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Running Head: EXACT AND APPROXIMATE NUMBER SKILLS IN CHILDREN WITH SLI

Impact of Language Abilities on Exact and Approximate Number Skills Development: Evidence from Children with Specific Language Impairment

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Abstract

Purpose – Counting and exact arithmetic rely on language-based representations, whereas number comparison and approximate arithmetic involve approximate quantity-based representations which are available early in life, before the first stages of language acquisition. The objective of this study is to examine the impact of language abilities on the later development of exact and approximate number skills.

Method – Twenty-eight 7- to 14-year-old children with Specific Language Impairment (SLI) completed exact and approximate number tasks involving quantities presented symbolically and nonsymbolically. They were compared to age-matched (AM) and vocabulary-matched (VM) children.

Results – In the exact arithmetic task, the accuracy of children with SLI was lower than that of AM and VM Controls, and related to phonological measures. In the symbolic approximate tasks, children with SLI were less accurate than AM Controls, but the difference vanished when their cognitive skills were considered or when they were compared to younger VM Controls. In the nonsymbolic approximate tasks, children with SLI did not differ significantly from Controls. Further, accuracy in the approximate number tasks was unrelated to language measures.

Conclusions – Language impairment is related to reduced exact arithmetic skills whereas it does not intrinsically affect the development of approximate number skills in children with SLI.

Keywords: Number skills, Approximate number system, Arithmetic, Language, SLI, Development, Mathematical development

Impact of language abilities on exact and approximate number skills development: Evidence from children with specific language impairment

Is the development of number skills determined by language abilities? Children with Specific Language Impairment (SLI), which refer to children with poor language skills in the absence of intellectual disability, hearing impairment, or obvious signs of neurological damage (Leonard, 1998), constitute a population which offers researchers an opportunity to examine this research question. In the present study, we explore the role played by language abilities in the development of number skills by comparing children with SLI with typically-developing peers.

Different types of number skills

Since number skills are multi-componential (Dehaene, 1992), answering the question as to whether they are related to language abilities during development necessitates first differentiating between the variety of numerical abilities and their underlying processes. Current theories of number processing (Dehaene, 1992; Dehaene & Cohen, 1995) suggest that *approximate* and *exact* number skills should be distinguished. *Approximate number skills* allow people to manipulate numerical quantities in an approximate fashion, so that they are able to apprehend, for instance, that a set of 56 elements is larger in number than a set of 40 elements and smaller than a set of 70 elements. Approximate number skills are deployed in all numerical activities that require to process quantities, such as quantity comparison (e.g., judging that 56 elements is larger than 40 elements) or approximate arithmetic (e.g., estimating that 35 elements plus 21 elements is larger than 40 elements). Being inherently imprecise, approximate number skills are characterized by a ratio effect according to which the ability to discriminate between two quantities decreases as the ratio of compared quantities approaches the unit. For instance, it is more difficult to discriminate between quantities that differ by a ratio of 3:2 (e.g., 12 vs. 8 elements) than between quantities that differ by a ratio of 2:1 (e.g., 16 vs. 8 elements). The ratio effect is considered as a fundamental signature of the approximate number system. The approximate number skills offer an interesting contrast with the *exact number skills* which allow people to use numbers precisely. Exact number skills intervene in numerical activities such as verbal counting, retrieval of exact arithmetic facts from long-term memory (e.g., immediately retrieving the fact that 5 plus 4 equals 9, without proceeding to any calculation), as well as multidigit exact arithmetic (e.g., computing that 35 plus 21 equals 56).

According to the triple-code model (Dehaene, 1992; Dehaene & Cohen, 1995), the aforementioned numerical activities are supported by three different mental representation systems mediated by distinct cerebral circuits. The three systems are interconnected so that representations can be mutually translated into one another (see Figure 1). In the first code, the *verbal representation,* numbers are manipulated as a word sequence (e.g., /naın/ or /fıftı/ /sıks/). In the second code, the *visual Arabic representation,* numbers are manipulated in Arabic format (e.g., 9 or 56). Because they rely on the conventional numerical symbols, these two representations support exact number skills. The verbal code is thought to be implicated in counting, retrieval of exact arithmetic facts, as well as mental calculation in multidigit exact arithmetic, and the Arabic code in the application of the standard written columnwise algorithms in multidigit exact arithmetic. Importantly, these two symbolic representations do not inherently contain any information about the quantity conveyed by the numerical symbols. This information is actually delivered by the third code, the *approximate number representation*. Such an approximate representation of quantity is activated when nonsymbolic numerical stimuli are presented (e.g., a set of nine elements), but it can also be accessed through symbol transcoding so that rough information about the meaning of numerical symbols can be retrieved. The recourse to this code, which supports approximate number skills, occurs in numerical activities such as number comparison or approximate arithmetic.

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Importance of language abilities in the development of exact and approximate number skills

In accordance with the basic assumptions of the triple-code model, exact number skills such as counting and mental arithmetic are supposed to be closely related to language and to the verbal representation of numbers (Dehaene, 1992; Dehaene & Cohen, 1995). However, the language components involved in these processes are not clearly specified in the model and remain to be identified. To the extent that the system of verbal representations is used as a support for the mental manipulation of number word sequences as well as for the storage of arithmetic facts in verbal memory, the availability and the quality of the phonological coding might appear crucial for the numerical activities that imply exact number processing.

In contrast to exact number skills, approximate number skills are generally assumed to emerge independently of language (Dehaene, 2001a). This is supported by the observation of approximate number skills in infants as well as in other animal species (e.g., Meck & Church, 1983; Xu & Spelke, 2000). For instance, Xu and Spelke (2000) demonstrated that 6-month-old infants are able to discriminate between sets of dots that differ by a 2:1 ratio (16 vs. 8 dots) on the basis of numerosity, indicating that approximate number skills emerge very early, well before the acquisition of language or of mathematical instruction.

Remarkably, approximate number skills gain in precision throughout the life span. Xu and Arriaga (2007) showed that 10-month-old infants discriminate numerical differences between sets of dots with a 3:2 ratio (12 vs. 8 dots) which 6-month-old infants failed to distinguish, demonstrating a significant improvement of the discrimination threshold in infancy. A refinement of the approximate number skills also further occurs in preschoolers and in school-aged children (e.g., Halberda & Feigenson, 2008; Piazza et al., 2010). For instance, Halberda and Feigenson (2008) reported that 6-year-old children detect finer numerical changes than do 3-year-old children when presented with sets of dots, suggesting that they had developed more precise approximate number skills. The authors speculated that age and maturation of the brain areas dedicated to the approximate processing of numerical quantity might be one cause of this developmental change.

Aside from biological maturation, language might also be a determinant of the development of approximate number skills. It seems plausible that language, particularly as far as it underlies the acquisition and availability of verbal symbols for numbers, affects the precision of approximate number skills during development. Indeed, children have to associate the preverbal approximate number representations with the culturally acquired exact verbal symbols. At around 24 months of age, with the emergence of language, children begin to acquire number words (e.g., Fuson, 1988; Wynn, 1992), but the initial phase is probably independent of the approximate number system (e.g., Carey, 2001) so that spoken numerals remain meaningless for a certain period of time. Then, children gradually learn to attach meaning to the initial number words, slowly progressing word by word. For instance, at around 30 months of age, the word "one" appropriately refers to one individual element, whereas the other numerals are indiscriminately associated to all the quantities larger than one. With age and increased experience with number words, the mapping between the verbal counting sequence and the corresponding quantities gains in precision (e.g., Carey, 2001; Wynn, 1992). During this period, children learn what the word "two" stands for, and some months later, "three". Finally, they grasp the logic of the successor principle so that, at around the age of 4, a particular number word from their counting list can be associated to the corresponding quantity (e.g., Wynn, 1992).

In line with the idea that the acquisition of verbal number symbols could influence the evolution of approximate number skills, some studies conducted with preschoolers have demonstrated a relationship between verbal counting abilities and the development of quantity processing (e.g., Brannon & Van de Walle, 2001; Lipton & Spelke, 2005; Rousselle, Palmers, & Noël, 2004). For instance, Rousselle and colleagues showed that only preschoolers who had already acquired a minimal level of counting proficiency (i.e., they produced at least one correct cardinal response when asked to give a certain number of items to the examiner) discriminated between visual collections on the basis of number. By contrast, the less skilled counters of the same age failed to detect numerical differences between collections controlled for non-numerical continuous variables. Thus the observation that preschool children who have more proficient verbal counting skills are better at discriminating between quantities raises doubts about the assumption that approximate number skills develop independently of verbal knowledge. This issue is addressed in the current study by investigating the number skills of school-aged children with Specific Language Impairment (SLI). We reasoned that if language abilities affect the development of approximate number skills, not only exact number skills but also approximate abilities should be delayed in children with SLI, and the developmental delay might increase with age and development.

Number skills in children with SLI

Previous studies have shown that, as a consequence of their language deficit, children with SLI have a very limited verbal counting sequence compared to age-matched children. For example, Fazio (1996) demonstrated that 7-year-old children with SLI count up to 42 on average while age-matched children count up to 85, and the counting sequence of children with SLI was equivalent to that of younger children matched for language. The ability of the children with SLI to manipulate the verbal counting sequence is also less developed than that of their peers matched for chronological age, as indicated by a difficulty to count up from a given number to any other given number and to count backwards (Cowan, Donlan, Newton, & Lloyd, 2005; Donlan, Cowan, Newton, & Lloyd, 2007; Fazio, 1996; Koponen, Mononen, Rasanen, & Ahonen, 2006). Despite the limitation of their verbal counting sequence, children with SLI know however that one and only one number word must be assigned to each counted object in a set, and that the number word applied to the last object in the set represents the quantity of objects of the set (Camos, Fayol, Lacert, Bardi, & Laquière, 1998; Fazio, 1994). This indicates that the understanding of the counting principles is preserved in children with SLI and suggests a lag between their verbal and conceptual development.

Previous studies also showed that children with SLI experience difficulties in exact arithmetic, which is coherent with their verbal deficit. Children with SLI have a less developed store of arithmetic facts than that of age-matched children (Cowan et al., 2005; Fazio, 1996), a difference which persists during development. For instance, Fazio (1996, 1999) found that children with SLI evaluated at the age of 7 were still less efficient three years later. Furthermore, they made more errors and were slower than age-matched children at solving more complex calculation problems, and they tended to use a higher proportion of immature calculation strategies (e.g., finger counting) for a longer period of time than their age-matched peers (Cowan et al., 2005; Donlan et al., 2007; Fazio, 1994, 1996; Koponen et al., 2006). Nonetheless, the language components which were used to perform these tasks were not clearly identified. This will be examined in the current study.

In contrast to their exact number skills, the approximate number skills of children with SLI were explored to a much lesser extent. Data from the study by Donlan and Gourlay (1999) revealed that 8-year-old children with SLI were less accurate than age-matched controls when asked to compare single and two-digit Arabic numerals although both groups did not differ statistically. According to the authors, the failure to reach significance probably occurred because of large individual differences, with low accuracy rates for only a part of the sample of children with SLI. Other studies found an significantly higher error rate for children with SLI than for age-matched children in symbolic comparison tasks involving multidigit numbers (Cowan et al., 2005; Donlan et al., 2007; Koponen et al., 2006). The authors interpreted these data as showing that language disorders hinder the understanding of the place-value principle characterizing Arabic numerals, according to which the value that an Arabic digit is representing depends on the place it occupies in the numeral. However, because comparing numerical symbols automatically activates approximate number representations (e.g., Moyer & Landauer, 1967), an alternative interpretation is that such a deficit reflects a basic impairment of approximate number skills. Surprisingly, only a few studies assessed the approximate number skills of children with SLI through the presentation of quantities displayed in a nonsymbolic format such as sets of dots (Donlan, Bishop, & Hitch, 1998; Siegel, Lees, Allan, & Bolton, 1981). Moreover, these studies did not control for the non-numerical continuous variables which co-vary with number (e.g., total occupied area, dot size) and which are known to affect performance (e.g., Nys & Content, 2012; see also Mix, Huttenlocher, & Levine, 2002 for a review). It therefore remains difficult to draw firm conclusions regarding the core approximate number skills of children with SLI, or, more generally, about the relationship between language abilities and approximate number skills. This was the principal objective of the present study.

Current study

The main aim of the current study is to test whether the development of number skills – both exact and approximate – is related to language abilities. Three main tasks are administered to 28 school-aged children with SLI and 122 control children, classified in two age groups: (1) an *exact addition task* in which the children have to exactly solve two-digit addition problems (e.g., 31 + 25 = ?); (2) an *approximate comparison task*, in which children have to estimate which of two quantities is the largest (e.g., 56 > 78?), with symbolic (numbers in an Arabic visual form) and nonsymbolic stimuli (visual sets of dots); (3) an *approximate addition task* in which they have to estimate two quantities and decide whether their approximate sum is larger than a third one (e.g., 31 + 25 > 78?). Again symbolic and nonsymbolic quantities are presented. Further, language tasks assessing phonology, vocabulary and morphosyntax are administered to children with SLI.

These tasks are designed to address three main research questions: (1) Are exact arithmetic skills impaired or preserved in children with SLI, and which language abilities (phonological, lexical or morphosyntactic) are mostly involved? (2) Are approximate comparison skills impaired or preserved in children with SLI? If impaired, is the deficit specific to the processing of numerical symbols or does it reflect a general impairment of the approximate number skills? Further, which language abilities are mostly involved? (3) Are the capacities to perform approximate arithmetic impaired or preserved in children with SLI, and which language abilities are mostly involved? Note that children from two age-ranges are assessed in each of the three tasks to examine whether the potential differences between children with SLI and control children change over time and with the experience with numbers.

The same set of analyses is conducted separately for each research question. First, group performance of young and older children with SLI are compared to those of age-matched (AM) and of younger vocabulary-matched (VM) control children, to examine whether performance reached by the children with SLI are impaired or preserved at the group level. Second, individual performance distributions are examined to assess whether the results observed at the group level hold at the individual level since some of the previous studies showed large interindividual differences in children with SLI, potentially exaggerating or masking certain effects at the group level. Finally, correlations between performance of children with SLI and language measures are computed to examine which components of language are involved.

If language abilities play a role in the development of both the exact and the approximate number skills, young and older children with SLI should show impaired performance relative to age-matched children, both at the group level and at the individual level, in the exact addition task as well as in the approximate comparison and addition tasks. Children with SLI should also progress more slowly than their peers, in line with their language development, although compensatory mechanisms might intervene to modulate the developmental course. Further, correlations between performance and specific language measures should be identified for each task. By contrast, if the development of approximate number skills is language-independent, young and older children with SLI should demonstrate impaired performance in the exact addition task but unaffected performance in the approximate number tasks. In that case, correlations between performance and language measures should be identified for the exact addition task only.

Method

Participants

Twenty-eight children with SLI took part in the study. The Control group consisted of 122 children with unimpaired language development.

SLI group – Forty-four children attending language units from special education schools were recruited. Special education units share the same objectives as the ordinary elementary school but promote learning at the child's own pace. Therefore, the number of children in a classroom is limited and teaching is adjusted according to each child’s strengths and weaknesses. Orientation in these special language units follows the recommendations of a neuropediatrician, based on a medical inspection and on a psychological and language examination by a psychologist and a speech therapist. Among the 44 children, 28 met the strict exclusion criteria for SLI ($N = 28$, mean age = 10 years; 1 month, SD = 1;11, range = 7;2 – 14;4): (i) their medical history revealed no hearing impairment, no obvious neurological abnormalities, no pervasive developmental disorder, and no attention-deficit/hyperactivity disorder; and (ii) their non-verbal intellectual abilities were within the age-appropriate range, as verified by the neuropsychologist (first author) who administered the Perceptual Reasoning Index (PRI ≥ 85; M = 96.8, SD = 9.8) from the French version of the Wechsler Intelligence Scale for Children (Wechsler, 2005). The other 16 children were excluded because at least one of the exclusion criteria was not satisfied (health record demonstrating hearing impairment, suspicion of neurological damage or of autism, or PRI < 85).

Language abilities were evaluated in the group of children with SLI through four tasks administered by the first author. Phonology was assessed using two word repetition tasks in which children had to repeat words of increasing complexity (L2MA : Chevrie-Muller, Simon, & Fournier, 1997; ELO : Khomsi, 2001). Receptive vocabulary was assessed through the EVIP, the French adaptation of the Peabody Picture Vocabulary Test (Dunn, Theriault-Whalen, & Dunn, 1993). Receptive morphosyntactic knowledge was assessed using the E.CO.S.SE test (Lecocq, 1996), a French adaptation of the Test for the Reception of Grammar (Bishop, 1983). Only children who had a deficient performance in at least two of the language tasks were included in the study. A stringent criterion was applied: performance was considered as deficient if at least 2 standard deviations below the mean performance provided in the normative data (5 children with SLI performed below criterion on two tasks; 18 on three tasks; and 5 on four tasks). Except two, all the children with SLI had phonological as well as morphosyntactic deficits. Only 6 of the children with SLI performed below our stringent criterion on the EVIP test, though the receptive vocabulary standard score of the majority of them was much lower than that of age-matched controls (16 performed at least 1 standard deviation below the mean and presented at least a 2-year delay). Table 1 includes the mean performance reached by the children with SLI; the number of children with SLI who performed below criterion; and the mean age to which their performance is equivalent. It also includes the normative data for the population of reference composed of typically-developing children of the same age as that of the children with SLI.

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Control group - The 122 control children (mean age = 9;9 , SD = 1;6, range = 7;2 – 13;0) were drawn from a local elementary school. Second, third, fourth, fifth and sixth graders were assessed. First graders were not selected because they have not yet received the adequate mathematical education which would have allowed them to perform the symbolic tasks in which two-digit Arabic numbers are presented (see Materials). None of the children from the control group was enrolled in speech or language therapy, and no history of diagnoses or concerns about their speech, language, or cognitive functions had been reported by their parents or teachers.

In the Results section, the main analyses are designed to compare the children with SLI to control children matched for chronological age (Age-Matched, henceforth AM). For each population, two groups were formed according to age: Young children with SLI ($N = 15$, mean age = 8;9, SD = 1;0, range = 7;2 – 10;0) and Young control children ($N = 71$, mean age = 8;8, SD = 0;10, range = 7;2 – 10;1); Older children with SLI ($N = 13$, mean age = 11;8, SD = 1;6, range = 10;2 – 14;4) and Older control children ($N = 51$, mean age = 11;3, SD = 0;8, range = 10;2 – 13;0). The cutoff for dividing children into young and older groups was established at 10 years 2 months. This age cutoff corresponded to that which delimited the fourth and fifth grades in control children. The age difference between children with SLI and AM children was not statistically significant in young children, $F(1, 85) = 0.18$, $\eta_p^2 = .002$; $p = .67$, nor in older children, $F(1, 63) = 2.32$, $\eta_p^2 = .036$; $p = .13$. However, because the latter level of match was less close than recommended by Mervis and Robinson (1999), a Z-score transformation of the ages computed within each age group was used as a covariate in the subsequent AM analyses.

To examine whether potential differences between children with SLI and control children subsist when the level of language is taken into account, a control group matched for language was also set up. However, the constitution of a language-matched control group raised methodological difficulties. Matching on morphosyntactic or phonological scores would have resulted in selecting a group of preschool children or of first graders who were much younger than the group of school-aged children with SLI (e.g., 5 years old, see Age equivalence in Table 1). Importantly, preschoolers and first graders had not yet received formal instruction in arithmetic and did not have knowledge of two-digit Arabic numbers or of addition procedures which were required to achieve the symbolic tasks used in the present study. Therefore, children matched for morphosyntactic or phonological abilities did not constitute a valid control group in the current study because their level of mathematical education differs massively from that of the children with SLI (see Leonard, 1998; Plante, Swisher, Kiernan, & Restrepo, 1993 for similar considerations). By contrast, the older children with SLI could be language-matched on the basis of their level of receptive vocabulary (Vocabulary-Matched, henceforth VM) with control children who had already received a sufficient level of mathematical education (i.e., 9 years old, see Age equivalence in Table 1). Importantly, beside being suitable to assess word learning ability, such a measure of receptive vocabulary is also considered appropriate to screen for general verbal ability (e.g., Dunn et al., 1993) and is highly correlated with omnibus measures of language (see Munson, Kurtz, & Windsor, 2005), suggesting that receptive vocabulary can be considered as an adequate proxy for language development. Therefore, the receptive vocabulary test (EVIP) was administered to the entire group of Control children (EVIP Mean Standard Score = 115.3, SD = 9.9). Twelve of them (EVIP Mean Raw Score = 101.4; SD = 14.3; Mean chronological age = 9;6 years) were vocabulary-matched with 12 older children with SLI (EVIP Mean Raw Score = 97.8, SD = 19.7; Mean chronological age = 11;9 years), $F(1, 23) = 0.27$, $\eta_p^2 = .01$; $p = .61$. One child from the group of older children with SLI was not included in the VM analyses due to a vocabulary level which was too low to be reliably matched (Age equivalence = 4;11 years).

Materials

In the *exact addition task*, 48 two-digit addition problems presented in a symbolic Arabic format (e.g., 31 + 25 =) were used. Sums ranged between 23 and 148 (mean = 69). None of the problems required a carry-over of the units. Tie problems (e.g., 21 + 21) and addends or sums multiple of 10 were excluded from the materials.

In the *approximate comparison task*, the stimuli consisted of 96 pairs of quantities of large numerical size, presented in a symbolic format and in a nonsymbolic format. Quantities were the same in both formats. Symbolic stimuli were 48 pairs of two-digit Arabic numbers (e.g., 56 vs. 78) printed in a Times New Roman font and displayed in black on a white background. Nonsymbolic stimuli were 48 pairs of sets of black dots (e.g., 56 dots vs. 78 dots) displayed on a white background. Sets of dots were generated using an adapted version of a Matlab program described in Dehaene, Izard and Piazza (2005), to control over non-numerical parameters. In half of the trials, total occupied area (size of the virtual enclosing rectangle) and summed dot area (luminance) were held constant in the sets of dots to be compared, while dot size and density covariated with number. Thus, the most numerous collection had smaller dots and was denser. In the other half of the trials, reverse parameters were used (i.e., dot size and density were held constant but total occupied area and summed dot area covaried with number) so that the most numerous collection had a larger occupied area and a larger summed dot area. The numerical size of each pair of quantities and the numerical distance between pairs were manipulated, resulting in 8 ratio bins of decreasing difficulty (13:12, 13:10, 13:9, 13:8, 13:7, 13:6, 13:5 and 13:4).

In the *approximate addition task*, the stimuli consisted of 96 triplets of quantities, presented in symbolic and nonsymbolic formats. Quantities were the same in both formats. To match the approximate addition task to both the approximate comparison task and the exact addition task, the two quantities first presented in the approximate addition task (e.g., 31 and 25): (i) were the result of the decomposition of the quantity first presented in the approximate comparison task (e.g., 56) and (ii) corresponded to the addends presented in the exact addition task. The third quantity was exactly the same as the second quantity presented in the approximate comparison task (e.g., 78). Symbolic stimuli were 48 triplets of Arabic numbers (e.g., 31 + 25 vs. 78) printed in a Times New Roman font and displayed in black on a white background. Nonsymbolic stimuli were 48 triplets of sets of black dots (e.g., 31 dots + 25 dots vs. 78 dots) displayed on a white background. Sets of dots were generated using the same program and the same controls as in the approximate comparison task. The ratio parameters were the same as those entered in the approximate comparison task.

Procedure

Computerized experimental tasks and general measures of cognitive abilities that have been shown to be implicated in numerical activities (Fayol, Barrouillet, & Marinthe, 1998; Geary, Hoard, Byrd-Craven, & DeSoto, 2004; Heathcote, 1994; Logie, Gilhooly, & Wynn, 1994) were administered typically in two individual sessions of approximately 50 minutes each on two separate school days. During the first session, the computerized approximate comparison task was first administered, then several cognitive measures (short-term memory and counting sequence) were taken, and finally the computerized approximate addition task was run. During the second session, the computerized exact addition task was first administered, then the others cognitive measures (executive functioning and finger gnosia) were taken. Intelligence and language tests were given to children with SLI during two supplemental sessions of approximately 50 minutes each. Note that the experimental task order has been deliberately fixed and not counterbalanced across participants, in order to take into account several task constraints. The comparison task was presented before the approximate addition task because preliminary testing revealed that completing the comparison task first really helped children to understand the instructions of the approximate addition task. Further, the approximate addition task was presented before the exact addition task to ensure that participants could not respond to the approximate addition task on the basis of the trace of the exact response that would have been activated if the exact addition task had been presented before.

Experimental tasks

In the *exact addition task*, participants were asked to mentally solve addition problems presented on a computer screen. The problems appeared in a horizontal configuration, and remained on the computer screen until the participant responded. The participant had to type the answer in Arabic digit format on the computer numerical keypad. Each trial was followed by an 800 ms blank interval. Two blocks of 24 trials were administered. A short break was allowed between blocks.

In the *approximate comparison task*, two quantities (Arabic numbers or sets of dots) were successively presented on a computer screen, and participants were asked to indicate the numerically largest one. To get the children involved, the trials were included within a simple appealing story, which differed as a function of the age group. For the group of young children, the quantities represented bees entering a beehive, and children were asked to decide which hive contained the largest number of bees. For the group of older children, the quantities represented coins inserted in a moneybox, and children had to guess which moneybox contained the largest amount of coins. Each trial started with the simultaneous presentation of two pictures (beehive or moneybox), one located on the lower left side of the computer screen, and the other on the lower right side. After a 400 ms delay, the first quantity appeared in the upper left part of the screen during 400 ms. After a 100 ms delay, the second quantity appeared during 400 ms in the upper right part of the screen. This brief presentation duration (400 ms) was chosen to prevent the use of counting strategies during the nonsymbolic form of the task. Participants were instructed to press a left or right colored key on the computer keypad, according to the side on which the largest quantity appeared on the screen. The side of the correct response was counterbalanced so that the largest quantity appeared on the left side for half of the trials, and on the right side for the other half. The next trial appeared after an 800 ms blank interval following the response given by the participant. Participants completed one training block (6 trials) and two subsequent blocks of 48 trials in which an equal number of symbolic and nonsymbolic stimuli were intermixed. Stimuli were presented in a fixed pseudo-randomized order. Short breaks were allowed between blocks.

In the *approximate addition task*, three quantities (Arabic numbers or sets of dots) were successively presented on a computer screen. Participants had to estimate the first two quantities and compare their approximate sum with the third quantity, to finally decide which was the largest numerically. The trials were included in the same narrative as in the approximate comparison task. Each trial started with the presentation of two pictures (beehive or moneybox), one located on the lower left side of the computer screen, the other on the lower right side. After a 400 ms delay, the first quantity appeared in the upper left part of the screen during 400 ms. After a 100 ms delay, the second quantity appeared again on the upper left of the screen during 400 ms. After a 100 ms delay, the third quantity was presented in the upper right part of the screen during 400 ms. This brief presentation duration was selected to prevent the use of both counting and exact addition strategies. Participants were asked to press a left or right colored key on the computer keypad, according to the side on which the largest quantity appeared on the screen. In each block, the correct response (the largest quantity) appeared equally often on the left and on the right side of the screen. The next trial was initiated after an 800 ms blank interval following the key press. One training block (6 trials) was passed, followed by two blocks of 48 trials containing an equal number of symbolic and nonsymbolic trials. Stimuli were presented in a fixed pseudo-randomized order. Short breaks were allowed between blocks.

For each experimental task, presentation of the stimuli and recording of the response were controlled by Psyscope software (Cohen, MacWhinney, Flatt, & Provost, 1993), running on an Apple Macintosh computer.

Background cognitive measures

Verbal short-term memory. The forward *Digit Span* subtest from the Wechsler Intelligence Scale – WISC IV (Wechsler, 2005) was used to evaluate verbal short-term memory. Participants had to recall a sequence of digits orally presented at a rate of one digit per second. Participants had to firstly recall sequences of two digits. If they succeeded, the span length was increased by one. Two trials were administered for each span length. The task ended after the participant consecutively failed two trials of the same span length. Number of trials correctly recalled was converted to standard scores (Mean = 10; SD = 3).

Visual short-term memory. Visual short-term memory was evaluated using an adaptation of the *Pattern Span* test (Della Sala, Gray, Baddeley, Allamano, & Wilson, 1999). A visual pattern (a matrix composed of filled and unfilled squares) was presented to the participant during two seconds. The participant was then presented with a pattern which was identical to the previous one, except that one filled square was missing (unfilled). The participant was asked to identify the missing square by filling it in. Participants were initially given visual patterns including two filled squares. If they succeeded, the span length was increased by one. Three trials were administered for each span length. The task ended after the participant consecutively failed two trials of the same span length. The visual span was the highest span length for which the participant succeeded for at least two trials (range between 2 and 16).

Spatial short-term memory. The *Corsi Block* task was used to evaluate spatial short-term memory. The experimenter presented a set of nine randomly arranged blocks to the participant. The experimenter then tapped blocks in different sequences of increasing length in turn, at a rate of one per second. The participant was required to tap the same sequence. Each span length involved three trials and the number of blocks increased by one until the participant consecutively failed two trials of the same span length. The spatial span was the longest sequence in which at least two of the three sequences were correctly recalled.

Executive functioning. An adaptation of the Children's Color Trails Test (Williams et al., 1995) was used to evaluate executive functioning. In part A of the test, the participant had to connect a set of numbers in an ascending sequence (1 through 25) as quickly as possible. In part B, the participant was required to connect as quickly as possible a set of numbers in an ascending sequence by alternating between numbers of different colors. For both parts of the test, the time needed to perform the trial as well as the error rate were recorded. The reaction time difference between Part A and Part B (RT in part B – RT in part A) in addition to the number of errors in Part B were used as dependent measures.

Finger gnosia. During the digital discrimination test, the examiner touched one or two fingers of the participant whose hands were removed from view. The participant was then required to identify the fingers which were touched by the examiner. The percentage of correct responses over the 20 trials was computed.

Verbal counting sequence. A task inspired by the Tedi-Math battery (Van Nieuwenhoven, Grégoire, & Noël, 2001) was used to assess the verbal counting sequence. During the first part of the test, participants were asked to recite the counting sequence as far as they could (Maximum

100). Each participant completed two trials. The sequence length was the highest number the participant could enounce without any error. In the second part of the test, five types of trials were administered to assess the capacity to manipulate the counting sequence: counting forward from 1 to n, counting forward from m, counting forward from m to n, counting backwards from n to 1, and counting by n. The percentage of correct trials was measured.

Data analysis

One preliminary set of statistical analyses focused on background cognitive measures. Performance obtained by the group of children with SLI was compared with that of the group of Age-matched controls (AM analyses) to examine whether Controls and children with SLI had equivalent cognitive performance. A univariate analysis of covariance was run for each cognitive measure and for each age group separately, with Population (SLI vs. AM Controls) as a between-subjects factor and with age standardized relative to the age group as a covariate.

The main set of analyses focused on the three experimental tasks and was repeated identically for each task separately. In a first step, univariate analyses of covariance were run on accuracy scores to assess whether young and older children with SLI performed similarly to Controls at the group level. AM analyses were run first, with Population (SLI vs. AM Controls) and Age Group (young vs. older) as between-subjects factors, using standardized age as a covariate. Afterwards, to examine whether group differences were caused by differences in cognitive skills, analyses were repeated with the cognitive measures for which differences between children with SLI and AM Controls were found, as additional covariates. Then, performance of children with SLI was compared with that of Controls matched for receptive Vocabulary (VM analyses). Univariate analyses of variance were run, with Population (SLI vs. VM Controls) as a between-subjects factor. In all ANOVAs and ANCOVAs, percentages of correct responses were arcsine-transformed to approximate normal distribution before the statistical analyses were carried out (Howell, 2010, p. 341). However, for ease of comprehension, raw means will be reported.

In a second step, analyses examined whether the group level results held at the individual level. In particular, we wanted to determine whether the differences observed between the groups of children with SLI and of AM Controls were caused by a large number of children with SLI or whether they resulted from only some participants with SLI whose particularly poor performance biased the group mean. To evaluate this issue, the cumulative percent of each child's percentage of correct responses was determined for each age group separately (Van Nieuwenhoven et al., 2001). A threshold was then established at the cumulative 10 percent to identify the children who obtained very poor results (i.e., a percentage of correct responses which was much lower than that reached by the majority of the children from the corresponding age group). When the cumulative percent of a child's performance corresponds to 10, it indicates that only 10% of the children from the same age group had a lower or equivalent accuracy rate and hence that 90% of the children had better scores, suggesting that the performance of this child is very poor relative to that of the other children. Children whose performance corresponded to a cumulative percent lower than 10 were identified, and Chi-square tests (or Fisher's exact test when expected values were less than 5) were used in each age group to compare the proportions of children who obtained such a poor performance.

In a final step, the correlation coefficients between accuracy scores in the experimental tasks and scores in the language tasks were computed for children with SLI to examine more straightforwardly the relation between number and language skills in children with SLI.

Results

Background cognitive measures

Compared to AM control children (see Table 2), children with SLI tended to have lower verbal short-term memory capacities ($p < .01$ for Young and Older children), lower executive function abilities ($p < .05$ for Young children but $p > .10$ for Older), as well as lower finger discrimination skills (Young: $p = .01$; Older: $p = .07$). Importantly, children with SLI showed lower performance than AM control children in the verbal counting sequence task ($p < .01$): both young and older children with SLI had a counting sequence whose length was reduced, and they were impaired when asked to manipulate the sequence (e.g., counting forward and backward). The difference between children with SLI and AM Controls was not significant for the visual and spatial short-term memory spans ($p > .10$). Because significant differences in verbal short-term memory, executive functioning, finger discrimination, and counting sequence were found, further AM analyses were carried out both without and with these measures as covariates.

----------------------- INSERT TABLE 2 ABOUT HERE -----------------------

Experimental tasks

1. *Exact Addition Task*

Group level. In the AM analysis, the effect of Age Group reached significance, $F(1, 145) = 26.89$, $\eta_p^2 = .16$, $p < .001$, showing lower percentages of correct responses for young than for older participants. As expected, the effect of Population was also significant, $F(1, 145) = 98.07$, $\eta_p^2 = .40$, $p < .001$, indicating that, in both age groups, children with SLI performed more poorly than AM control children when asked to add two-digit Arabic numbers exactly (see Table 3). Interestingly, the performance remained lower for children with SLI than for AM Controls when the five abilities for which a deficit was observed during the cognitive assessment were entered as additional covariates, $F(1, 140) = 8.01$, $\eta_p^2 = .05$, $p = .005$. Furthermore, the VM analysis in which performance reached by the group of older children with SLI was compared to the group of vocabulary-matched control children revealed that the Population effect was still significant, $F(1, 23) = 4.66$, $\eta_p^2 = .18$, $p = .04$, demonstrating that the 12 older children with SLI had lower accuracy scores (75.5%) than VM Controls (94.3%).

Individual level. The proportion of children who fell out of the normal range (i.e., within the 10 percent lowest scores) was much larger for the children with SLI than for AM Controls, both for young children (53% of SLI vs. 1% of AM Controls; Mean accuracy rate = 1% vs. 0%), $\chi^2 (1, N = 86) = 35.63$, $p < .001$, and older children, (46% of SLI vs. 2% of AM Controls; Mean accuracy rate = 40% vs. 88%), $\chi^2 (1, N = 64) = 20.77$, $p < .001$ (see Figure 2 for an illustration).

Correlations. The accuracy rate of the children with SLI did not correlate significantly with receptive vocabulary, $r(28) = -.15$, $p = .46$, nor with morphosyntax, $r(28) = -.22$, $p = .26$. By contrast, it correlated significantly with the number of errors in the word repetition task (L2MA), $r(28) = -.52$, $p = .01$, even after the verbal short-term memory score was partialled out, $r(25) = -.40$, $p = .04$. This indicates that the exact arithmetic skills of children with SLI were related to their phonological abilities, over and above the contribution of verbal short-term storage capacities.

----------------------- INSERT TABLE 3 ABOUT HERE -----------------------

2. *Approximate Comparison Task*

2.1. Symbolic form

Preliminary inspection of the data showed that, as expected, the accuracy rate increased with the numerical ratio (ratio 13:12 = 80.5% correct responses; 13:10 = 89.1%; 13:9 = 88.6%; 13:8 = 95.5%; 13:7 = 93.2%; 13:6 = 93.0%; 13:5 = 96.5%; 13:4 = 95.4%), confirming that the task tapped into approximate number representations.

Group level. In addition to the effect of Age Group, $F(1, 145) = 9.38$, $\eta_p^2 = .06$, $p = .003$, children with SLI were less accurate than AM Controls when asked to compare two-digit Arabic numbers, $F(1, 145) = 4.78$, $\eta_p^2 = .03$, $p = .03$. Though the interaction between Population and Age was not significant, $F(1, 145) = 2.08$, $\eta_p^2 = .01$, $p = .15$, the group difference was however only noticeable in the data for young children (see Table 3). More importantly, the difference between SLI and AM Controls no longer appeared when cognitive covariates were introduced in the analysis, $F(1, 140) = 0.09$, $\eta_p^2 = .001$, $p = .76$. Furthermore, the accuracy rate of the 12 older children with SLI (94.7%) was slightly better but not statistically different from that of the VM Controls (91.8%), $F(1, 23) = 2.35$, $\eta_p^2 = .10$, $p = .14$.

Individual level. The proportion of children who performed below the cutoff point was higher for young children with SLI than for young AM control children (27% of SLI vs. 7% of AM Controls; Mean accuracy rate = 68% vs. 76%), χ^2 $(1, N = 86) = 5.09$, $p = .046$. In older children, the proportions of outliers in both groups did not differ significantly, χ^2 $(1, N = 64) = 0.05$, $p \approx 1$.

Correlations. The accuracy rate of the children with SLI was significantly related to none of the language measures (phonology: $r(28) = -.29$, $p = .14$; vocabulary: $r(28) = -.28$, $p = .15$;

morphosyntax: $r(28) = -.10, p = .61$).

2.2. Nonsymbolic form

Preliminary inspection of the data revealed that the accuracy rate was higher (91%) when total occupied area and summed dot area covaried with number (dot size and density were constant) than when the reverse parameters were used (79%). Importantly, children did not base their strategy solely on these continuous variables, as demonstrated by the fact that performance still remained above chance when total occupied area and summed dot area were held constant, both for children with SLI, $t(121) = 29.60, p <.001$ and for AM Controls, $t(27) = 16.87, p <.001$. Furthermore, the accuracy rate increased with the numerical ratio (13:12 = 58.7% correct responses; 13:10 = 77.9%; 13:9 = 82.4%; 13:8 = 87.4%; 13:7 = 85.2%; 13:6 = 93.0%; 13:5 = 97.2%; 13:4 = 96.0%).

Group level. The AM analysis showed that performance improved with age, $F(1, 145) = 6.94, \eta_p^2 = .05, p = .009$. Interestingly, there was no indication of a Population effect either in the AM analysis, $F(1, 145) = 0.03, \eta_p^2 < .001, p = .87$ (see Table 3) or when cognitive skills were entered as covariates, $F(1, 140) = 0.05, \eta_p^2 = .001, p = .83$. The VM analysis similarly indicated no difference between older children with SLI (87.4%) and VM Controls (85.8%), $F(1, 23) = 0.28, \eta_p^2 = .01, p = .60$ when asked to compare visual sets of dots on the basis of the number of dots.

Individual level. The proportion of children with SLI who showed very poor performance relatively to the age group did not differ from that of AM Controls, either for young, $\chi^2 (1, N = 86) = 0.15, p \approx 1$, or older children, $\chi^2 (1, N = 64) = 0.18, p \approx 1$.

Correlations. None of the correlations between the accuracy rate and the language measures within the group of children with SLI approached significance (phonology: $r(28) = -.11, p = .59$; vocabulary: $r(28) = -.10, p = .62$; morphosyntax: $r(28) = .04, p = .86$).

3. Approximate Addition Task

3.1. Symbolic form

As for the approximate comparison task, the pattern of performance was characterized by the ratio effect (ratio 13:12 = 59.1% correct responses; 13:10 = 74.0%; 13:9 = 77.3%; 13:8 = 87.3%;

13:7 = 92.0%; 13:6 = 93.7%; 13:5 = 92.7%; 13:4 = 92.6%).

Group level. In addition to the effect of Age Group, $F(1, 145) = 42.16$, $\eta_p^2 = .23$, $p < .001$, the AM analysis yielded a significant effect of Population, $F(1, 145) = 26.89$, $\eta_p^2 = .16$, $p < .001$, with children with SLI being less accurate than AM Controls. As for the symbolic approximate comparison task, the difference between children with SLI and AM Controls was more pronounced for young children (see Table 3). Importantly however, the difference vanished when cognitive measures were entered as covariates, $F(1, 140) = 0.19$, $\eta_p^2 = .001$, $p = .66$. The VM analysis revealed that the older children with SLI performed better (88.4%) than VM Controls (81.5%), $F(1, 23) = 4.43$, $\eta_p^2 = .17$, $p = .05$, which is compatible with the observation of similar accuracy rates for the older children with SLI and for their AM Controls.

Individual level. There were more young children with SLI than AM Controls (40% of SLI vs. 4% of AM Controls; Mean accuracy rate = 64% vs. 63%) who showed very poor performance, χ^2 (1, $N = 86$) = 16.92, $p = .001$. In older children, the difference between both populations was not significant, χ^2 (1, $N = 64$) = 1.29, $p = .27$.

Correlations. The accuracy rate reached by the children with SLI did not correlate significantly with any of the language measures (phonology: $r(28) = -.25$, $p = .20$, vocabulary: $r(28) = -.27$, $p = .17$, morphosyntax: $r(28) = -.16$, $p = .42$).

3.2. Nonsymbolic form

Again, performance was sensitive to ratio (13:12 = 52.1% correct responses; 13:10 = 71.9%; 13:9 = 79.4%; 13:8 = 84.3%; 13:7 = 86.5%; 13:6 = 93.7%; 13:5 = 97.2%; 13:4 = 94.5%).

Group level. The effect of Age Group was significant, $F(1, 145) = 5.60$, $\eta_p^2 = .04$, $p = .019$. The Population effect was significant neither in the comparison with AM Controls, $F(1, 145) = 2.09$, $\eta_p^2 = .01$, $p = .151$ (see Table 3), nor with cognitive measures as covariates, $F(1, 140) = 0.09$, $\eta_p^2 = .001$, $p = .76$, nor in the comparison with VM Controls (17.2%), $F(1, 23) = 0.25$, $\eta_p^2 = .001$, $p = .87$.

Individual level. The proportion of children with SLI who were below the threshold did not differ from that of AM Controls, both for young, χ^2 (1, N = 86) = 0.05, $p \approx 1$, and older children, χ^2 (1, N = 64) = 0.69, p = .59 (see Figure 2 for the distribution observed in the nonsymbolic approximate addition task and the contrast with that in the symbolic exact addition task).

Correlations. None of the correlations between the accuracy rate of the children with SLI and the language measures reached significance (phonology: r(28) = -.08, p = .68, vocabulary: r(28) = -.29, p = .14, morphosyntax: r(28) = .16, p = .43).

------------------------ INSERT FIGURE 2 ABOUT HERE ------------------------

Discussion

The processing of large quantities can be achieved through the use of two systems. First, humans biologically inherit a core system of approximate number representations which emerges independently of language and provides the ability to approximately process quantities. Secondly, the system of numerical symbols which supports the acquisition of exact number skills arises later in development, probably under the mixed influence of language and instruction (Dehaene, 2001a). In the present study, number skills and language abilities of school-aged children with SLI from two age ranges were assessed to determine whether the development of exact and approximate number skills is related to the development of language abilities. In particular, the study was designed to address three research questions: First, are exact arithmetic skills impaired or preserved in children with SLI, and which language abilities are involved? Second, are their approximate comparison skills impaired or preserved, and which language abilities are involved? Third, are their approximate arithmetic skills impaired or preserved, and which language abilities are involved? If the development of both systems is related to language abilities, the exact and the approximate number skills of young and older children with SLI should be poorer than those of typically developing children, as well as related to specific language measures. By contrast, if the development of the approximate number system is unaffected by language abilities, the approximate number skills of children with SLI should be unimpaired and unrelated to language measures.

The key findings of the study can be summarized as follows. First, both at the group level regarding average performance and at the individual level in terms of the distribution of scores, children with SLI performed more poorly in the exact addition task than their age-matched peers. Their performance remained weaker when controlling for their cognitive abilities, and the deficit was still present in the older group, compared to both age-matched and vocabulary-matched controls. Intertask correlations indicated that exact arithmetic was specifically related to phonological abilities. Second, in the approximate comparison task, children with SLI did not differ from controls when asked to compare approximately *nonsymbolic* quantities (i.e., sets of dots). With *symbolic* quantities (i.e., Arabic numbers), children with SLI, especially the younger ones, were less accurate than age-matched children. However, the difference disappeared when their cognitive abilities were taken into account, or when the older participants were compared to younger vocabulary-matched children. Third, in the approximate addition task, a pattern of results similar to that of the approximate comparison task was observed. All the group level analyses held up at the individual level in the approximate number tasks, and no correlation was found with any of the language measures.

The results from the symbolic approximate number tasks are interesting for several reasons. On the one hand, they argue against a nonspecific explanation of the SLI disorder. Some authors have suggested that the range of deficits observed in the SLI disorder might be explained by a general deficit in processing symbolic information (e.g., Kamhi, 1981; Morehead & Ingram, 1973; Stone & Connell, 1993). According to this hypothesis, we should have observed altered performance in all the tasks involving symbolic material, both for young and for older children with SLI. Because the older children with SLI did not differ from age-matched controls in the symbolic approximate tasks, the results do not support the hypothesis of a global nonspecific symbolic deficit.

On the other hand, in addition to being compatible with previous studies (Cowan et al., 2005; Donlan et al., 2007; Koponen et al., 2006), the current findings provide new insights into the question of the origin of the impairment of the symbolic approximate number skills observed in young children with SLI. Previous studies were not designed to determine whether the deficit resulted from a general impairment of the core approximate number skills or whether it was due to a more circumscribed impairment of the ability to process numerical symbols. Interestingly, the present study offers several indications supporting the latter proposition. First, the fact that controlling for cognitive and verbal counting skills abolishes the difference between groups in the symbolic approximate number tasks suggests that the difficulty experienced by young children with SLI is mainly due to their limited knowledge of the numerical Arabic symbols. Second, the observation that children with SLI did not differ from controls in the nonsymbolic form of the approximate number tasks supports the view that they do not suffer from a deficit in the approximate number system per se. Moreover, the lack of correlation between the language measures and accuracy in the approximate number tasks adds to the evidence that well-developed language abilities are not, by themselves, the key condition shaping the development of approximate number skills.

The observation of an age effect with better performance for older children, in both populations and for both symbolic and nonsymbolic approximate number tasks provides some evidence that maturation, experience or school training might account for the enhancement of the approximate number skills during childhood. Remarkably, the fact that children with SLI - at least the older ones – were indistinguishable from age-matched controls in the approximate addition task suggests that the approximate arithmetic skills can progress effectively in elementary school-aged children in the absence of well-developed language abilities. This offers a striking contrast to exact arithmetic skills, which were found to be clearly impaired in children with SLI as in earlier studies (Cowan et al., 2005; Donlan et al., 2007; Fazio, 1996, 1999; Koponen et al., 2006). These contrasting results demonstrate that the arithmetic skills of children with SLI are not impaired as a whole, i.e. whatever the task demands, but only when exact processing is required. One might perhaps wonder whether the poorer performance of the children with SLI in the exact addition task could stem from fatigue or lack of motivation, due to the number of tasks that they had to pass. However, as experimental tasks were typically administered in two relatively short sessions with the exact addition task at the beginning of the second one, it is unlikely that children with SLI would be particularly fatigued when completing the exact addition task and that such factors would suffice to explain the huge discrepancy observed.

Importantly, the difficulty experienced by the children with SLI in the exact addition task still existed for older children, and the difference was still significant when general cognitive functions implicated in exact calculation, such as knowledge of verbal number symbols, verbal short-term memory, finger gnosia and executive functioning, were controlled for (Fayol et al., 1998; Geary et al., 2004; Logie et al., 1994). An interpretation of these findings is that the language deficit of the children with SLI is one of the factors responsible for their difficulties in exact arithmetic. Interestingly, the current study helps to identify more precisely which components of language could be involved when children with SLI are asked to perform exact arithmetic. The observation that children with SLI were still less accurate than controls when compared to younger children matched for receptive vocabulary suggests that their lexical knowledge is not directly associated to exact arithmetic. The same conclusion applies to morphosyntactic skills because their association with the exact addition skills was non significant. By contrast, the significant correlation between accuracy scores in the exact addition task and phonological measures clearly supports the hypothesis of a strong relationship between exact arithmetic skills and phonological processing in children with SLI.

Why would phonological processing be so important in children with SLI for exact number skills, in particular for exact arithmetic performance? One first possible explanation would be that exact calculation and phonological processing involve common general processing mechanisms. Indeed, both exact complex calculation and speech understanding and production involve sequential processing and thus require temporary storage of information. Multidigit mental arithmetic is typically thought as relying on complex resolution algorithms. Apart from the direct retrieval from memory which can only apply to simple and familiar problems such as single-digit operations, all resolution strategies that have been described (e.g., Guillaume, Nys, & Content, in press; Nys &

Content, 2010) involve several calculation steps, hence requiring the temporary storage of interim results in verbal working memory. Indeed, evidence from adult studies indicates that performance in multidigit exact arithmetic is affected by phonological variables such as phonological similarity (e.g., Noël, Desert, Aubrun, & Seron, 2001) and is disrupted by articulatory suppression (e.g., Logie et al., 1994), supporting the role of phonological encoding in working memory during exact calculation. Children with SLI might thus fail at complex calculation because their capacities of storage and of information manipulation in verbal working memory are less robust than those of typically developing children. However, a general disturbance of sequential processing does not account for the present results, since no deficit was observed for the spatial span memory task which is also sequential. Similarly, a weakness of verbal working memory cannot be the whole explanation since the exact arithmetic skills of the children with SLI were still clearly impaired when verbal span was used as covariate, and since they still correlated significantly with the phonological measure even after verbal span was partialled out. Moreover, it may seem perplexing that the correlations between the exact arithmetic skills and the morphosyntax and vocabulary measures were not significant given that both language tasks also involve verbal working memory.

Another explanation relies on the role of arithmetic fact memory in exact calculation. Multidigit exact calculation might require the retrieval of elementary arithmetic facts which are assumed to be stored as verbal associations (e.g., /faɪv pləs fɔr ɪz naɪn/) in rote verbal memory (Dehaene, 1992; Dehaene & Cohen, 1995). Operands would thus have to be transcoded into phonological form in order to retrieve stored arithmetic facts, and this could already constitute an obstacle for children with SLI whose language is characterized by unstable phonological word deformation (Mazeau, 2005). The inconsistency of their speech representation could thus obstruct the access to specific verbal associations. Furthermore, it is likely that language impairments hinder or delay the constitution of the arithmetic facts network, because phonological deficits affect the acquisition of the number word sequence and the development of verbal counting skills, which are known to play an essential role in early calculation. Indeed, an arithmetic problem and its correct response cannot be associated effectively in long-term memory if the enunciation of the counting sequence is too slow or inaccurate (e.g., Geary, Brown, & Samaranayake, 1991), a difficulty affecting most of the children with SLI. In sum, the present findings point to the importance of the relationship between phonological processing and exact number skills. An in-depth examination of that issue would deserve further research, for instance by evaluating whether training phonological skills helps to improve exact number skills and arithmetic abilities in particular.

Finally, the fact that the exact arithmetic skills of the children with SLI are highly compromised as well as related to their phonological abilities seems to be a strong argument in favor of the triple-code model (Dehaene, 1992; Dehaene & Cohen, 1995), according to which exact calculation abilities are mediated by language. At first glance, the analysis of the individual profiles, which showed that around 50 percent of children with SLI obtained an atypical performance in the exact addition task, seems consistent with this. However, this result automatically implies the mirror conclusion that around half of them performed in the normal range. This contrasted observation highlights the fact that analyzing individual profiles is important as it invites to nuance our main conclusions. In particular, the fact that some of the children with SLI had preserved exact arithmetic skills despite their poor performance on language measures might suggest that they could achieve complex arithmetic by relying on weaker language-based representations, or through the use of alternative, compensatory, mechanisms (for instance, see Rasmussen & Bisanz, 2005; Stigler, 1984 for visuospatial-based processing). The use of such substitute mechanisms would require assuming that, though probably facilitating, well-developed language (phonological) abilities are not a necessary condition for the development of the exact number skills (Butterworth, Reeve, Reynolds, & Lloyd, 2008; Dehaene, 2001b), at least in children with SLI. Future studies should help define the cognitive mechanisms used by children with SLI who are good at exact calculation and whether these mechanisms differ from those used by their age-matched peers.

To sum up, the current study shows that children with SLI who have important difficulties in exact arithmetic may simultaneously have quite sophisticated symbolic and nonsymbolic approximate number skills which enable approximate arithmetic. Though future studies exclusively devoted to typically-developing children are required to test the generalizability of our conclusions, the present findings seem to have further implications, both at theoretical and educational levels. Theoretically, these accounts are compatible overall with the more general idea that the effects of language do not apply across-the-board, but are only noticeable during specific activities. The most primitive route for encoding and processing numerical information, which allows for approximate number skills, appears to remain language-independent, even during development. By contrast, because it acts as a *cognitive technology* providing a powerful tool to create, store, and manipulate precisely the mental representations of cardinality for large quantities (Frank, Everett, Fedorenko, & Gibson, 2008), language for numbers would offer a second but preferred route for processing numbers. In that sense, language would have allowed humans to transcend approximate number abilities by helping them to acquire new complex capacities such as exact calculation.

The observation of good approximate number skills in children with SLI - despite poor exact arithmetic skills – also seems to be very promising at an educational level. In our view, educational programs focusing on children who have language disabilities should take into account that the approximate number system provides robust numerical competences to children with SLI, especially if one considers that approximate number skills are at least as important in our every-day life as are exact number competencies. For these reasons, we propose that schools should (1) as usual, teach the exact number procedures but also (2) enrich this traditional practice by concurrently promoting the use of approximate number skills. For instance, teachers could encourage children to evoke approximate number representations when they process symbolic numbers embedded in a complex calculation problem, so that they can use them as a scaffold for the computation. We present the hypothesis that the development of exact number skills would be more efficient if it was supported complementarily by the approximate number system. Further research is needed to investigate how this kind of educational program could impact on the acquisition of number skills.

References

Bishop, D. V. M. (1983). *The test for reception of grammar (TROG)*. Manchester, England: Age and Cognitive Performance Research Centre.

Brannon, E. M., & Van de Walle, G. A. (2001). The development of ordinal numerical competence in young children. *Cognitive Psychology*, *43*(1), 53–81.

Butterworth, B., Reeve, R., Reynolds, F., & Lloyd, D. (2008). Numerical thought with and without words: Evidence from indigenous Australian children. *Proceedings of the National Academy of Sciences*, *105*(35), 13179–13184.

Camos, V., Fayol, M., Lacert, P., Bardi, A., & Laquière, C. (1998). Le dénombrement chez des enfants dysphasiques et des enfants dyspraxiques. *ANAE-Approche Neuropsychologique des Apprentissages chez l'enfant*, *10*(3), 86–91.

Carey, S. (2001). Cognitive foundations of arithmetic: Evolution and ontogenisis. *Mind & Language*, *16*, 37–55.

Chevrie-Muller, C., Simon, A.-M., & Fournier, S. (1997). *Batterie Langage oral et écrit. Mémoire. Attention. (L2MA)*. Paris, France: Les Editions du Centre de Psychologie Appliquée.

Cohen, J. D., MacWhinney, B., Flatt, M., & Provost, J. (1993). PsyScope: A new graphic interactive environment for designing psychology experiments. *Behavior Research Methods, Instruments, and Computers*, *25*(2), 257–271.

Cowan, R., Donlan, C., Newton, E. J., & Lloyd, D. (2005). Number skills and knowledge in children with specific language impairment. *Journal of Educational Psychology*, *97*(4), 732–744.

Dehaene, S. (1992). Varieties of numerical abilities. *Cognition*, *44*(1-2), 1–42.

Dehaene, S. (2001a). Precis of the number sense. *Mind & Language*, *16*, 16–36.

Dehaene, S. (2001b). Authors response: Is number sense a patchwork? *Mind & Language*, *16*, 89–100.

Dehaene, S., & Cohen, L. (1995). Towards an anatomical and functional model of number processing. *Mathematical Cognition*, *1*, 83–120.

Dehaene, S., Izard, V., & Piazza, M. (2005). Control over non-numerical parameters in numerosity experiments. *Unpublished manuscript.*

Della Sala, S., Gray, C., Baddeley, A., Allamano, N., & Wilson, L. (1999). Pattern span: a tool for unwelding visuo-spatial memory. *Neuropsychologia*, *37*(10), 1189–1199.

Donlan, C., Bishop, D. V. M., & Hitch, G. J. (1998). Magnitude comparisons by children with specific language impairments: evidence of unimpaired symbolic processing. *International Journal of Language & Communication Disorders*, *33*(2), 149–160.

Donlan, C., Cowan, R., Newton, E. J., & Lloyd, D. (2007). The role of language in mathematical development: evidence from children with specific language impairments. *Cognition*, *103*(1), 23–33.

Donlan, C., & Gourlay, S. (1999). The importance of non-verbal skills in the acquisition of place-value knowledge: Evidence from normally-developing and language-impaired children. *British Journal of Developmental Psychology*, *17*(1), 1–19.

Dunn, L., Theriault-Whalen, C., & Dunn, L. (1993). *Echelle de Vocabulaire en Images Peabody. Adaptation française du Peabody Picture Vocabulary Test-Revised.* Toronto, ON: Psycan.

Fayol, M., Barrouillet, P., & Marinthe, C. (1998). Predicting arithmetical achievement from neuro-psychological performance: a longitudinal study. *Cognition*, *68*(2), B63–B70.

Fazio, B. B. (1994). The counting abilities of children with specific language impairment: a comparison of oral and gestural tasks. *Journal of Speech and Hearing Research*, *37*(2), 358–368.

Fazio, B. B. (1996). Mathematical abilities of children with specific language impairment: A 2-year follow-up. *Journal of Speech, Language and Hearing Research*, *39*(4), 839–849.

Fazio, B. B. (1999). Arithmetic calculation, short-term memory, and language performance in children with specific language impairment: a 5-year follow-up. *Journal of Speech, Language and Hearing Research*, *42*(2), 420–431.

Frank, M. C., Everett, D. L., Fedorenko, E., & Gibson, E. (2008). Number as a cognitive technology: Evidence from Pirahã language and cognition. *Cognition*, *108*(3), 819–824.

Fuson, K. C. (1988). *Children's counting and concepts of number*. New York, NY: Springer Verlag.

Geary, D., Brown, S., & Samaranayake, V. (1991). Cognitive addition: a short longitudinal study of strategy choice and speed-of-processing differences in normal and mathematically disabled children. *Developmental psychology*, *27*(5), 787–798.

Geary, D., Hoard, M., Byrd-Craven, J., & DeSoto, M. (2004). Strategy choices in simple and complex addition: Contributions of working memory and counting knowledge for children with mathematical disability. *Journal of Experimental Child Psychology*, *88*(2), 121–151.

Guillaume, M., Nys, J., & Content, A. (in press). Is adding 48 + 25 and 45 + 28 the same? How addend compatibility influences the strategy execution in mental addition. *Journal of Cognitive Psychology*.

Halberda, J., & Feigenson, L. (2008). Developmental change in the acuity of the “number sense”: The approximate number system in 3-, 4-, 5-, and 6-year-olds and adults. *Developmental Psychology*, *44*(5), 1457–1465.

Heathcote, D. (1994). The role of visuo-spatial working memory in the mental addition of multi-digit addends. *Cahiers de Psychologie Cognitive*, *13*(2), 207–245.

Howell, D. C. (2010). *Statistical methods for psychology, 7th edition*. Belmont, CA: Wadsworth.

Kamhi, A. G. (1981). Nonlinguistic symbolic and conceptual abilities of language-impaired and normally developing children. *Journal of Speech and Hearing Research*, *24*(3), 446–453.

Khomsi, A. (2001). *ELO□: Evaluation du langage oral*. Paris, France: Les Editions du Centre de Psychologie Appliquée.

Koponen, T., Mononen, R., Rasanen, P., & Ahonen, T. (2006). Basic numeracy in children with specific language impairment: Heterogeneity and connections to language. *Journal of Speech, Language and Hearing Research*, *49*(1), 58–73.

Lecocq, P. (1996). *L’ECOSSE□: Une épreuve de compréhension syntaxico-sémantique*. Villeneuve d’Ascq, France: Presses Universitaires du Septentrion.

Leonard, L. B. (1998). *Children with specific language impairment*. Cambridge, MA: MIT Press.

Lipton, J. S., & Spelke, E. S. (2005). Preschool children’s mapping of number words to nonsymbolic numerosities. *Child Development*, *76*(5), 978–988.

Logie, R. H., Gilhooly, K. J., & Wynn, V. (1994). Counting on working memory in arithmetic problem solving. *Memory & Cognition*, *22*(4), 395–410.

Mazeau, M. (2005). *Neuropsychologie et troubles des apprentissages: du symptôme à la rééducation*. Paris, France: Elsevier Masson.

Meck, W. H., & Church, R. M. (1983). A mode control model of counting and timing processes. *Journal of Experimental Psychology: Animal Behavior Processes*, *9*(3), 320–334.

Mervis, C. B., & Robinson, B. F. (1999). Methodological issues in cross□syndrome comparisons: Matching procedures, sensitivity (se), and specificity (sp). *Monographs of the Society for Research in Child Development*, *64*(1), 115–130.

Mix, K. S., Huttenlocher, J., & Levine, S. C. (2002). Multiple cues for quantification in infancy: Is number one of them? *Psychological Bulletin*, *128*(2), 278–294.

Morehead, D. M., & Ingram, D. (1973). The Development of base syntax in normal and linguistically deviant children. *Journal of Speech and Hearing Research*, *16*(3), 330–352.

Moyer, R., & Landauer, T. (1967). Time required for judgements of numerical inequality. *Nature*, *215*(5109), 1519–1520.

Munson, B., Kurtz, B. A., & Windsor, J. (2005). The influence of vocabulary size, phonotactic probability, and wordlikeness on nonword repetitions of children with and without specific language impairment. *Journal of Speech, Language, and Hearing Research*, *48*(5), 1033–1047.

Noël, M.-P., Desert, M., Aubrun, A., & Seron, X. (2001). Involvement of short-term memory in complex mental calculation. *Memory and Cognition*.

Nys, J., & Content, A. (2010). Complex mental arithmetic: The contribution of the number sense. *Canadian Journal of Experimental Psychology*, *64*(3), 215–220.

Nys, J., & Content, A. (2012). Judgement of discrete and continuous quantity in adults: Number counts! *Quarterly Journal of Experimental Psychology*, *65*(4), 675–690.

Piazza, M., Facoetti, A., Trussardi, A. N., Berteletti, I., Conte, S., Lucangeli, D., Dehaene, S., et al. (2010). Developmental trajectory of number acuity reveals a severe impairment in developmental dyscalculia. *Cognition*, *116*(1), 33–41.

Plante, E., Swisher, L., Kiernan, B., & Restrepo, M. A. (1993). Language matches: Illuminating or confounding? *Journal of Speech and Hearing Research*, *36*(4), 772–776.

Rasmussen, C., & Bisanz, J. (2005). Representation and working memory in early arithmetic. *Journal of Experimental Child Psychology*, *91*(2), 137–157.

Rousselle, L., Palmers, E., & Noël, M.-P. (2004). Magnitude comparison in preschoolers: what counts? Influence of perceptual variables. *Journal of Experimental Child Psychology*, *87*(1), 57–84.

Siegel, L. S., Lees, A., Allan, L., & Bolton, B. (1981). Non-verbal assessment of piagetian concepts in preschool children with impaired language development. *Educational Psychology: An International Journal of Experimental Educational Psychology*, *1*(2), 153–158.

Stigler, J. W. (1984). "Mental abacus": The effect of abacus training on Chinese children's mental calculation. *Cognitive Psychology*, *16*(2), 145–176.

Stone, C. A., & Connell, P. J. (1993). Induction of a visual symbolic rule in children with specific language impairment. *Journal of Speech and Hearing Research*, *36*(3), 599–608.

Van Nieuwenhoven, M., Grégoire, J., & Noël, M.-P. (2001). *Tedi-Math□: Test diagnostique des compétences de base en mathématiques*. Paris, France: Les Editions du Centre de Psychologie Appliquée.

Wechsler, D. (2005). *Echelle d'intelligence de Wechsler pour enfants (WISC-IV).* Paris, France: Les Editions du Centre de Psychologie Appliquée.

Williams, J., Rickert, V., Hogan, J., Zolten, A. J., Satz, P., D'Elia, L. F., Asarnow, R. F., et al. (1995). Children's color trails. *Archives of Clinical Neuropsychology: The Official Journal of the National Academy of Neuropsychologists*, *10*(3), 211–223.

Wynn, K. (1992). Children's acquisition of the number words and the counting system. *Cognitive Psychology*, *24*(2), 220–251.

Xu, F., & Arriaga, R. (2007). Number discrimination in 10-month-old infants. *British Journal of Developmental Psychology*, *25*(1), 103–108.

Xu, F., & Spelke, E. S. (2000). Large number discrimination in 6-month-old infants. *Cognition*, *74*(1), B1–B11.

Table 1

Normative Data and Characteristics of Children with SLI for Language Measures

	Young Children (Mean Age = 8;9)						Older Children (Mean Age = 11;8)					
	Normative data		SLI (*n* = 15)		Performance < criterion	Age equivalence	Normative data		SLI (*n* = 13)		Performance < criterion	Age equivalence
Measure	M	SD	M	SD	*n* of SLI	year; month	M	SD	M	SD	*n* of SLI	year; month
Phonology												
ELO Raw Score (Max. = 32)	31.5	0.8	17.7	8.7	15/15	4;9	31.7	0.5	22.0	8.3	12/13	6;0
L2MA Number of Errors (Max. =77)	2	3	23.2	10.6	15/15	-	1	3	18.5	13.6	9/13	-
Morphosyntax												
ECOSSE Number of Errors (Max. = 92)	9.5	5.9	23.7	7.4	14/15	5;2	5.7	4.2	17.9	5.6	13/13	6;2
Receptive Vocabulary												
EVIP Standard Score	100	15	82.6	17.5	3/15	6;7	100	15	79.8	16.1	3/13	9;0

Table 2

Descriptive statistics (Mean Performance, Standard Deviation) and Analyses of Covariance Results (F tests, partial eta squared) for Cognitive Tasks as a function of Population (children with SLI vs. Age-Matched control children) for Young and Older Children

	Young Children						Older Children					
	SLI (n = 15)		AM Control (n = 71)		SLI vs. AM difference		SLI (n = 13)		AM Control (n = 51)		SLI vs. AM difference	
Measure	M	SD	M	SD	*F*	η_p^2	M	SD	M	SD	*F*	η_p^2
Short-Term Memory												
Verbal STM – Standard Score	4.7	1.9	9.8	2.4	59.09**	.42	5.4	2.4	10.1	2.9	32.06**	.35
Visual STM – Span	6.2	2.4	7.3	2.3	3.03†	.04	8.5	3.1	8.9	2.8	< 1	
Spatial STM – Span	4.1	0.7	4.2	0.9	< 1		5.0	1.2	5.1	1.0	< 1	
Executive Functioning												
RT	38.0	25.7	29.6	19.0	2.10		31.2	24.9	25.2	13.0	2.23	
Number of Errors	1.1	0.9	0.5	0.9	5.33*	.06	0.5	1.0	0.6	0.8	< 1	
Finger Discrimination (% of Correct Resp.)	87.8	9.6	93.1	6.5	8.58**	.09	93.6	4.8	96.2	4.6	4.13*	.06
Verbal Counting Sequence												
Length (Max. 100)	58.0	32.4	98.9	7.3	103.35**	.56	76.2	30.3	99.6	3.2	39.12**	.39
Manipulation Score (% of Correct Resp.)	56.7	21.0	91.2	12.0	82.02**	.50	80.8	16.9	98	4.8	44.77**	.42

Note. * : $p \leq .05$; ** : $p \leq .01$; †: $p \leq .10$
Effect size is represented by partial eta squared (η_p^2)

Table 3

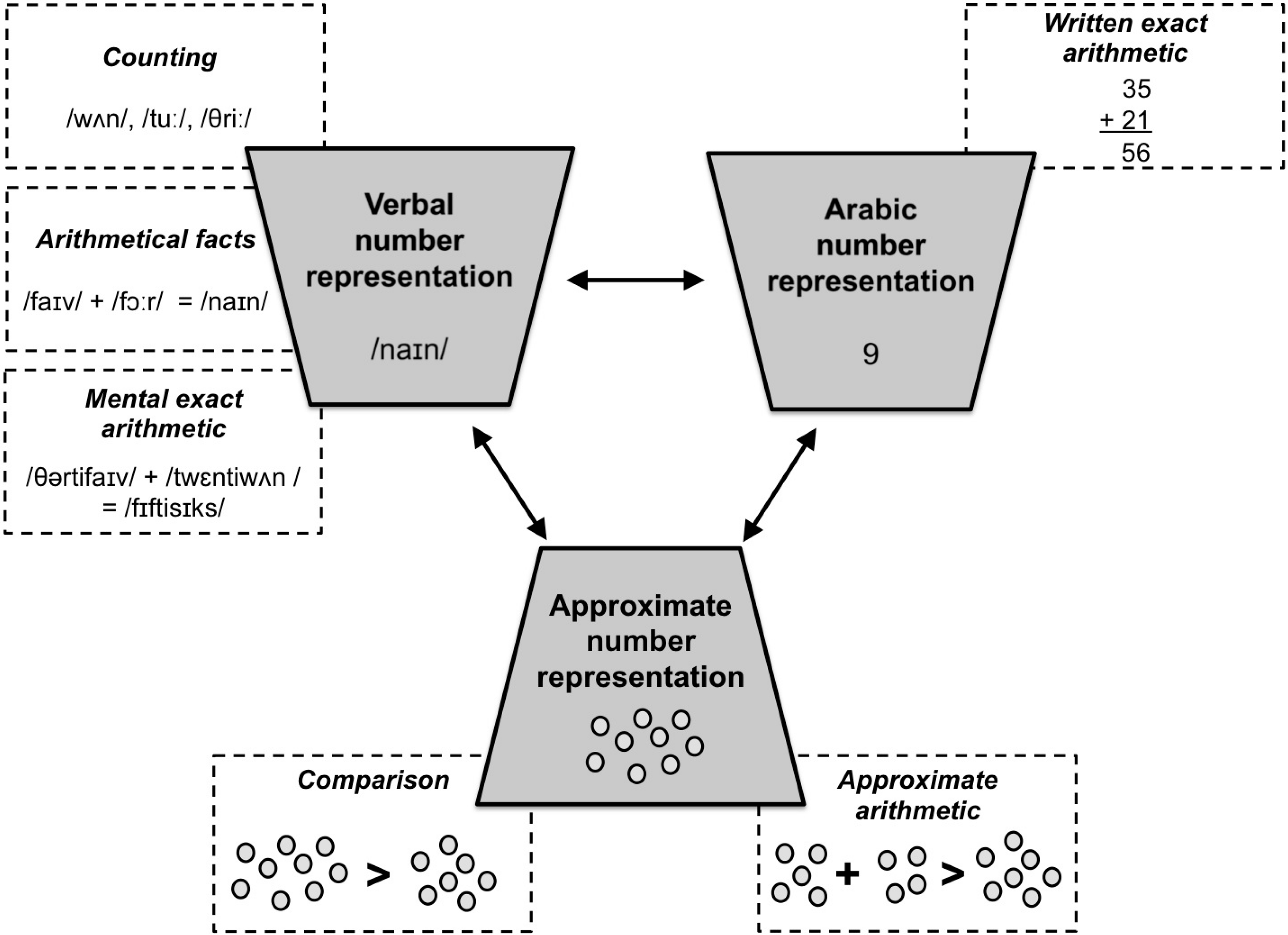
Mean Accuracy Scores and Standard Deviations for each Population (children with SLI and AM control children) as a function of Task, Format and Age Group

		Symbolic Exact Addition		Symbolic Approximate Comparison		Nonsymbolic Approximate Comparison		Symbolic Approximate Addition		Nonsymbolic Approximate Addition	
Age Group	Population	M	SD	M	SD	M	SD	M	SD	M	SD
Young	SLI (*n* = 15)	38.3	43.0	86.7	12.9	82.9	5.0	74.2	11.1	80.5	6.5
	AM Control (*n* = 71)	85.9	23.2	92.8	6.4	83.6	8.0	82.7	8.7	81.9	7.1
Older	SLI (*n* = 13)	69.7	36.1	95.0	3.7	87.6	6.2	88.2	5.7	83.6	5.6
	AM Control (*n* = 51)	97.5	2.6	94.9	4.2	86.4	5.7	90.5	4.9	85.5	5.8

Figure captions

Figure 1. Illustration of the different types of numerical activities (white rectangles with dashed lines) and their underlying representations (grey trapezes with solid lines). The arrows represent the bidirectional activations between representations.

Figure 2. Individual Cumulative Percent score in the Exact Addition Task (left panel) and in the Nonsymbolic Approximate Addition Task (right panel), for each Age Group and Population. The dashed line shows the lower cut-off point of normal range (cumulative percent equals to 10). Individuals who fell out of the normal range are identified (capital letters).


Counting
/wʌn/, /tuː/, /θriː/
Arithmetical facts
/faɪv/ + /fɔːr/ = /naɪn/
Mental exact arithmetic
/θərtifaɪv/ + /twɛntiwʌn / = /fɪftisɪks/
Verbal number representation
/naɪn/
Arabic number representation
9
Written exact arithmetic
35
+ 21
56
Approximate number representation
Comparison
>
Approximate arithmetic
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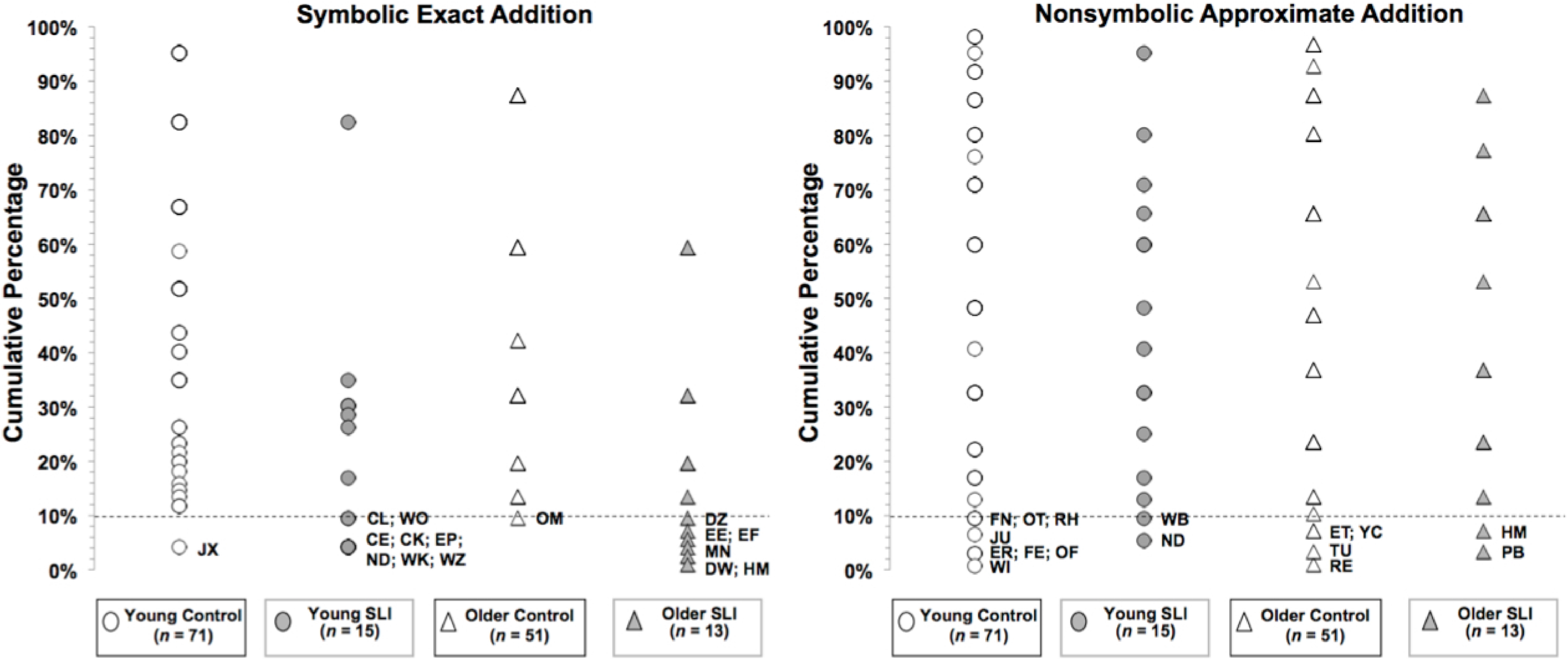

Symbolic Exact Addition
Cumulative Percentage
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
JX
CL; WO
CE; CK; EP;
ND; WK; WZ
OM
DZ
EE; EF
MN
DW; HM
Young Control (n = 71)
Young SLI (n = 15)
Older Control (n = 51)
Older SLI (n = 13)
Nonsymbolic Approximate Addition
Cumulative Percentage
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
FN; OT; RH
JU
ER; FE; OF
WI
WB
ND
ET; YC
TU
RE
HM
PB
Young Control (n = 71)
Young SLI (n = 15)
Older Control (n = 51)
Older SLI (n = 13)