2001). In an earlier study, Bradley and Bryant (1983) reported that phonological awareness assessed in kindergarten correlated not only with reading and spelling but also with math achievement assessed 3 years later. Alloway et al. (2005) found a significant relationship between phonological awareness assessed at 4 and 5 years of age and teacher-reported mathematical competence at the beginning of first grade (6 years of age). Similarly, in a longitudinal study, Simmons, Singleton, and Horne (2008) showed that phonological awareness assessed at 5 years of age predicted reading and arithmetical ability 1 year later.

Despite this increasing support for a relationship between phonological awareness and mathematic achievement, some studies produced inconsistent results (Durand, Hulme, Larkin, & Snowling, 2005; Durand, Hulme, Larkin, & Snowling, 2006; Fuchs et al., 2005; Krajewski & Schneider, 2009). A longitudinal study by de Jong and van der Leij (1999) followed children from nursery school to their second year of primary school and indicated that the children's phonological awareness did not predict their mathematical ability but rather was only a specific predictor of reading ability. Using a comprehensive assessment of mathematical abilities in first-graders, Passolunghi, Vercelloni, and Schadee (2007) found working memory and counting ability to be the most powerful discriminators and efficient precursors in their structural equation model, whereas phonological ability was not a significant precursor. So, for the time being, it is not clear when phonological ability contributes to the development of mathematical abilities.

In light of the above information, our study aimed to elucidate the relationship, if any, between phonological ability and early mathematical learning. We assumed that the inconsistencies seen in the above-mentioned earlier results were partly due to the types of task used to assess mathematical skills. The influence of phonological skills emerges mainly in simple arithmetic tasks that rely on early numerical abilities learned early in life, whereas it fades to insignificance in the case of more complex tasks such as problem-solving and when mathematical achievement is assessed. It may be that the connection between phonological abilities and mathematical achievement is age related given that studies on older children found a significant relationship between these variables, whereas studies on children in kindergarten or the first and second grades of primary school did not.

Counting

Counting implies the ability to deal with quantities, such as to recite the number sequence, as well as the ability to establish a one-to-one relationship between objects in a set and their numerical representations. Many studies support hypotheses of early sensitivity to numerical clues, and counting ability is believed to develop well before any teaching is received at school (see Gelman & Gallistel, 1978). We consequently opted to consider counting separately from phonological abilities. As explained in the introductory paragraphs, counting can be included under the umbrella term *early numerical abilities,* but different types of counting task have different levels of difficulty. To assess counting in the current study, we opted to use tasks that measure basic counting skills (e.g., verbal counting, counting spots).

Some studies have identified differences in counting ability level between individuals obtaining different scores in arithmetic tasks (see Geary, Bow-Thomas, & Yao, 1992; Geary, Hoard, & Hamson, 1999). Passolunghi and colleagues (2007) also found counting ability and working memory to be the most discriminating and efficient precursors of early mathematical learning during the first year of primary school. On the strength of these findings, therefore, we aimed to explore the relationship between counting and early numerical abilities when other cognitive variables were included in the model.

Intelligence level

The results of previous studies exploring the relationship between intelligence and mathematical abilities are controversial. Some studies found a relationship between IQ and mathematical performance (Geary et al., 1999; Passolunghi et al., 2008), whereas other studies failed to find any correlation (Passolunghi et al., 2007). Considering the controversial results, we planned to explore whether there is a direct relationship between intelligence and early numerical abilities or whether this relationship is mediated by cognitive variables such as short-term and working memory, processing speed, counting, and phonological abilities.

The current study

This study focused on identifying which of the cognitive variables discussed in the previous sections, such as intelligence, working memory, verbal and visuospatial STM, processing speed, and phonological and counting skills, are linked to children's early numerical abilities at the beginning and end of their last year at kindergarten. This extends previous research in several ways. First, in children attending kindergarten, we analyzed the relationship between these cognitive variables in a unitary model. Few studies have considered all of the variables emerging from previous research as being related to mathematical abilities in a unique model, and they all concentrated on primary school children (e.g., Cowan & Powell, 2014; Fuchs et al., 2006; Geary, 2011; Szucs et al., 2014), hence our decision to focus instead on the early numerical abilities developed during the last year of kindergarten. At the same time, we considered all working memory components (i.e., verbal STM, visuospatial STM, and working memory) in our model, whereas most of the previous studies considered only some of them. Finally, we considered both the concurrent and predictive values of the contributions of intelligence, working memory, verbal and visuospatial STM, processing speed, and phonological and counting skills to early numerical abilities, assessing the latter at the start and end of the last year of kindergarten so that the correlation between cognitive variables and early numerical abilities at the end of the year would be over and above the domain-specific competences.

We administered a battery of tests to children starting their last year of kindergarten (mean age = 5.3 years) to measure intelligence, working memory, verbal and visuospatial STM, phonological ability, counting ability, processing speed, and early numerical abilities. Their early numerical abilities were assessed using the Utrecht Early Numeracy Test, Form A (Van Luit, Van de Rijt, & Pennings, 1994), and Form B of the same test was administered to the children at the end of the same school year. To test our hypothesis, we constructed path analysis models starting in a systematic way, as a top-down procedure, from the most complex model that included all of the variables deduced from the literature and simplifying it to obtain the final model.

Method

Participants

A total of 100 children (55 girls and 45 boys) took part in the study. These children were part of a larger cohort of children who took part in a longitudinal project on cognitive ability and mathematics. All children were Caucasian and from a middle socioeconomic background, and they were all native Italian speakers. At the time of data collection (Phases 1 and 2), the children were attending their final year of kindergarten. By the end of Phase 2, 12 children had dropped out of the study because they had moved away or were unavailable for assessment due to illness. Only the 88 children who completed both phases were considered in the analysis. In Phase 1, the children had a mean age of 5 years 3 months (*SD* = 4 months); in Phase 2, they had a mean age of 5 years 9 months (*SD* = 4 months).

In Italy, kindergarten lasts for 3 years and is for children from 3 to 6 years of age. Attendance is not compulsory, and the activities proposed focus mainly on play and concrete experiences to improve the children's knowledge of the world and socialization.

Procedure

The children were tested in two phases: the first in October/November and the second in the following May. The first phase involved assessing the following basic cognitive abilities: (a) intelligence, using the block design task as a test of nonverbal aspects and the vocabulary task as a test of verbal skills, both drawn from the Wechsler Preschool and Primary Scale of Intelligence (WPPSI; Wechsler, 1967/1987); (b) working memory and short-term memory; (c) phonological ability; (d) counting; and (e) processing speed. Early numerical abilities were also assessed using Form A of the Utrecht Early Numeracy Test (Van Luit et al., 1994). In the second phase, a parallel form of the Utrecht Early Numeracy Test (Form B) was used to assess early numerical abilities at the end of the school year. In both phases, the children were tested individually in a quiet room over a total of five sessions (four sessions at the beginning of the school year and one at the end). The order of task presentation was counterbalanced across participants.

Measures

Intelligence

We used one performance task (block design) and one verbal task (vocabulary) from the WPPSI (Wechsler, 1967/1987) to obtain performance and verbal IQ scores, respectively (Sattler, 1992). The two scores can be used to obtain an overall IQ (see Hecht et al., 2001; Sattler, 1992), with the vocabulary subtest bearing the strongest correlation with overall IQ in children (Sattler, 1988).

Processing speed

Two measures of processing speed were used (see Fuchs et al., 2006):

(a) Woodcock–Johnson (WJ) III Visual Matching (Woodcock, McGrew, & Mather, 2001) measures processing speed by asking participants to find and circle two identical numbers appearing in a row of six numbers. The children were allowed 3 min to complete 60 rows, and they earned credit by correctly circling the matching numbers in each row.

(b) Speed pattern comparison, using a modified version of Salthouse's (1993) speed pattern comparison task, which involves quickly examining complex patterns. A total of 60 pairs of patterns were presented, and participants needed to decide as quickly as possible whether or not the two patterns in each pair were identical. A time limit of 1 min was allowed to complete the task. The total score was the number of correct answers given in the allocated time.

Verbal short-term memory

Forward recall of word and digit tasks was used to assess verbal STM. Participants were presented with a series of familiar two-syllable words or single digits and asked to recall them in the same order. There were two trials for each span length (from two to five for words and from two to eight for digits), and the children's answer was considered correct when all items were recalled in the right order. The task was administered using the classic self-terminating procedure.

Visuospatial short-term memory

Two tasks were used to assess visuospatial STM:

(a) Corsi blocks task: The experimenter showed participants a path on a board with nine black wooden blocks and asked them to recall the path immediately afterward. There was 1 point awarded for each sequence recalled correctly.

(b) Pathway recall (Lanfranchi, Carretti, Spanò, & Cornoldi, 2009; Lanfranchi, Cornoldi, & Vianello, 2004): Participants were shown a path taken by a frog on a matrix and asked immediately afterward to recall the pathway. There were five levels of difficulty depending on the number of jumps along the frog's path and the size of the board. The frog's jumps were presented at approximately 2-s intervals. We decided to use this second task too because it may be easier for our children's age range because it is bidimensional instead of tridimensional, because the matrices are smaller, and because the positions are arranged regularly on the matrix, not randomly as in the Corsi blocks task.

Both visuospatial STM tasks were administered using the classic self-terminating procedure.

Working memory

There were four tasks to assess working memory:

(a) Verbal dual task (Lanfranchi, Baddeley, Gathercole, & Vianello, 2012; Lanfranchi, Jerman, & Vianello, 2009; Lanfranchi et al., 2004): Participants were presented with a list of two to five words and asked to remember the first word on the list and to tap on the table when the word *palla* (ball) was presented. Tapping served as a secondary task in this case. Scores ranged between 0 and 8.

(b) Visuospatial dual task (Lanfranchi et al., 2004, 2009): Participants needed to remember a frog's starting position along a path it covered on a 4 × 4 matrix, where one of the 16 cells was colored red. They also needed to tap on the table when the frog moved onto the red square. The task had four different levels of difficulty depending on the number of times the frog jumped (two, three, four, or five). Scores ranged between 0 and 8.

(c) Backward digit recall task from the Wechsler Intelligence Scale for Children–Revised (WISC-R) digit span subtest: Participants were presented with digits and asked to recall them in reverse order. There were two trials for each span length presented (from two to eight), and 1 point was awarded for each list recalled correctly. These three working memory tasks (this one and the first two above) were administered using a self-terminating procedure.

(d) Word fluency (Newcombe, 1969): As suggested by Andersson (2007, 2008), a verbal fluency task was included to assess controlled retrieval of information from long-term memory, which Baddeley (1996; but see also Baddeley & Logie, 1999) considers one of the functions managed by the central executive. Participants were given 1 min to generate verbally as many words as possible beginning with a given letter (e.g., F, A, S) or as many items from various semantic categories (e.g., animals, objects, occupations). Participants were given a score corresponding to the number of words generated correctly. Each child's final score was the sum of the scores obtained for each trial.

Counting

Two tasks were used to assess counting:

(a) Verbal counting: This measures number sequence knowledge. Participants were asked to count from 1 to 10 as quickly as possible, and the time it took them was recorded. The task was repeated three times in a row, and the sum (in seconds) of the three times was obtained. This task provides a mixed measure, testing both the numerical aspect of acquaintance with the number sequence and phonological–articulatory aspects involving the phonological loop (Baddeley & Hitch, 1974).

(b) Counting spots: This is another measure of knowledge of the number sequence and the principles of counting. The task was based on the counting spots task used by Hitch and McAuley (1991). Eight cards were used, each showing 13 balls, some of them yellow and some of them blue. The number of yellow balls varied from 5 to 10 to prevent participants from subitizing (i.e., immediately guessing the numbers rather than actually counting the balls). The experimenter showed one card at a time, asking participants to count the yellow balls as quickly as possible, and recorded the total time taken (in seconds) to count the yellow balls on all the cards and the number of correct answers.

Phonological abilities

Phonological abilities were tested using a series of four types of task, drawn from recent studies, that estimate the ability to analyze and combine phonetic elements (de Jong & van der Leij, 1999; Hecht et al., 2001; Oakhill & Kyle, 2000). In the word and pseudoword repetition tasks, participants repeated a word or nonword (e.g., *mela* [apple], *nanta* [pseudoword]) immediately after hearing it spoken by the experimenter, using the ability of phonetic analysis (recognition of sound by perception) and phonetic blending (combining parts of a word or nonword in order to pronounce it correctly). There were 20 trials for word repetition and 20 trials for pseudoword repetition. In the tasks involving phonetic analysis, participants needed to recognize and repeat the first and last sounds of a word or nonword spoken by the experimenter. There were 10 trials for first-sound repetition and 10 trials for last-sound repetition. In the phonemic segmentation tasks, children were asked to repeat the words spoken by the experimenter letter by letter (phoneme by phoneme) (e.g., "piede" [foot] = p-i-e-d-e). There were 10 trials. In the syllable blending tasks, participants needed to combine the syllables spoken by the experimenter to form a word (e.g., "ca-val-lo" [horse] = *cavallo*). There were 10 trials. For all of these tasks, 1 point was given for each word/syllable/phoneme used correctly.

Early numerical abilities (Phases 1 and 2)

Early numerical abilities were assessed in Phases 1 and 2 using two parallel versions (Forms A and B) of the Utrecht Early Numeracy Test (Van Luit et al., 1994). The test was translated into Italian by one of the authors using standard translation and back-translation procedures (Brisling, 1986). This test consists of 40 items, divided into eight categories of 5 items each, underlying eight aspects of young children's early numerical abilities as follows: *comparison,* which involves comparing two non-equivalent cardinal or ordinal situations in four given pictures; *classification*, which involves distinguishing between objects and grouping them; *one-to-one correspondence*, which is designed to ascertain whether children are able to establish a one-to-one relationship between different objects; *seriation,* which involves recognizing the correct rank order in the task; *use of number words*, which examines children's knowledge of cardinal and ordinal numbers up to 20; *structured counting,* which is designed to ascertain children's ability to count quantities up to 20; *resultative counting*, which is designed to assess children's ability to count structured or unstructured collections without using their fingers or when the items are hidden; and *general knowledge of numbers,* which is designed to ascertain children's use of numbers up to 20 in simple situations.

The whole test is administered individually and takes approximately 30 min. The items are scored by awarding 1 point for a correct answer and no points for a wrong answer, and the maximum score is 40 (e.g., Van de Rijt & Van Luit, 1999). The Utrecht Early Numeracy Test was developed as a one-dimensional test (Van de Rijt & Van Luit, 1999), so there is only one total score to interpret.

Statistical analyses

To address the main questions of our study, analyses were performed in two successive steps, where the first was cross-sectional and the second was longitudinal. In particular, two series of path analysis models (structural equation models using observed variables) were estimated with the LISREL 8.7 statistical package (Jöreskog & Sörbom, 1993):

> *Step 1 (cross-sectional study)* to examine the relationships among the dependent variable, the mediators, and the independent variables considered in Phase 1. The baseline theoretical model is shown in Fig. 1.
>
> *Step 2 (longitudinal study)* to examine the relationships between the dependent variable in Phase 2 and the mediators and independent variables in Phase 1, adjusting for the autocorrelation between the dependent variables across the two phases.

In both cases, starting from a baseline model, we removed paths and variables in light of both statistical reasoning (the significance and effect size of the corresponding structural parameter estimates) and the theoretical aspects discussed in the Introduction. Paths were removed one by one to take each variation into account in the parameter estimates in the models.

The goodness of fit for each model was tested on the basis of several indexes. Because the chi-square statistic depends on sample size, we considered two relative fit indexes, the non-normed fit index (NNFI) and the comparative fit index (CFI), which perform well with both small and large samples. Values above .97 are usually considered satisfactory (Schermelleh-Engel, Moosbrugger, & Muller, 2003). The root mean square error of approximation (RMSEA) was also used and is an absolute fit index assessing approximation of parameter estimates to true parameters in the population. Values below .05 reflect a good fit (Schermelleh-Engel et al., 2003).

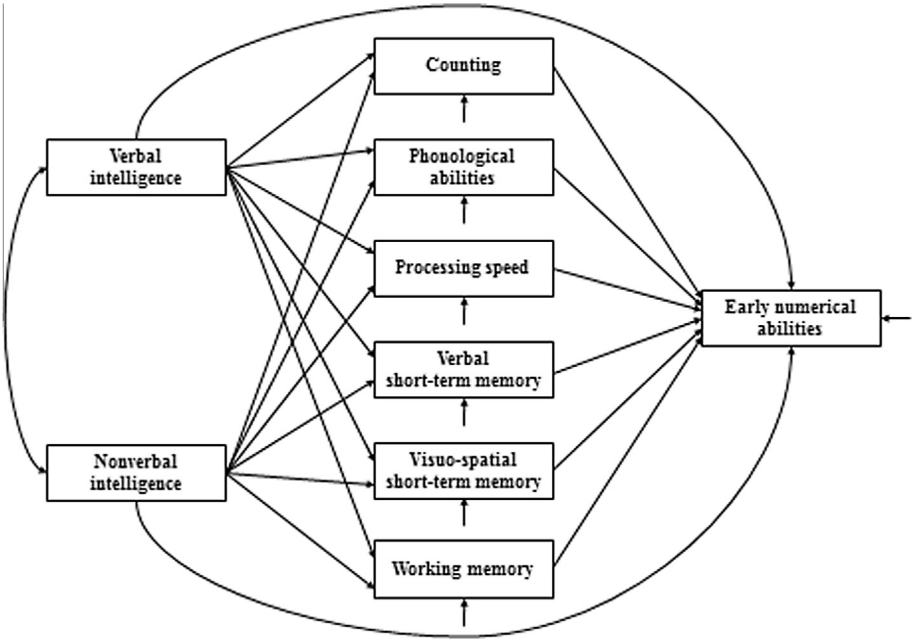

Fig. 1. Baseline theoretical model in Phase 1.

Results

Descriptive statistics for the tasks are given in Table 1.

Cross-sectional study

In the current study, the independent variables were verbal and nonverbal intelligence and the dependent variable was the early numerical abilities score. The dimensionality of early numerical abilities, as assessed in the current study, was examined using a series of maximum likelihood exploratory factor analyses on the eight subscale scores in the Utrecht Early Numeracy Test. Specifically, at each time point (i.e., Phase 1 [the beginning of the last kindergarten year] or Phase 2 [the end of the last kindergarten year]), a one-dimensional model was compared with several multi-dimensional models (two-, three-, and four-dimensional solutions) using the Bayesian information criterion (BIC; Schwarz, 1978). According to this criterion, given a set of models for the same data, the model with the lowest BIC value can be regarded as the best-fitting model (i.e., the model that is rendered most plausible by the observed data). In both phases, the one-dimensional solution (with all subscales characterized by positive loadings) yielded a smaller BIC than the multi-dimensional solutions, thereby supporting the unidimensionality of early numerical abilities.

The mediator variables were working memory, verbal STM, visuospatial STM, processing speed, and phonological and counting skills. The mediator variables were compacted to build unique variables based on theoretical reasons as well as on correlation scores (shown in Table 2).

In particular, working memory was calculated from the standard mean scores in the backward digit span, verbal and visuospatial dual tasks, and word fluency task. Verbal STM was calculated from the standard mean scores obtained in the word and forward digit span tasks. Visuospatial STM was calculated from the standard mean scores in the speed pattern comparison and Corsi blocks tasks.

The phonological skills measure was calculated from the standard mean scores for the word/pseudoword repetition, phonetic analysis, syllable blending, and phonetic segmentation tasks. The

Table 1
Descriptive statistics.

	M	*SD*	Min	Max	Reliability
Phase 1					
Intelligence					
Vocabulary	18.16	5.90	2	30	.74
Block design	14.14	4.026	3	19	.80
Processing speed					
Visual matching	20.60	6.05	6	34	.91
Speed pattern comparison	15.81	4.29	5	23	.70
Verbal STM					
Word span	4.88	1.06	0	8	.88
Digit span	3.34	1.25	0	7	.87
Visuospatial STM					
Pathway recall	5.57	1.23	2	8	.70
Corsi blocks task	4.09	1.67	1	8	.79
Working memory					
Verbal dual task	4.55	1.84	0	8	.84
Visuospatial dual task	5.52	1.81	1	8	.81
Backward digit recall	1.91	1.18	0	4	.85
Word fluency	31.15	7.02	10	52	.83
Counting					
Verbal counting time	9.60	3.93	5	29	.85
Counting spots time	26.38	5.55	17	46	.83
Counting spots correct answer	6.93	1.23	3	8	–
Phonological abilities					
Word/pseudoword repetition	35.62	2.73	29	40	.78
Phonetic analysis	9.58	7.90	0	20	.90
Phonemic segmentation	8.05	8.67	0	20	.88
Syllable blending	18.15	3.51	0	20	.83
Early numerical abilities	26.97	6.27	10	39	.90
Phase 2					
Early numerical abilities	28.93	4.20	18	38	.84

Note. The reported values are raw scores for tasks.

counting measure was calculated from the standard mean scores awarded in the verbal counting and counting spots tasks. Finally, a compact measure representing processing speed was also calculated based on the standard mean scores obtained in the WJ III Visual Matching and speed pattern comparison tasks. Correlations among these measures are given in Table 3.

The fully saturated model (Fig. 1) was tested on the covariance matrix among the study variables for Phase 1 using the maximum likelihood (ML) method of estimation (Jöreskog & Sörbom, 1996).

We first examined the direct relations between the independent variables (verbal and nonverbal intelligence) and the outcome variable (early numerical abilities). The direct relation between nonverbal intelligence and early numerical abilities was not significant ($\beta = .04$, $z = .43$, $p = .667$), so it was removed from the model. Next, we examined the direct relations between the independent variables and the six mediator variables (working memory, verbal STM, visuospatial STM, processing speed, and phonological and counting skills). The path coefficients revealed that all of the paths from nonverbal intelligence to the mediators and the path from verbal intelligence to working memory were significant at the .05 level, so these variables were retained. Finally, we examined the expected direct relationships between the mediator variables and the outcome variable. Whereas phonological abilities, processing speed, and working memory were significantly and positively related to early numerical abilities, the paths between counting, verbal STM, visuospatial STM, and the outcome variable were not statistically significant (and these paths and the corresponding mediators were consequently removed). The resulting model, with all of the significant structural parameters, gave rise to an unsatisfactory fit, $\chi^2(6, N = 88) = 19.32$, $p = .004$, NNFI = .82, CFI = .93, RMSEA = .162.

A further look at the modification indexes (Jöreskog & Sörbom, 1996) suggested that the correlation between phonological abilities and processing speed should be included in the model, so this relationship was added. The final model presented in Fig. 2 showed an excellent fit to the observed data:

Table 2
Correlations between variables considered in the study.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Inteligence																					
1. Vocabulary[a]																					
2. Block design[a]	.23*																				
Processing speed																					
3. Visual matching	.16	.43**																			
4. Speed pattern comparison	.03	.20	.37**																		
Verbal STM																					
5. Word span	.07	.14	.09	.07																	
6. Digit span	−.03	.30**	.31**	.35**	.27*																
Visuospatial STM																					
7. Pathway recall	.19	.28**	46**	.16	.04	.05															
8. Corsi blocks	.08	.13	.29*	.06	−.06	.01	.28**														
Working memory																					
9. Verbal dual task	.28**	−.02	.01	−.07	.11	.13	−.01	.13													
10. Visuospatial dual task	.35**	.18	.30**	.16	.02	.13	.35**	.13	.20												
11. Backward digit recall	.37**	.50**	.27*	.05	.18	.07	.09	.02	.06	.20											
12. Word fluency	.40**	.22*	.31**	.17	−.03	.04	.31**	.10													
Phonological abilities																					
13. Word repetition	.07	.02	.17	.13	.32**	.19	.11	−.05	−.04	−.06	.15	.01									
14. Pseudoword repetition	.20	.26*	.11	.17	.34**	.32**	.14	−.07	.15	.12	.24*	−.01	.36*								
15. Phonetic analysis, first sound	.06	.37**	.37**	.42**	.25*	.41**	.21*	.08	−.01	.15	.34**	.12	.15	.33**							
16. Phonetic analysis, last sound	.14	.31**	.53**	.34**	.26*	.51**	.25*	.17	−.02	.18	.26*	.18	.28**	.40**	.69**						
17. Phonemic segmentation	.15	.30**	.42**	.30**	.20	.41**	.17	.11	.11	.24*	.30**	.20	.30**	.38**	.68**	.75**					
18. Syllable blending	.01	.19	.22*	.10	.18	.20	.04	−.01	.01	.11	.19	−.02	.05	.32**	.33*	.32**	.33**				
Counting																					
19. Verbal counting time	.02	−.10	−.34**	−.23*	−.17	−.30**	−.10	−.09	.04	−.10	−.01	−.02	−.06	−.22*	−.34**	−.42*	−.34**	−.28**			
20. Counting spots time	−.03	−.12	−.51**	−.40**	−.10	−.19	−.29**	−.15	−.04	−.06	−.09	−.10	−.07	−.17	−.33**	−.39**	−.29**	−.20	.54**		
Early numerical abilities																					
21. Early numerical abilities, Phase 1	.42**	.36**	.46**	.44**	.15	.12	.24*	.23*	.03	.36**	.44**	.41**	.12	.18	.50**	.51**	.45**	.15	−.28	−.32**	
22. Early numerical abilities, Phase 2	.43**	.30**	.43**	.35**	.18	.14	.26*	.16	.12	.23*	.51**	.42**	.33**	.22*	.41**	.47**	.51**	.13	−.19	−.31**	.67*

[a] These variables consist of standard scores in the WPPSI vocabulary and block design subtests.

* $p < .05$.

** $p < .01$.

Table 3
Correlations between compacted variables.

	1	2	3	4	5	6	7	8	9
1. Verbal intelligence	–								
2. Performance intelligence	.23*	–							
3. Processing speed	.12	.38**	–						
4. Verbal STM	.30	.27**	.31**	–					
5. Visuospatial STM	.16	.25*	.36**	.02	–				
6. Working memory	.55**	.35**	.28**	.17	.28**	–			
7. Phonological skills	.16	.35**	.47**	.55**	.18	.27**	–		
8. Counting	.02	.23*	.49**	.29**	.20	.06	.42**	–	
9. Early numerical abilities, Phase 1	.42**	.36**	.55**	.17	.29**	.49**	.46**	.36**	–
10. Early numerical abilities, Phase 2	.43**	.30**	.47**	.20	.26*	.50**	.50**	.33**	.67**

* $p < .05$.
** $p < .01$.

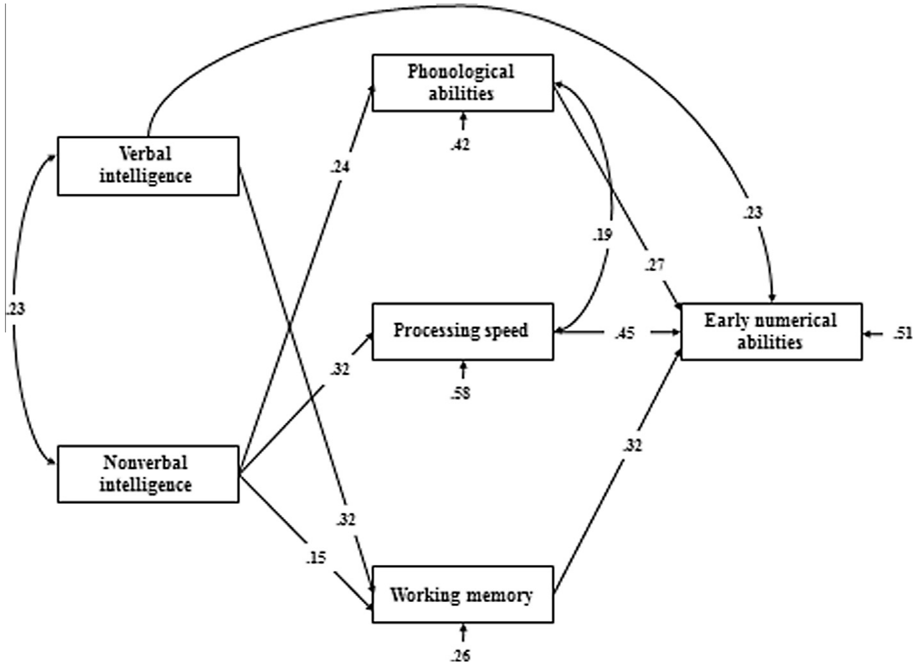

Fig. 2. Standardized solution for the final cross-sectional path model in Phase 1. All structural parameters are significant above the $p < .05$ level. $\chi^2(5, N = 88) = 4.39$, $p = .495$, NNFI = .98, CFI = 1.0. RMSEA = .001.

$\chi^2(5, N = 88) = 4.39$, $p = .495$, NNFI = .98, CFI = 1.00, RMSEA = .001 (Schermelleh-Engel et al., 2003). In particular, the whole model accounted for 49% of the variance for early numerical abilities and 58%, 42%, and 74% of the variance for phonological abilities, processing speed, and working memory, respectively.

In the final model, all of the relationships were significant and positive. There was evidence of a direct effect of verbal intelligence, phonological abilities, working memory, and processing speed on early numerical abilities. The effect of nonverbal intelligence on early numerical abilities was also mediated through phonological abilities, working memory, and processing speed.

Longitudinal study

The aim of the longitudinal study was to examine the relationship between the independent variables and the mediators considered in Phase 1 and the early numerical abilities measured in Phase 2, adjusting for the children's early numerical abilities in Phase 1. A series of path analysis models, therefore, was tested on the covariance matrix among the study variables assessed in Phases 1 and 2. For the baseline model, we adapted the model resulting from the cross-sectional study to include the children's early numerical abilities in Phase 2. In particular, direct paths were added from the independent variables and the mediators to the early numerical abilities in Phase 2. To consider the autocorrelation across the phases, a direct path was introduced that went from the early numerical abilities assessed in Phase 1 to those assessed in Phase 2.

We first examined the direct relations between the independent variables and the early numerical abilities in Phase 2. The two paths were not statistically significant, so they were removed from the model. Next, we examined the paths from phonological abilities, processing speed, and working memory to early numerical abilities in Phase 2. After adjusting for early numerical abilities in Phase 1, phonological abilities and working memory showed a significant relationship with early numerical abilities in Phase 2 but processing speed did not, so the corresponding path was removed.

The resulting model shown in Fig. 3 (with all structural parameters significant at the .05 level) yielded an excellent fit to the observed data: $\chi^2(8, N = 88) = 7.80$, $p = .453$, NNFI = 1.00, CFI = 1.00, RMSEA = .001. As expected, there was a positive and significant relationship between early numerical abilities in the two phases ($\beta = .46$, $z = 5.04$, $p < .001$.). The whole model accounted for 53% of the variance for early numerical abilities in Phase 2.

In the final model, all of the relationships were significant and positive. There was a direct effect of verbal intelligence, phonological abilities, working memory, and processing speed on early numerical abilities in Phase 1, and there was a direct effect of phonological abilities and working memory on early numerical abilities in Phase 2. The effect of nonverbal intelligence on early numerical abilities

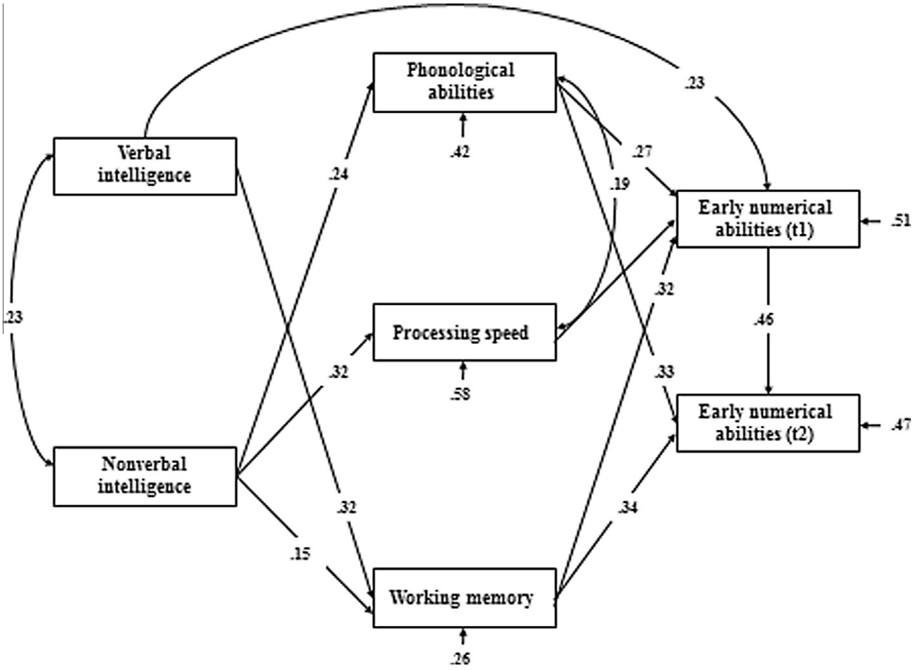

Fig. 3. Standardized solution for the final longitudinal path model. All structural parameters are significant above the $p < .05$ level. $\chi^2(8, N = 88) = 7.80$. $p = .453$, NNFI = 1.0. CFI = 1.0. RMSEA = .001.

in Phase 1 was mediated by phonological abilities, working memory, and processing speed, whereas the effect of nonverbal intelligence on early numerical abilities in Phase 2 was mediated by phonological abilities and working memory. Finally, there was a direct relationship between early numerical abilities in Phase 1 and those in Phase 2.[1]

Discussion

Our study aimed to identify the cognitive abilities associated with numerical abilities in kindergarten children. In the Introduction, we emphasized that there are only a few studies available on kindergarten children and that some considered only general abilities, such as working memory, as possible correlates of early numerical abilities, whereas other studies focused only on the predictive power of specific abilities, such as early numerical abilities. This is a limitation of previous studies. We think that it is important to consider both domain-general and domain-specific abilities as possible correlates of early numerical abilities in order to describe a unitary model that can obtain a complete frame and shed light on the specific influence of each ability.

After a critical review of the literature, several cognitive variables (verbal and nonverbal intelligence, working and short-term memory, processing speed, counting, and phonological abilities) were chosen as potential correlates of early numerical abilities and were examined, together with early numerical abilities, in children attending the last year of kindergarten. The study was articulated in two phases. In the first phase, cognitive variables and early numerical abilities were assessed at the beginning of the school year; in the second phase, early numerical abilities were reassessed at the end of the school year. The current study, using and comparing several different predictors, supports the view that phonology, processing speed, and working memory are the main cognitive correlates of early numerical abilities. Our path analysis model showed that early numerical abilities at the beginning of the year correlated directly with phonological abilities, processing speed, and working memory. As for intelligence, there was a direct relationship between verbal intelligence and numerical abilities, whereas the latter's relationship with nonverbal intelligence was mediated by phonological abilities, processing speed, and working memory.

More specifically, our model supports the hypothesis that working memory is a distinct and significant correlate of early numerical abilities at the start of the last preschool year .The same cannot be said, however, of either verbal or visuospatial STM. These results provide substantial evidence for separating the involvement of short-term memory and working memory as correlates of early mathematical learning (Cowan, 1995; Shah & Miyake, 2005; Swanson, 2006), with working memory having an essential influence on early numerical abilities. Similar results were found for mathematical achievement in older children as well (e.g., Geary, 2011; Hassinger-Das et al., 2014; Passolunghi & Lanfranchi, 2012).

We found a significant relationship between early numerical abilities and processing speed (over and above the relationship with working memory) in children attending their final year of kindergarten. A similar relationship between processing speed and mathematical achievement (over and above the influence of intelligence and working memory) was found in primary school children (e.g., Bull & Johnston, 1997; Fuchs et al., 2006; Geary, 2011). As suggested by some authors (e.g., Fuchs et al., 2006; Lemaire & Siegler, 1995), a good performance in terms of processing speed may facilitate a variety of tasks by increasing the speed at which stimuli are processed, establishing associations in short- and long-term memory and successfully pairing problems with their answers in working memory before decay sets in, and this would apply to early numerical abilities as well as to later mathematical achievement.

Our results also showed a significant relationship between early numerical abilities and phonological abilities, confirming previous findings in primary school children (e.g., Fuchs et al., 2006;

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[1] Given that traditional maximum likelihood methods in the presence of relatively small samples can lead to incorrect standard error estimates, and consequently to erroneous significance tests, we reestimated all of our path models using the MLM (maximum likelihood with robust standard errors) estimator in the lavaan package of the R software (see Rosseel, 2012, for details). The new analysis fully confirmed our previous findings, indicating that the maximum likelihood method performed well for our data and was virtually unaffected by sample size, thereby supporting the reliability of our findings.

Leather & Henry, 1994; Szucs et al., 2014). As Fuchs and colleagues (2006) suggested, phonological abilities might be involved when children use phonological name codes for numbers to count (Logie & Baddeley, 1987) and also in fact retrieval, both of which are involved not only in later mathematical achievement but also in early numerical abilities, differently from innate and preverbal abilities or approximate number abilities.

Regarding intelligence, we found a direct influence of verbal intelligence on early numerical abilities. This may be because the test used to assess early numerical abilities (the Utrecht Early Numeracy Test) broadly involves verbal aspects of intelligence both in understanding the instructions and in performing the tasks. On the other hand, we found an indirect effect of nonverbal intelligence on early numerical abilities. This result is in line with other studies showing an indirect relationship between nonverbal intelligence and mathematics in first-graders (e.g., Passolunghi et al., 2007).

In the current study, we could not confirm the direct relationship between counting and early numerical abilities reported in previous studies (e.g., Geary et al., 1999; Passolunghi et al., 2007). This might be because of some degree of correlation between the counting and processing speed tasks (ranging from .23 to .51) due partially to the tasks used to measure counting skills. On the other hand, the overlap between these two variables (shown by the correlation value) was only partial, and although these tasks involved some aspects relating to processing speed (time was one of the variables considered in both tasks), they also involved separate aspects such as the knowledge of counting principles. We are aware that this is a potential limitation of our study, and we hope that future research will reiterate this study but using a broader range of tasks for measuring counting ability.

An additional aim of our study was to assess the relationship between cognitive variables and early numerical abilities at the beginning of the last year of kindergarten and early numerical abilities at the end of the school year in order to identify cognitive abilities that support the development of these early numerical abilities. For this purpose, we developed a path analysis model that included early numerical abilities measured at the beginning and end (Phases 1 and 2) of the final kindergarten year. The same precursors (phonological abilities, working memory, and nonverbal intelligence) remained significant in determining the children's early numerical abilities in Phase 2 even when early numerical abilities in Phase 1 had been included in the model. These results support a network view of mathematical abilities, as suggested by Szucs and colleagues (2014), where cognitive abilities—specifically working memory, processing speed, and phonological abilities—sustain the development of early numerical abilities over and above the role of more domain-specific abilities. Similar results have been reported in primary school children as well (e.g., Geary, 2011; Passolunghi & Lanfranchi, 2012; Szucs et al., 2014). No significant relationship between processing speed and early numerical abilities was found, however, unlike what happened at Time 1. We surmise that the relationship between these two variables in the Phase 1 and 2 model is mediated by performance in early numerical abilities at Time 1.

This study has some limitations. For a start, it focused only on the last year of kindergarten. Because kindergarten lasts for 3 years in Italy, it would be interesting to run a longitudinal study to chart the development of early numerical abilities across all 3 years. Second, the sample size was small. A larger sample size would certainly have added to the generalizability of our results and enabled an analysis of the influence of mediator variables on different aspects of early numerical abilities. Considering that previous data showed a stronger role of visuospatial working memory in the math performance of young children (see Holmes, Adams, & Hamilton, 2008), further studies on larger samples should also explore the separate contribution of verbal and visuospatial working memory in the development of early numerical abilities.

Taken together, our results highlight the importance of both general and specific cognitive abilities in supporting the acquisition of early numerical abilities in the last year of kindergarten. In particular, they support a network view of mathematical abilities, as suggested by Szucs and colleagues (2014), where cognitive abilities—specifically working memory, processing speed, and phonological abilities—sustain the development of early numerical abilities over and above the role of more domain-specific skills. Our results also suggest that timely action to prevent children from developing early difficulties in mathematical learning should focus not only on domain-specific variables, such as number competence, but also on more general abilities, such as working memory, phonological abilities, and processing speed.

Although there are reports of controversial effects of working memory interventions (see the meta-analysis by Melby-Lervåg & Hulme, 2013), our results—showing the relevance of the relationship between working memory and early numerical abilities—are in line with several recent studies showing that training working memory had beneficial effects not only on working memory but also on mathematical skills in children attending primary school (Alloway, Bibile, & Lau, 2013; Holmes & Gathercole, 2013; Kuhn & Holling, 2014) and on early numerical abilities in kindergarten-age children (Passolunghi & Costa, 2014).

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