Journal of Experimental Child Psychology 154 (2017) 146–163

Contents lists available at ScienceDirect

Journal of Experimental Child Psychology

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

Examining the relationship between rapid automatized naming and arithmetic fluency in Chinese kindergarten children

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ARTICLE INFO

Article history:
Received 5 January 2016
Revised 1 September 2016
Available online 21 November 2016

Keywords:
Rapid automatized naming
Arithmetic fluency
Phonological processing
Speed of processing
Approximate number system acuity
Chinese

ABSTRACT

Rapid automatized naming (RAN) has been found to predict mathematics. However, the nature of their relationship remains unclear. Thus, the purpose of this study was twofold: (a) to examine how RAN (numeric and non-numeric) predicts a subdomain of mathematics (arithmetic fluency) and (b) to examine what processing skills may account for the RAN–arithmetic fluency relationship. A total of 160 third-year kindergarten Chinese children (83 boys and 77 girls, mean age = 5.11 years) were assessed on RAN (colors, objects, digits, and dice), nonverbal IQ, visual–verbal paired associate learning, phonological awareness, short-term memory, speed of processing, approximate number system acuity, and arithmetic fluency (addition and subtraction). The results indicated first that RAN was a significant correlate of arithmetic fluency and the correlations did not vary as a function of type of RAN or arithmetic fluency tasks. In addition, RAN continued to predict addition and subtraction fluency even after controlling for all other processing skills. Taken together, these findings challenge the existing theoretical accounts of the RAN–arithmetic fluency relationship and

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http://dx.doi.org/10.1016/j.jecp.2016.10.008

suggest that, similar to reading fluency, multiple processes underlie the RAN–arithmetic fluency relationship.

Introduction

It is indisputable that rapid automatized naming (RAN), defined as the ability to name as quickly as possible an array of highly familiar visual stimuli such as colors, objects, numbers, and letters, is a strong predictor of reading (e.g., de Jong, 2011; Georgiou, Aro, Liao, & Parrila, 2016; Landerl & Wimmer, 2008; Liao et al., 2015; Powell, Stainthorp, Stuart, Garwood, & Quinlan, 2007). However, more recently a number of studies have shown that RAN also predicts mathematics (e.g., Berg, 2008; Cowan & Powell, 2014; Georgiou, Tziraki, Manolitsis, & Fella, 2013; Koponen, Aunola, Ahonen, & Nurmi, 2007; Koponen, Salmi, Eklund, & Aro, 2013; Swanson, 2011) and distinguishes children with and without math disabilities (e.g., Landerl, Bevan, & Butterworth, 2004; Mazzocco & Grimm, 2013). Although several theoretical accounts have been proposed to explain the RAN–reading relationship (see Georgiou & Parrila, 2013, for a review), it remains unclear what cognitive processes underlie the relationship between RAN and mathematics. This is important in light of the diverse use of RAN tasks in mathematics research (e.g., as a measure of processing speed: Berg, 2008; as a measure of phonological processing: Swanson, 2004; as a language-related skill: Mazzocco & Myers, 2003). In this study, we aimed to examine the relationship between RAN and a subdomain of mathematics, arithmetic fluency, in an unselected group of Chinese kindergarten children.

The first studies examining the role of RAN in mathematics made their appearance during the early 2000s (e.g., Hecht, Torgesen, Wagner, & Rashotte, 2001; Mazzocco & Myers, 2003; Swanson & Sachse-Lee, 2001; Temple & Sherwood, 2002).[1] Since then, several studies have shown that RAN continues to predict mathematics (particularly arithmetic fluency) even after controlling for the effects of other known predictors of mathematics such as working memory (e.g., Swanson & Kim, 2007), executive functions (e.g., van der Sluis, de Jong, & van der Leij, 2004), counting (e.g., Koponen et al., 2007), and reading (e.g., Berg, 2008). However, previous studies have at least four limitations. First, only a few studies have examined the RAN–mathematics relationship using an unselected sample of kindergarten children (Georgiou et al., 2013; Koponen et al., 2013) and none has administered measures of RAN digits and quantities (measured in our study with dice). This allows us to test whether the relationship between RAN and mathematics is format specific (being higher when RAN is assessed with tasks that involve numbers). Second, most previous studies have examined whether RAN, among other processing skills, predicts mathematics and not what processes underlie the RAN–mathematics relationship. Third, the few studies that examined more closely the RAN–mathematics relationship (e.g., Georgiou et al., 2013; Koponen et al., 2013) have assessed only a limited set of cognitive processes (e.g., phonological awareness, phonological short-term memory) that may underlie the RAN–mathematics relationship. Finally, to our knowledge, no studies have examined the relationship between RAN and mathematics in Chinese. Given the well-documented linguistic and cultural differences between China and North America in mathematics learning (see below for a more detailed description of these differences), it is important to examine how RAN relates to mathematics in this population.

According to a popular view, RAN relates to mathematics because it taps the ability to access and retrieve phonological representations from long-term memory (De Smedt, Taylor, Archibald, & Ansari, 2010; Simmons & Singleton, 2008). If phonological representations for number words and number facts in long-term memory are weak and imprecise, then this will affect how quickly they can be retrieved from long-term memory, which in turn will impact math development. Geary (1993) further suggested that both representation and retrieval of phonological information from long-term memory

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[1] We review here the literature on RAN and mathematics in general because there are only a few studies on RAN and arithmetic fluency alone and because the theoretical accounts of the RAN–mathematics relationship were not tied to arithmetic fluency.

may underlie problems in learning calculation facts as well as comorbidity of calculation and reading difficulties. Although several researchers have used RAN tasks to operationalize phonological processing (e.g., Fuchs et al., 2005; Hecht et al., 2001; Swanson, 2004; Swanson & Sachse-Lee, 2001), two pieces of evidence challenge this theoretical account. First, some studies have shown that RAN continues to predict mathematics even after controlling for the effects of other measures of phonological processing such as phonological awareness and phonological short-term memory (e.g., Georgiou et al., 2013; Hecht et al., 2001; Koponen et al., 2013; Wise et al., 2008). Second, children with a double deficit in phonological awareness and RAN should perform poorer in math than children with single deficits in either phonological awareness or RAN. Recently, Heikkilä, Torppa, Aro, Närhi, and Ahonen (2016) have shown that children with a double deficit were impaired in reading but not in math.

Based on the finding that RAN accounts for unique variance in math fluency over and above phonological awareness and phonological short-term memory, Koponen et al. (2013) argued that the reason RAN predicts mathematics is extra-phonological. They further proposed that RAN and mathematics are likely related because both rely on learning and retrieval of arbitrary associations between visual symbolic forms (numbers) and phonological forms (number words). If this is true, then we should observe two things. First, children with math disabilities should experience deficits in RAN tasks (e.g., letter and digit naming) that require mapping of a visual symbol to a verbal label. The few studies that have tested this hypothesis showed that children with math disabilities experience deficits in naming quantities (Landerl, Fussenegger, Moll, & Willburger, 2009; Willburger, Fussenegger, Moll, Wood, & Landerl, 2008) or math-related symbols (i.e., digits and quantities; Pauly et al., 2011; van der Sluis et al., 2004) but not in naming letters or objects. Landerl et al. (2009) suggested that the domain-specific problems of children with math disabilities can be traced to fundamental deficits in the number module. Butterworth (2005) described number module as an inborn capacity specialized in recognizing and manipulating numerosities. Approximate representations of large numerosities are provided by a specialized cognitive system called the approximate number system (ANS). Although ANS acuity is recognized as an important predictor of mathematics development (Fuchs et al., 2010; Halberda, Mazzocco, & Feigenson, 2008; Libertus, Feigenson, & Halberda, 2011; Mazzocco, Feigenson, & Halberda, 2011; however, see also Chen & Li, 2014; Schneider et al., in press, for evidence from recent meta-analyses), its connection to RAN remains unknown. Second, visual–verbal paired associate learning (PAL), defined as the ability to form a connection between a symbol and its name (e.g., Litt, de Jong, van Bergen, & Nation, 2013) should be related to both RAN and mathematics. Although a few studies have reported significant correlations between visual–verbal PAL and RAN (e.g., Liao et al., 2015; Liu & Georgiou, 2016; Warmington & Hulme, 2012), the connection between visual–verbal PAL and mathematics remains unknown. Because mathematics development relies to some extent on the automaticity of the visual (quantity)–verbal (number word) connections (e.g., Krajewski & Schneider, 2009), visual–verbal PAL should predict mathematics.

Finally, the relationship between RAN and mathematics (particularly arithmetic fluency) may be driven by a domain-general factor such as speed of processing (Kail & Hall, 1994; Kail, Hall, & Caskey, 1999). Kail and colleagues (1999) argued that "naming and reading are linked because skilled performance in both naming and reading depends, in part, on the rapid execution of the underlying processes" (p. 312). Given that mathematics also involves coordination of multiple sub-processes (e.g., Dehaene, 1997) and it correlates significantly with speed of processing (e.g., Bull & Johnston, 1997; Cowan & Powell, 2014; Fuchs et al., 2010), speed of processing may underlie RAN's connection to mathematics. Examining the role of speed of processing in the RAN–mathematics relationship is interesting for two more reasons. First, because both RAN and arithmetic fluency tasks are speeded, we would expect at least part of their shared variance to be accounted for by processing speed. Second, several math researchers have used RAN tasks as measures of speed of processing (e.g., Berg, 2008; Chan & Ho, 2010; Geary, 2011; Moll, Göbel, Gooch, Landerl, & Snowling, 2016; Vanbinst, Ghesquière, & De Smedt, 2015; Vukovic & Siegel, 2010). This is in spite of evidence showing that RAN does not load on the same factor with speed of processing measures (e.g., Bowey, Storey, & Ferguson, 2004; van den Bos, Zijlstra, & van den Broeck, 2003). If RAN is a measure of speed of processing, then controlling for other measures of speed of processing should eliminate RAN's contribution to arithmetic fluency.

The current study

The purpose of the current study was twofold: (a) to examine how RAN (numeric and non-numeric) relates to arithmetic fluency (addition and subtraction) and (b) to examine what processing skills (phonological awareness, short-term memory, visual–verbal PAL, speed of processing, and ANS acuity) may account for the relationship between RAN and arithmetic fluency. If Georgiou and colleagues' (2013) conclusion that there is nothing unique to the RAN–arithmetic fluency relationship that cannot be accounted for by reading is correct, then the processing skills such as speed of processing, phonological awareness, and orthographic processing that have been found to contribute to the RAN–reading fluency relationship (e.g., Georgiou et al., 2016; Georgiou, Papadopoulos, Fella, & Parrila, 2012; Papadopoulos, Spanoudis, & Georgiou, 2016) should also be involved in the RAN–arithmetic fluency relationship. Given that orthographic processing[2] is unlikely to be involved in mathematics and ANS acuity is unlikely to be involved in reading, the processing skills underlying the RAN–arithmetic fluency relationship might be slightly different from the ones reported to underlie (at least partly) the RAN–reading fluency relationship. Both lines of research, however, suggest that we will likely need multiple processes to explain the RAN–arithmetic fluency relationship.

An important feature of this study is that it was conducted with Chinese children. Chinese or East Asian kindergarten children have been found to outperform their European or North American counterparts in many aspects of numeracy such as counting (e.g., Fuson & Kwon, 1991; Miller & Stigler, 1987), production of cardinal and ordinal number names (e.g., Miller, Major, Shu, & Zhang, 2000), numerical estimation (e.g., Helmreich et al., 2011; Siegler & Mu, 2008), autonomous numerical quantity processing (e.g., Zhou et al., 2007), and simple arithmetic calculations (e.g., Dowker, Bala, & Lloyd, 2008; Geary, Bow-Thomas, Liu, & Siegler, 1996).

The origin of this early numeracy advantage for Chinese children has been attributed to both linguistic and cultural factors (see Miller, Kelly, & Zhou, 2005, and Ng & Rao, 2010, for reviews), some of which have important implications for the RAN–arithmetic fluency relationship. First, the Chinese digits are monosyllabic and have shorter pronunciation duration than digits in other languages such as English (e.g., Chen & Stevenson, 1988; Stigler, Lee, & Stevenson, 1986). Georgiou, Parrila, and Liao (2008) showed that Chinese children's RAN digits total time was significantly shorter than that of their English or Greek peers and that, because of the brevity of digit names in Chinese, articulation time (the mean time to articulate the names of the digits in the array) was not uniquely related to reading. At the same time, shorter names allow for a greater number of digits to be stored in working memory. Chen and Stevenson (1988) found that as early as preschool age Chinese children already had a larger digit span than American children (5.0 digits for Chinese children and 4.1 digits for American children). The shorter pronunciation duration has been argued to partly account for Chinese children's superior performance in mental calculation (e.g., Stevenson et al., 1990) and Chinese adults' faster mental multiplication (e.g., Campbell & Xue, 2001). Amtmann, Abbott, and Berninger (2007) further argued that RAN letters and digits are measures of the phonological loop in working memory. This view of RAN is interesting in light of arguments regarding the involvement of the phonological loop in simple and complex arithmetic calculations by different cultural groups (e.g., Imbo & LeFevre, 2009, 2010, 2011). For example, Imbo and LeFevre (2009) showed that Chinese university students required fewer working memory resources than Belgian or Canadian university students when solving complex addition problems. This effect was attributed to Chinese students' greater degree of practice during the elementary school years that allowed them to achieve high levels of automaticity in solving even multi-digit addition or multiplication problems. However, Imbo and LeFevre (2010) reported similar reliance on phonological short-term memory by Chinese and Canadian university students when solving complex subtraction problems. If RAN is an index of the phonological loop in working memory (Amtmann et al., 2007) and Chinese children solve simple addition and subtraction problems by relying on rote memorization, then phonological short-term memory should account for some of the shared variance between RAN and arithmetic fluency.

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[2] Stanovich and West (1989) defined orthographic processing as the ability to form, store, and access orthographic representations.

Second, the better performance of Chinese children in numerical literacy has been attributed to linguistic factors (e.g., Miura et al., 1994). There is much greater regularity in Chinese number naming between 11 and 20 and also between 10 and 100. For example, in Chinese, 11 would be ten-one, 12 ten-two, 20 two-ten, 21 two-ten-one, and 22 two-ten-two. In English, the formation of number names is more complicated. For example, although thirteen and fifteen are derived from the corresponding names for 3 and 5, the sound of the corresponding digit is modified (three → thir, five → fif). Finally, whereas Chinese is consistent in using unit values in decade names (e.g., two-tens, four-tens) and in using the unmodified name for ten to designate decades, English uses "twen", "thir", "fif" and the special "-ty". The consistency of the Chinese number naming system has been hypothesized to assist children in doing well on tasks relevant to base-10 values (e.g., Ho & Fuson, 1998; Miller et al., 2005). Given that the Chinese number naming system is relatively transparent, the relationship between visual–verbal PAL and RAN digits/quantities in Chinese should also be weaker than in other languages.

Finally, Chinese families' and preschools' early training in mathematics (e.g., Cai, 2003; Deng, Silinskas, Wei, & Georgiou, 2015; Huntsinger, Jose, Liaw, & Ching, 1997) add to the linguistic advantage Chinese children already have. For example, Huntsinger et al. (1997) found that, compared with European Americans, Chinese preschool and kindergarten children scored higher in a test of mathematics abilities and, at the same time, Chinese parents reported providing more direct mathematics instruction and encouragement to their children. The linguistic and cultural advantages in early numerical learning and exposure likely lead Chinese children to an earlier onset of automatic processing that, in turn, should strengthen the relationships between RAN and addition or subtraction fluency.

Method

Participants

A total of 160 third-year kindergarten Chinese children (83 boys and 77 girls, mean age = 5.11 years, *SD* = 0.28) participated in the study.[3] All children were recruited on a voluntary basis from four public inner-city kindergartens in Beijing, serving children from diverse socioeconomic backgrounds (based on the location of the schools). All children were native Mandarin speakers (immigrant children were excluded from the study) and had normal or corrected-to-normal vision. None of the children were diagnosed with any intellectual, behavioral, or sensory deficits. The schools from which the data were collected follow the national curriculum, and all teachers were female with more than 5 years of teaching experience. By the end of the third kindergarten year, Chinese children are expected to have a good mastery of number concepts and perform simple calculations. Parental consent was obtained prior to testing.

Measures

Nonverbal IQ

The nonverbal matrices task from the Cognitive Assessment System (CAS; Naglieri & Das, 1997) was used to assess nonverbal IQ. Participants were asked to identify the missing segment of a figure according to the figure's inherent regularity. Participants were instructed to choose the correct answer from five or six candidate answers by clicking with a mouse their choice of preference. There were 33 items arranged in increasing difficulty, and the test was discontinued after 4 consecutive errors. The child's score was the total number of correct responses.

Rapid automatized naming

RAN was assessed with four measures: digits, objects, colors, and dice. Children were asked to name as quickly as possible five digits (2, 4, 5, 7, and 9, pronounced as er[4], si[4], wu[3], qi[1], and jiu[3], with the number in brackets indicating the tone), objects (book, dog, flower, shoes, and door,

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[3] This would be similar to the kindergarten year in America. Kindergarten Years 1 and 2 in China correspond to preschool in America.

pronounced as shu[1], gou[3], hua[1], xie[2], and men[2]), colors (red, yellow, black, blue, and green, pronounced as hong[2], huang[2], hei[1], lan[2], and lyu[4]), and dice (e.g., ⚀, ⚁, ⚂, ⚃, ⚄) that were arranged in semi-random order in five rows of seven. As soon as children finished naming the matrix, the experimenter would click the "next" button on the computer screen (this automatically registered the child's naming time). In the next screen, the experimenter recorded the number of naming errors by inputting an Arabic numeral in the dialog box. There were two trials in the timed phase, with the same stimuli arranged in a different order. The child's score was the average time of the two naming trials. The number of naming errors was negligible (the mean number of errors was <1 in each RAN task), and for this reason it was not considered further.

Visual–verbal paired associate learning

This task was adopted from Li, Shu, McBride-Chang, Liu, and Xue (2009) and required children to pair five spoken Chinese syllables (mei[2], yuan[2], gong[1], hui[4], and qi[3], none of which had a clear meaning) with five pictures of imaginary animals. There was no relationship between the pictures and their corresponding names. Children were instructed to learn the names of these unfamiliar animals. During the practice phase, children would see the pictures of these animals on the screen and hear the corresponding names through audio, one at a time, for approximately 5 s in each trial. Then, children were asked to repeat the names of the animals, and the experimenter would correct them when a false or vague response was provided. Each symbol was practiced once. During the test trials, the pictures of the five animals were randomly presented on a computer screen one at a time, and children were asked to provide the name of each animal orally. Feedback was provided following each item. One point was given for each correct response. The test consisted of four blocks of five trials (max = 20). If the child correctly named all five pictures in two successive blocks, the task was discontinued and the examiner assigned a full score for the remaining trials.

Phonological awareness

Phonological awareness was assessed with rime detection and syllable deletion. Both tasks were adopted from Li, Shu, McBride-Chang, Liu, and Peng (2012) and have been used in previous studies (e.g., Xue, Shu, Li, Li, & Tian, 2013; Zhang et al., 2013). In Rime Detection, children were first asked to listen carefully to a target word (e.g., /wan3/ [meaning bowl]) and then to two more words (e.g., /san3/ [meaning umbrella] and /hu3/ [meaning tiger]), one of which shared the same rime as the target word. The children's task was to say which one of the two option words sounded similar to the target word. All items included monosyllabic words and the two option words used were names of common objects. All words were semantically unrelated and familiar to the children. To reduce the potential effect of memory load, the two candidate answers in each item were presented not only verbally, but also pictorially (simple line drawing) on a computer screen. The experimenter recorded the child's answer by clicking on the picture associated with the child's response. The task consisted of 2 practice items and 16 test items and was discontinued after 4 consecutive errors. The child's score was the total number of correct responses. Syllable deletion required children to listen to a two- or three-syllabic word and then say what was left in the word after deleting one of the syllables (e.g., /mian4-bao1/ [bread] without /mian4/ would be /bao1/ [bag]). The task consisted of 4 practice items and 20 experimental items (15 involved real words and 5 involved pseudowords). Half of the two-syllabic items (4 items) required deleting the first syllable, and the other half (4 items) required deleting the last syllable. In the three-syllabic items, 4 items required deleting the initial syllable, 4 items required deleting the middle syllable, and 4 items required deleting the final syllable. The experimenter recorded the accuracy of each answer by clicking either Box 1 (correct answer) or Box 2 (incorrect answer), located at the bottom of the computer screen. A discontinuation rule of 4 consecutive errors was applied. The child's score was the total number of correct responses.

Short-term memory

Short-term memory was assessed with word span and visual memory span. The word span task from the CAS (Naglieri & Das, 1997; see Deng, Liu, Wei, Chan, & Das, 2011, for the adaptation in Chinese) was used as a measure of phonological short-term memory. Single-character Chinese words (e.g., /hua1/ [flower], /ya1/ [duck], and /shu1/ [book]) were presented one by one through a headset, and children were asked to repeat them in the same order that they had heard them. The number of words ranged from two to nine. The test started with two words, and then a word was added at each difficulty level. The test was discontinued after 3 consecutive errors. The experimenter recorded the accuracy of each trial by clicking either Box 1 (correct answer) or Box 2 (incorrect answer), located at the bottom of the computer screen. The child's score was the total number of correct trials (max = 27). In turn, visual memory span was adapted from Wei, Yuan, Chen, and Zhou (2012) to assess visual–spatial short-term memory. In visual memory span, several dots were sequentially presented in a 3×3 lattice on the screen. Each dot remained on the screen for 1000 ms, and the interval in between dot appearances was 1000 ms. As soon as the last dot disappeared from the screen, children were asked to click the positions in the lattice where the dots had appeared in the same sequence that they had appeared. The number of dots ranged from 3 to 10, with 3 items at each difficulty level. The test was discontinued if the child got all 3 items of a specific difficulty level wrong. The child's score was the total number of correct trials (max = 24).

Processing speed

Processing speed was assessed with the simple reaction time task. A white dot was presented on a black screen either to the left (15 items) or to the right (15 items) of a fixation cross. Children were asked to press as quickly as possible the "Q" button on a keyboard when the dot appeared to the left of the fixation cross and the "P" button when the dot appeared to the right of the fixation cross. The dots were randomly presented, and the interstimulus interval varied between 1000 and 2000 ms. The child's score was the median reaction time across the 30 trials.

Approximate number system acuity

ANS acuity was assessed with a non-symbolic comparison task adapted by Zhou, Wei, Zhang, Cui, and Chen (2015) for the purpose of testing young children. Two sets of dots of varying sizes were presented simultaneously on the screen, and children were asked to judge which dot array contained more dots while ignoring the sizes of individual dots. Children pressed "Q" if they thought that the array on the left contained more dots and pressed "P" if they thought that the array on the right contained more dots. The number of dots in each set varied from 5 to 32. The dot arrays to be compared were created following a common procedure to control for continuous quantities in non-symbolic numerical discrimination (e.g., Halberda et al., 2008). For half of the trials, the total combined area of all dots in each set was controlled to be the same. For the other half, the average area of all dots in each set was controlled to be the same. The dots in a dot array were randomly distributed within a circle, and the dots' sizes varied. The ratio for the two dot arrays ranged from 1.67 to 2.00. The two dot arrays for each trial were presented on the screen for 600 ms. Following participants' response, there was a 1-s blank screen before the next trial. The test consisted of 40 trials. The child's score was the total number correct.

Arithmetic fluency

Arithmetic fluency was assessed with two tasks: addition fluency and subtraction fluency. The addition fluency task has been designed for 2- to 7-year-old children and has been used in several previous studies (e.g., Deng et al., 2015; Rodic et al., 2015). An addition problem (e.g., $6 + 4$, $3 + 8$) was presented in the center of a computer screen. Each addend in the addition problem ranged from 1 to 9, and the larger addend could appear on either side of the plus (+) sign. Children were asked to choose as accurately and quickly as possible the correct answer from two candidate answers shown below the problem (the incorrect answer differed from the correct answer by ±1 or 2) by pressing the "Q" button every time the correct answer was to the left of the addition problem and pressing the "P" button every time the correct answer was to the right of the problem. The task contained 49 items, and children were given 2 min to finish as many addition problems as possible. To correct for the possibility of guessing, a child's score was an adjusted number of correct trials (total correct trials – total incorrect trials). The subtraction fluency task has been developed for 6- to 80-year-olds and has been used in previous studies (e.g., Wei et al., 2012; Zhou et al., 2015). A subtraction problem (e.g., $6 - 4$, $12 - 8$) was presented at the center of a computer screen. All subtraction problems were the reverse operation of the single-digit additions. Thus, the largest minuend was 18 ($18 - 9$, from 9 + 9). Each minuend in the subtraction problems ranged from 2 to 18, and each subtrahend ranged from 1 to 9. The answers were always greater than 0. Similar to the addition problems, children were asked to select as accurately and quickly as possible the correct answer from two candidate answers shown below the problem (the incorrect answer differed from the correct answer by ±1 or 2) by pressing the "Q" button every time the correct answer was to the left of the subtraction problem and pressing the "P" button every time the correct answer was to the right of the problem. The task contained 92 items, and children were given 2 min to finish as many subtraction problems as possible. The child's score was an adjusted number of correct trials (total correct trials – total incorrect trials).

Procedure

Testing was conducted in January (5 months after the beginning of the school year) in a quiet room at the school by trained graduate students. All tests were computerized using the web-based applications of the Online Experimental Psychological System (OEPS) (www.dweipsy.com/lattice) (see Fig. 1). The experimenters provided the instructions for each task to children prior to testing. The tests were administered in the same order for all children. For the addition fluency, subtraction fluency, ANS acuity, and simple reaction time tasks, children indicated their choice of preference by pressing one of two buttons on a computer keyboard. In the RAN, rime detection, syllable deletion, word span, and visual–verbal PAL tasks, children gave their answer orally and the experimenter recorded their answer by clicking with a mouse on Box 1 (correct answer) or Box 2 (incorrect answer), located at the bottom of the computer screen. In nonverbal matrices children clicked the left mouse button to select their answer among the candidate answers, and in visual memory span children clicked the positions where the dots had appeared with the mouse (if children could not use the mouse efficiently, the experimenter clicked the positions following children's responses). Children's responses were automatically recorded and safely transmitted over the internet to a server that is hosted at the State Key Laboratory of Cognitive Neuroscience and Learning at Beijing Normal University.

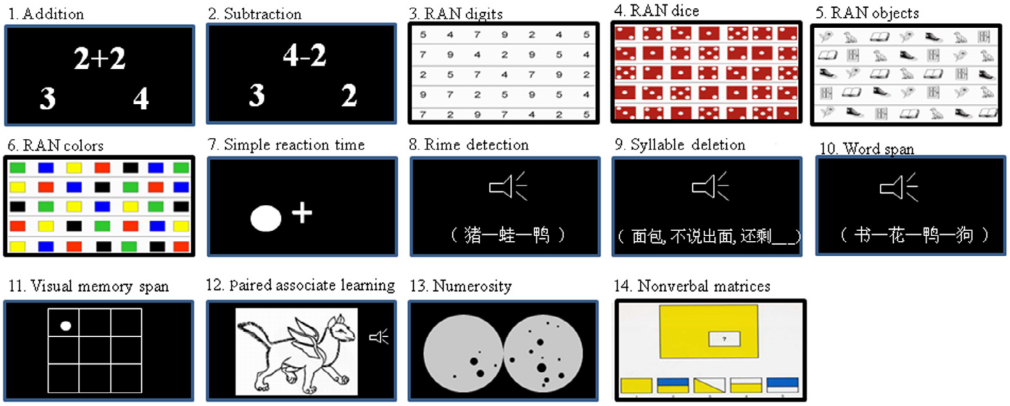
Testing was completed in three 30-min sessions. The first session contained five tests: simple reaction time, addition fluency, subtraction fluency, ANS acuity, and visual memory span. The second session contained five tests: RAN objects, syllable deletion, RAN colors, rime detection, and word span. Finally, the third session contained four tests: nonverbal matrices, RAN digits, visual–verbal PAL, and RAN dice. The order of task administration was fixed within each session and across all participants.

Results

Preliminary data analyses

Table 1 shows the descriptive statistics for all the measures used in the study. There were no missing data, and all subsequent analyses were conducted with a complete dataset. An examination of the distributional properties of the variables revealed some problems. All RAN tasks and simple reaction time were positively skewed, and log transformation was used to normalize their distributions. In turn, syllable deletion and rime detection were negatively skewed. To normalize their distribution, we first reflected and then log transformed their scores. Subsequently, we multiplied their transformed scores by -1 to correct for direction.

Next, we examined the factor structure of the RAN tasks by performing a principal components factor analysis. The results indicated that all RAN tasks loaded on one factor (factor loadings ranged from .813 to .872), with an eigenvalue higher than 3 explaining 69% of the variance. The factor score derived from this analysis was used in subsequent analyses. In addition, because some previous studies have shown that RAN numeric (digits and dice) may be more strongly related to mathematics than RAN non-numeric (colors and objects) (e.g., Pauly et al., 2011; Wise et al., 2008), we further created two composites scores (by averaging their respective *z* scores)—one for RAN numeric and one for RAN non-numeric—and examined separately their effects on addition fluency and subtraction fluency.



1. Addition
2. Subtraction
3. RAN digits
4. RAN dice
5. RAN objects
6. RAN colors
7. Simple reaction time
8. Rime detection
9. Syllable deletion
10. Word span
11. Visual memory span
12. Paired associate learning
13. Numerosity
14. Nonverbal matrices

Fig. 1. Illustration of tests used in the current study.

Table 1
Descriptive statistics for all the measures used in the study.

Task	Index	Mean (*SD*)	Skewness[a]	Kurtosis[a]	Split-half reliability	Min	Max
Addition	Adjusted number of correct responses	17.28 (8.59)	−1.034	2.639	.88	−18	37
Subtraction	Adjusted number of correct responses	13.62 (7.67)	−0.166	0.895	.85	−12	38
RAN digits	Reaction time (s)	34.5 (11.0)	1.039	1.446	.85	9.4	75.8
RAN dice	Reaction time (s)	40.6 (13.6)	1.339	2.088	.87	21.2	94.1
RAN objects	Reaction time (s)	47.5 (13.2)	1.640	4.659	.81	26.3	113.3
RAN colors	Reaction time (s)	52.0 (18.5)	1.179	1.272	.87	25.7	112.6
Simple reaction time	Reaction time (s)	.508 (.120)	1.077	3.771	.85	.320	1.006
Rime detection	Number of correct responses	12.3 (3.4)	−1.284	1.745	.81	0	16
Syllable deletion	Number of correct responses	18.6 (4.3)	−1.584	3.055	.85	0	23
Word span	Number of correct responses	13.7 (4.2)	0.404	1.252	.85	2	27
Visual memory span	Number of correct responses	9.7 (5.9)	0.377	−0.102	.97	0	25
Paired associate learning	Number of correct responses	11.9 (4.1)	−0.200	−0.396	.74	1	20
ANS acuity	Number of correct responses	30.2 (6.6)	−0.684	−0.504	.90	11	40
Nonverbal matrices	Number of correct responses	12.1 (4.5)	0.146	0.587	.87	0	25

[a] These are the values before conducting any transformations. The standard errors associated with skewness and kurtosis were .192 and .321, respectively.

Correlational analyses

Table 2 presents the zero-order (above diagonal) and partial (controlling for age and nonverbal IQ; below diagonal) correlations among the measures used in the study. RAN correlated significantly with both addition fluency ($r = -.38$) and subtraction fluency ($r = -.34$). RAN numeric and RAN nonnumeric also correlated significantly with addition and subtraction fluency (*r*s ranged from −.28 to −.37). Finally, RAN correlated significantly with measures of phonological awareness, verbal short-term memory, visual–verbal PAL, speed of processing, and ANS acuity (*r*s ranged from .18 to −.28). Visual–verbal PAL was the only cognitive skill that did not correlate significantly with the arithmetic fluency measures.

Regression analyses

To examine what cognitive processes may account for the relationship between RAN and arithmetic fluency, we performed two sets of hierarchical regression analyses: one with addition fluency

Table 2

Pearson's correlations between the measures used in the study (above diagonal) and partial correlations (controlling for child's age, gender, and nonverbal IQ; below diagonal).

	1	2	3	4	5	6	7	8	9	10	11	12
1. Addition	–	.65**	−.38**	−.34**	−.37**	−.17**	.30**	.36**	.28**	.28**	.12	.42**
2. Subtraction	.61**	–	−.34**	−.36**	−.28**	−.19*	.30**	.24**	.24**	.30**	.09	.36**
3. RAN	−.37**	−.33**	–	.93**	.93**	.18*	−.27**	−.27**	−.20*	−.14	−.17*	−.28**
4. RAN numeric	−.34**	−.36**	.93**	–	.73**	.18*	−.21**	−.22**	−.19*	−.12	−.13	−.27**
5. RAN non-numeric	−.35**	−.26**	.92**	.73**	–	.15	−.29**	−.28**	−.19*	−.14	−.18*	−.25**
6. Simple reaction time	−.16*	−.17*	.17*	.18*	.13	–	.06	−.09	.06	−.03	.07	−.05
7. Rime detection	.23**	.24**	−.24**	−.19*	−.26**	.09	–	.30**	.27**	.22**	.26**	.24**
8. Syllable deletion	.31**	.19*	−.24**	−.20*	−.25**	−.09	.24**	–	.34**	.16*	.24**	.22**
9. Word span	.23**	.19*	−.17*	−.17*	−.15	.07	.21**	.29**	–	.10	.29**	.14
10. Visual memory span	.20*	.23**	−.09	−.09	−.08	−.00	.14	.08	.02	–	.11	.21**
11. Visual–verbal PAL	.01	.00	−.13	−.10	−.14	.13	.18*	.20*	.24**	.01	–	.08
12. ANS acuity	.38**	.32**	−.24**	−.24**	−.20*	−.03	.16*	.17*	.07	.14	−.02	–

* $p < .05$.

** $p < .01$.

as the outcome measure and one with subtraction fluency as the outcome measure. In each analysis, we tested two models. In Model 1, the variables of interest were entered into the regression equation in the following order: (1) child's age, gender, and nonverbal IQ (entered as a block); (2) phonological awareness, short-term memory, speed of processing, and ANS acuity (entered one at a time); and (3) RAN, RAN numeric, and RAN non-numeric (entered one at a time). In Model 2, after controlling for the effects of child's age, gender, and nonverbal IQ (entered as a block at Step 1), we entered all processing skills as a block at Step 2 and the RAN tasks (entered one at a time) at Step 3 of the regression equation. Visual–verbal PAL and visual memory span were not entered into the regression equation because the former did not correlate significantly with the math outcomes and the latter did not correlate significantly with RAN. Table 3 presents the results with addition fluency as the outcome measure, and Table 4 presents the results with subtraction fluency as the outcome measure. Significance levels, standardized beta coefficients, *t* values, R^2 changes, and *F* values associated with each step are presented in both tables.

When addition fluency was the outcome measure, none of the processing skills was able to eliminate RAN's contribution. RAN accounted for 6% to 10% of unique variance after controlling for either one of the processing skills and accounted for 3% of unique variance after controlling for all processing

Table 3
Results of hierarchical regression analyses predicting addition fluency.

Step	Variables	Addition fluency			
		β	t	F	ΔR^2
Model 1					
1.	Age	.133	1.753	6.814	.12***
	Gender[a]	−.084	−1.111		
	Nonverbal IQ	.292***	3.844		
2.	Rime detection	.176**	2.274	11.342	.11***
	Syllable deletion	.267***	3.532		
3.	RAN	−.267***	−0.369	13.630	.06***
3.	RAN numeric	−.255***	−3.597	12.937	.06***
3.	RAN non-numeric	−.237***	−3.196	10.215	.05**
2.	Word span	.227**	2.980	8.878	.05**
3.	RAN	−.317***	−4.389	19.263	.09***
3.	RAN numeric	−.294***	−4.087	16.705	.08***
3.	RAN non-numeric	−.295***	−4.034	16.272	.08***
2.	Simple reaction time	−.137*	−1.797	2.880	.03*
3.	RAN	−.331***	−4.549	20.690	.10***
3.	RAN numeric	−.310***	−4.246	18.030	.09***
3.	RAN non-numeric	−.307***	−4.161	17.311	.09***
2.	ANS acuity	.378***	5.138	26.397	.13***
3.	RAN	−.283***	−4.050	16.401	.07***
3.	RAN numeric	−.255***	−3.644	13.280	.06***
3.	RAN non-numeric	−.272***	−3.883	15.079	.07***
Model 2					
2.	Rime detection	.121	1.633	10.210	.23***
	Syllable deletion	.176*	2.363		
	Word span	.133	1.831		
	Simple reaction time	−.125	−1.831		
	ANS acuity	.318***	4.457		
3.	RAN	−.202**	−2.791	7.789	.03**
3.	RAN numeric	−.179*	−2.515	6.323	.03*
3.	RAN non-numeric	−.192*	−2.657	7.060	.03**

[a] Binary coded (0 for girls and 1 for boys).
* $p < .05$.
** $p < .01$.
*** $p < .001$.

Table 4
Results of hierarchical regression analyses predicting subtraction fluency.

Step	Variables	Subtraction fluency			
		β	t	F	ΔR^2
Model 1					
1.	Age	.096	1.229	3.767	.07*
	Gender[a]	–.051	–0.654		
	Nonverbal IQ	.229**	2.934		
2.	Rime detection	.220**	2.695	7.100	.08***
	Syllable deletion	.153*	1.925		
3.	RAN	–.249***	–3.241	10.502	.06***
3.	RAN numeric	–.287***	–3.862	14.918	.08***
3.	RAN non-numeric	–.165*	–2.078	4.320	.02*
2.	Word span	.202*	2.565	6.579	.04*
3.	RAN	–.286***	–3.790	14.362	.08***
3.	RAN numeric	–.314***	–4.245	18.016	.09***
3.	RAN non-numeric	–.214**	–2.757	7.604	.04**
2.	Simple reaction time	–.160*	–2.069	4.281	.03*
3.	RAN	–.292***	–3.854	14.855	.08***
3.	RAN numeric	–.320***	–4.291	18.410	.10***
3.	RAN non-numeric	–.219**	–2.829	8.001	.05**
2.	ANS acuity	.330***	4.271	18.244	.10***
3.	RAN	–.263***	–3.546	12.573	.06***
3.	RAN numeric	–.285***	–3.907	15.262	.08***
3.	RAN non-numeric	–.200**	–2.655	7.047	.04**
Model 2					
2.	Rime detection	.177*	2.241	7.434	.19***
	Syllable deletion	.057	0.715		
	Word span	.135	1.743		
	Simple reaction time	–.178*	–2.459		
	ANS acuity	.279***	3.680		
3.	RAN	–.184*	–2.379	5.560	.03*
3.	RAN numeric	–.215**	–2.853	8.139	.04**
3.	RAN non-numeric	–.118	–1.511	2.283	.01

[a] Binary coded (0 for girls and 1 for boys).

[*] $p < .05$.

[**] $p < .01$.

[***] $p < .001$.

skills. Syllable deletion and ANS acuity remained significant predictors of addition fluency in Model 2. The results with RAN numeric and RAN non-numeric were similar to each other and to RAN.

When subtraction fluency was the outcome measure, RAN accounted for 6% to 8% of unique variance after controlling for either one of the cognitive processing skills and accounted for 3% of unique variance after controlling for all processing skills. RAN numeric was a better predictor of subtraction fluency than RAN non-numeric. In addition, the effects of RAN non-numeric on subtraction fluency dropped to nonsignificant levels after controlling for the effects of all processing skills. Rime detection, simple reaction time, and ANS acuity remained significant predictors of subtraction fluency even after controlling for child's age, gender, and nonverbal IQ and all other processing skills.

Discussion

The purpose of this study was twofold: (a) to examine how RAN relates to arithmetic fluency (addition and subtraction) and (b) to examine what processing skills may account for the RAN–arithmetic fluency relationship. In regard to our first goal, we found that RAN was significantly related to both addition fluency ($r = -.38$) and subtraction fluency ($r = -.34$). These correlations are similar to those reported between RAN and calculation fluency (a composite score derived from addition and subtraction) with children of the same age (e.g., Cirino, 2011; Geary, 2011; Georgiou et al., 2013; Koponen et al., 2013; Lepola, Niemi, Kuikka, & Hannula, 2005) and suggest that RAN is a good correlate not only of reading fluency (e.g., Georgiou et al., 2012; Georgiou et al., 2016; Juul, Poulsen, & Elbro, 2014; Papadopoulos et al., 2016) but also of arithmetic fluency.

In regard to our second goal, we found that none of the processing skills was able to fully explain the RAN–arithmetic fluency relationship on its own. This is in line with the findings of previous studies (Georgiou et al., 2013; Koponen et al., 2013) and suggests that we need to explore a combination of factors in order to fully account for the RAN–arithmetic fluency relationship. However, compared with previous studies examining the role of different processing skills in the RAN–reading fluency relationship (e.g., Georgiou et al., 2012; Georgiou, Parrila, & Kirby, 2009; Liao et al., 2015; Papadopoulos et al., 2016), we found that approximately 80% of the covariance between RAN and addition fluency was shared with other predictors. Specifically, RAN's effects on addition fluency decreased from 14.2% (when RAN was used as the only predictor of addition fluency) to 3% (after controlling for all other processing skills; a 79% reduction). In turn, RAN's effects on subtraction fluency dropped from 11.1% (when used as the only predictor of subtraction fluency) to 3% (after controlling for all other processing skills; a 73% reduction).

A big part in this decrease appears to be related to ANS acuity. The role of ANS acuity in the RAN–arithmetic fluency relationship is interesting in light of the argument that the specific deficit of children with dyscalculia in RAN quantities (assessed here with RAN dice) reflects an underlying deficit in the number module (e.g., Landerl et al., 2009; van der Sluis et al., 2004; Willburger et al., 2008). Although our study did not include children with dyscalculia, we did find that ANS acuity was a significant predictor of addition and subtraction fluency. Most important, approximately 40% of the covariance between RAN and addition or subtraction fluency (after controlling for the effects of age, gender, and nonverbal IQ) was shared with ANS acuity.[4] Some studies have shown that ANS acuity is a significant predictor of mathematics (e.g., Fuhs & McNeil, 2013; Halberda et al., 2008; Libertus et al., 2011; Mazzocco et al., 2011),[5] but the connection between RAN and ANS acuity has not been examined before. Some researchers have argued that ANS acuity plays an important role in number word learning (e.g., Dehaene, 1997; Gelman & Gallistel, 1978; Gelman & Gallistel, 2004). If ANS acuity is involved in number word learning, then it is not hard to see why it may relate to RAN, which depends on automatic number naming. Although this is a plausible explanation, it leads to an important prediction that is not supported by our findings. Specifically, if ANS acuity is involved in number word learning, then it should correlate more strongly with RAN numeric than with RAN non-numeric. As shown in Table 2, ANS acuity correlated −.27 with RAN numeric and −.25 with RAN non-numeric. Future studies need to examine the relationship between ANS acuity (symbolic and non-symbolic) and RAN more thoroughly.

The relationship between ANS acuity and RAN is also interesting in light of evidence that ANS acuity is not significantly related to reading (e.g., Hannula, Lepola, & Lehtinen, 2010; Landerl, 2013; LeFevre et al., 2010). This implies that RAN may be related to reading and arithmetic fluency for partly different reasons. This argument is further supported by neuroimaging evidence showing that RAN digits activate a more extensive and bilateral network than RAN letters and word reading fluency (Cummine, Chouinard, Szepesvari, & Georgiou, 2015). The additional activation in RAN digits was found in right middle occipital regions and parietal supramarginal gyrus, both of which are implicated in number processing and simple calculations (e.g., Park, Hebrank, Polk, & Park, 2012; Zago et al., 2001).

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[4] After controlling for age, gender, and nonverbal IQ, RAN accounted for 11.4% of the variance in addition fluency and 9.3% of the variance in subtraction fluency. These amounts dropped to 7% and 6%, respectively, after also controlling for ANS acuity. This means that RAN shares 4.4% and 3.3% of its predictive variance in addition fluency and subtraction fluency, respectively, with ANS acuity: $4.4/11.4 = 38.59$ and $3.3/9.3 = 35.48$.

[5] However, there are also studies reporting nonsignificant effects of ANS acuity on mathematics performance (e.g., Bartelet, Vaessen, Blomert, & Ansari, 2014; Kolkman, Kroesbergen, & Leseman, 2013; Passolunghi, Cargnelutti, & Pastore, 2014) as well as studies showing that the relation between ANS acuity and mathematics performance is mediated by symbolic quantitative knowledge such as cardinality (e.g., Chu, van Marle, & Geary, 2015; van Marle, Chu, Li, & Geary, 2014).

The finding that speed of processing also shared some of the covariance between RAN and arithmetic fluency (albeit significant when predicting subtraction fluency) should not come as a surprise given that both RAN and arithmetic fluency tasks were speeded (see, e.g., Georgiou et al., 2013, for a similar finding). However, RAN continued to predict addition and subtraction fluency even after controlling for speed of processing. This is important because it challenges the use of RAN tasks as measures of speed of processing (e.g., Berg, 2008; Geary, 2011; Moll et al., 2016; Vanbinst et al., 2015; Vukovic & Siegel, 2010).

Our findings further showed that RAN is not related to arithmetic fluency because they both tap the ability to form arbitrary associations between visual symbolic forms (numbers) and phonological forms (number words) (see Koponen et al., 2013). Although RAN correlated significantly with visual–verbal PAL ($r = -.17$), visual–verbal PAL did not correlate significantly with the arithmetic fluency tasks. As indicated below (see limitations in next paragraph), this may be due to the fact that we assessed visual–verbal PAL with an accuracy measure and assessed reading fluency with a speeded measure. Similar to visual–verbal PAL, RAN continued to predict addition and subtraction fluency even after controlling for phonological short-term memory. In fact, word span did not survive as a predictor of addition or subtraction fluency after controlling for all other processing skills (see Model 2 in Tables 3 and 4). This might be due to the fact that the subtraction problems were relatively easy and the answers could be retrieved directly from long-term memory. As shown by Imbo and LeFevre (2010), both Chinese and Canadian adults relied on the phonological loop to perform complex subtraction problems.

Some limitations of our study are worth mentioning. First, we assessed only a group of kindergarten children, and therefore we do not know whether the findings generalize to other grades. Second, our study was conducted with Chinese children. Given the documented differences between the Chinese and North American school systems, math language, and parental expectations, our results might not generalize to North American children. Third, some of our constructs (e.g., visual-verbal PAL, processing speed) were operationalized with single measures. Any single measure is likely to capture both true variance associated with the construct and also task-specific variance including measurement error. Task-specific variance may have weakened to some extent the strength of association between our measures and variability in arithmetic. A measurement model using latent variables would further clarify the strength of the unique effects of RAN on addition and subtraction fluency while controlling for other cognitive processes. Future studies should replicate our findings using latent variables composed of multiple measures of each construct. Fourth, we assessed only arithmetic fluency in our study. Future studies should examine the role of RAN in other mathematical domains. Fifth, visual–verbal PAL was scored in terms of accuracy. If RAN reflects children's efficiency in accessing visual–verbal connections from long-term memory, then speed might have been a more appropriate score. Sixth, other core cognitive capacities not assessed in this study (e.g., executive functions) may be important for mathematics learning (e.g., Cantin, Gnaedinger, Gallaway, Hesson-McInnis, & Hund, 2016; Cragg & Gilmore, 2014) and may even account for some of the unexplained variance in the relationship between RAN and arithmetic fluency. Finally, to assess addition and subtraction fluency, we administered a verification task rather than a production task. This has two important implications. First, it may have decreased the role of phonological short-term memory in arithmetic fluency because the students were given two options from which to choose. Second, verification itself may have added decision-related cognitive processes that may have influenced children's performance in arithmetic fluency and, subsequently, the contribution of our predictors. Certainly, our findings need to be replicated with arithmetic fluency tasks that require production rather than verification.

To conclude, our findings showed that RAN continues to predict arithmetic fluency even after controlling for several processing skills, some of which have a long history of success in predicting mathematics (e.g., nonverbal IQ, ANS acuity, phonological short-term memory, speed of processing). This challenges the existing theoretical accounts of the RAN–mathematics relationship and suggests that, similar to reading fluency, multiple processes account for the RAN–arithmetic fluency relationship. Future studies should examine the relationship between RAN and mathematics longitudinally and in languages with a more arbitrary number naming system than Chinese (e.g., English).

References

Amtmann, D., Abbott, R. D., & Berninger, V. W. (2007). Mixture growth models of RAN and RAS row by row: Insight into the reading system at work over time. *Reading and Writing, 20*, 785–813.

Bartelet, D., Vaessen, A., Blomert, L., & Ansari, D. (2014). What basic number processing measures in kindergarten explain unique variability in first-grade arithmetic proficiency? *Journal of Experimental Child Psychology, 117*, 12–28.

Berg, D. H. (2008). Working memory and arithmetic calculation in children: The contributory roles of processing speed, short-term memory, and reading. *Journal of Experimental Child Psychology, 99*, 288–308.

Bowey, J. A., Storey, T., & Ferguson, A. N. (2004). The association between continuous naming speed and word reading skills in fourth- to sixth-grade children. *Australian Journal of Psychology, 56*, 155–163.

Bull, R., & Johnston, R. S. (1997). Children's arithmetical difficulties: Contributions from processing speed, item identification, and short-term memory. *Journal of Experimental Child Psychology, 65*, 1–24.

Butterworth, B. (2005). The development of arithmetical abilities. *Journal of Child Psychology and Psychiatry, 46*, 3–18.

Cai, J. (2003). Investigating parental roles in students' learning of mathematics from a cross-national perspective. *Mathematics Education Research Journal, 15*, 87–106.

Campbell, J. I., & Xue, Q. (2001). Cognitive arithmetic across cultures. *Journal of Experimental Psychology: General, 130*, 299–315.

Cantin, R. H., Gnaedinger, E. K., Gallaway, K. C., Hesson-McInnis, M. S., & Hund, A. M. (2016). Executive functioning predicts reading, mathematics, and theory of mind during the elementary years. *Journal of Experimental Child Psychology, 146*, 66–78.

Chan, B. M., & Ho, C. S. (2010). The cognitive profile of Chinese children with mathematics difficulties. *Journal of Experimental Child Psychology, 107*, 260–279.

Chen, Q., & Li, J. (2014). Association between individual differences in non-symbolic number acuity and math performance: A meta-analysis. *Acta Psychologica, 148*, 163–172.

Chen, C., & Stevenson, H. W. (1988). Cross-linguistic differences in digit span of preschool children. *Journal of Experimental Child Psychology, 46*, 150–158.

Chu, F. W., van Marle, K., & Geary, D. C. (2015). Early numerical foundations of young children's mathematical development. *Journal of Experimental Child Psychology, 132*, 205–212.

Cirino, P. T. (2011). The interrelationships of mathematical precursors in kindergarten. *Journal of Experimental Child Psychology, 108*, 713–733.

Cowan, R., & Powell, D. (2014). The contributions of domain-general and numerical factors to third-grade arithmetic skills and mathematical learning disability. *Journal of Educational Psychology, 106*, 214–229.

Cragg, L., & Gilmore, C. (2014). Skills underlying mathematics: The role of executive function in the development of mathematics proficiency. *Trends in Neuroscience and Education, 3*, 63–68.

Cummine, J., Chouinard, B., Szepesvari, E., & Georgiou, G. K. (2015). An examination of the rapid automatized naming–reading relationship using functional magnetic resonance imaging. *Neuroscience, 305*, 49–66.

de Jong, P. F. (2011). What discrete and serial rapid automatized naming can reveal about reading. *Scientific Studies of Reading, 15*, 314–337.

De Smedt, B., Taylor, J., Archibald, L., & Ansari, D. (2010). How is phonological processing related to individual differences in children's arithmetic skills? *Developmental Science, 13*, 508–520.

Dehaene, S. (1997). *The number sense: How the mind creates mathematics*. New York: Oxford University Press.

Deng, C., Liu, M., Wei, W., Chan, R. C. K., & Das, J. P. (2011). Latent factor structure of the Das-Naglieri Cognitive Assessment System: A confirmatory factor analysis in a Chinese setting. *Research in Developmental Disabilities, 32*, 1988–1997.

Deng, C., Silinskas, G., Wei, W., & Georgiou, G. (2015). Cross-lagged relationships between home literacy/numeracy environment and academic achievement in Chinese. *Early Childhood Research Quarterly, 33*, 12–20.

Dowker, A., Bala, S., & Lloyd, D. (2008). Linguistic influences on mathematical development: How important is the transparency of the counting system? *Philosophical Psychology, 21*, 523–538.

Fuchs, L. S., Compton, D. L., Fuchs, D., Paulsen, K., Bryant, J. D., & Hamlett, C. L. (2005). The prevention, identification, and cognitive determinants of math difficulty. *Journal of Educational Psychology, 97*, 493–513.

Fuchs, L. S., Geary, D. C., Compton, D. L., Fuchs, D., Hamlett, C. L., & Bryant, J. D. (2010). The contributions of numerosity and domain-general abilities to school readiness. *Child Development, 81*, 1520–1533.

Fuhs, M. W., & McNeil, N. M. (2013). ANS acuity and mathematics ability in preschoolers from low-income homes: Contributions of inhibitory control. *Developmental Science, 16*, 136–148.

Fuson, K. C., & Kwon, Y. (1991). Chinese-based regular and European irregular systems of number words: The disadvantages for English-speaking children. In K. Durkin & B. Shire (Eds.), *Language in mathematical education: Research and practice* (pp. 211–226). Milton Keynes, UK: Open University Press.

Geary, D. C. (1993). Mathematical disabilities: Cognitive, neuropsychological, and genetic components. *Psychological Bulletin, 114*, 345–362.

Geary, D. C. (2011). Consequences, characteristics, and causes of mathematical learning disabilities and persistent low achievement in mathematics. *Journal of Developmental & Behavioral Pediatrics, 32*, 250–263.

Geary, D. C., Bow-Thomas, C. C., Liu, F., & Siegler, R. S. (1996). Development of arithmetical competencies in Chinese and American children: Influence of age, language, and schooling. *Child Development, 67*, 2022–2044.

Gelman, R., & Gallistel, C. (1978). *The child's understanding of number*. Cambridge, MA: Harvard University Press.

Gelman, R., & Gallistel, C. (2004). Language and the origin of numerical concepts. *Science, 306*, 441–443.

Georgiou, G., Aro, M., Liao, C.-H., & Parrila, R. (2016). Modeling the relationship between rapid automatized naming and literacy skills across languages varying in orthographic consistency. *Journal of Experimental Child Psychology, 143*, 48–64.

Georgiou, G. K., Papadopoulos, T. C., Fella, A., & Parrila, R. (2012). Rapid naming speed components and reading development in a consistent orthography. *Journal of Experimental Child Psychology, 112*, 1–17.

Georgiou, G. K., Parrila, R., & Kirby, J. (2009). RAN components and reading development from Grade 3 to Grade 5: What underlies their relationship? *Scientific Studies of Reading, 13*, 508–534.

Georgiou, G. K., Parrila, R., & Liao, C. H. (2008). Rapid naming speed and reading across languages that vary in orthographic consistency. *Reading and Writing, 21*, 885–903.

Georgiou, G. K., & Parrila, R. (2013). Rapid naming and reading: A review. In H. L. Swanson, K. Harris, & S. Graham (Eds.), *Handbook of learning disabilities* (pp. 169–185). New York: Guilford.

Georgiou, G. K., Tziraki, N., Manolitsis, G., & Fella, A. (2013). Is rapid automatized naming related to reading and mathematics for the same reason(s)? A follow-up study from kindergarten to Grade 1. *Journal of Experimental Child Psychology, 115*, 481–496.

Halberda, J., Mazzocco, M. M., & Feigenson, L. (2008). Individual differences in non-verbal number acuity correlate with maths achievement. *Nature, 455*, 665–668.

Hannula, M., Lepola, J., & Lehtinen, E. (2010). Spontaneous focusing on numerosity as a domain-specific predictor of arithmetical skills. *Journal of Experimental Child Psychology, 107*, 394–406.

Hecht, S. A., Torgesen, J. K., Wagner, R. K., & Rashotte, C. A. (2001). The relations between phonological processing abilities and emerging individual differences in mathematical computation skills: A longitudinal study from second to fifth grades. *Journal of Experimental Child Psychology, 79*, 192–227.

Heikkilä, R., Torppa, M., Aro, M., Närhi, V., & Ahonen, T. (2016). Double-deficit hypothesis in a clinical sample: Extension beyond reading. *Journal of Learning Disabilities, 49*, 546–560.

Helmreich, I., Zuber, J., Pixner, S., Kaufmann, L., Nuerk, H. C., & Moeller, K. (2011). Language effects on children's non-verbal number line estimations. *Journal of Cross-Cultural Psychology, 42*, 598–613.

Ho, C., & Fuson, K. C. (1998). Children's knowledge of teen quantities as tens and ones: Comparisons of Chinese, British, and American kindergartners. *Journal of Educational Psychology, 90*, 536–544.

Huntsinger, C. S., Jose, P. E., Liaw, F. R., & Ching, W. D. (1997). Cultural differences in early mathematics learning: A comparison of Euro-American, Chinese-American, and Taiwan-Chinese families. *International Journal of Behavioral Development, 21*, 371–388.

Imbo, I., & LeFevre, J. A. (2009). Cultural differences in complex addition: Efficient Chinese versus adaptive Belgians and Canadians. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 35*, 1465–1476.

Imbo, I., & LeFevre, J. A. (2010). The role of phonological and visual working memory in complex arithmetic for Chinese- and Canadian-educated adults. *Memory & Cognition, 38*, 176–185.

Imbo, I., & LeFevre, J. A. (2011). Cultural differences in strategic behavior: A study in computational estimation. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 37*, 1294–1301.

Juul, H., Poulsen, M., & Elbro, C. (2014). Separating speed from accuracy in beginning reading development. *Journal of Educational Psychology, 106*, 1096–1106.

Kail, R., & Hall, L. K. (1994). Processing speed, naming speed, and reading. *Developmental Psychology, 30*, 949–954.

Kail, R., Hall, L. K., & Caskey, B. J. (1999). Processing speed, exposure to print, and naming speed. *Applied Psycholinguistics, 20*, 303–314.

Kolkman, M. E., Kroesbergen, E. H., & Leseman, P. P. M. (2013). Early numerical development and the role of non-symbolic and symbolic skills. *Learning and Instruction, 25*, 95–103.

Koponen, T., Aunola, K., Ahonen, T., & Nurmi, J. E. (2007). Cognitive predictors of single-digit and procedural calculation skills and their covariation with reading skill. *Journal of Experimental Child Psychology, 97*, 220–241.

Koponen, T., Salmi, P., Eklund, K., & Aro, T. (2013). Counting and RAN: Predictors of arithmetic calculation and reading fluency. *Journal of Educational Psychology, 105*, 162–175.

Krajewski, K., & Schneider, W. (2009). Early development of quantity to number–word linkage as a precursor of mathematical school achievement and mathematical difficulties: Findings from a four-year longitudinal study. *Learning and Instruction, 19*, 513–526.

Landerl, K. (2013). Development of numerical processing in children with typical and dyscalculic arithmetic skills—A longitudinal study. *Frontiers in Psychology, 4*. http://dx.doi.org/10.3389/fpsyg.2013.00459.

Landerl, K., Bevan, A., & Butterworth, B. (2004). Developmental dyscalculia and basic numerical capacities: A study of 8–9-year-old students. *Cognition, 93*, 99–125.

Landerl, K., Fussenegger, B., Moll, K., & Willburger, E. (2009). Dyslexia and dyscalculia: Two learning disorders with different cognitive profiles. *Journal of Experimental Child Psychology, 103*, 309–324.

Landerl, K., & Wimmer, H. (2008). Development of word reading fluency and spelling in a consistent orthography: An 8-year follow-up. *Journal of Educational Psychology, 100*, 150–161.

LeFevre, J. A., Fast, L., Skwarchuk, S. L., Smith-Chant, B. L., Bisanz, J., Kamawar, D., et al (2010). Pathways to mathematics: Longitudinal predictors of performance. *Child Development, 81*, 1753–1767.

Lepola, J., Niemi, P., Kuikka, M., & Hannula, M. M. (2005). Cognitive–linguistic skills and motivation as longitudinal predictors of reading and arithmetic achievement: A follow-up study from kindergarten to Grade 2. *International Journal of Educational Research, 43*, 250–271.

Li, H., Shu, H., McBride-Chang, C., Liu, H., & Peng, H. (2012). Chinese children's character recognition: Visuo-orthographic, phonological processing, and morphological skills. *Journal of Research in Reading, 35*, 287–307.

Li, H., Shu, H., McBride-Chang, C., Liu, H. Y., & Xue, J. (2009). Paired associate learning in Chinese children with dyslexia. *Journal of Experimental Child Psychology, 103*, 135–151.

Liao, C. H., Deng, C., Hamilton, J., Lee, C. S., Wei, W., & Georgiou, G. K. (2015). The role of rapid naming in reading development and dyslexia in Chinese. *Journal of Experimental Child Psychology, 130*, 106–122.

Libertus, M. E., Feigenson, L., & Halberda, J. (2011). Preschool acuity of the approximate number system correlates with school math ability. *Developmental Science, 14*, 1292–1300.

Litt, R. A., de Jong, P. F., van Bergen, E., & Nation, K. (2013). Dissociating cross-modal and verbal demands in paired associate learning (PAL): What drives the PAL–reading relationship? *Journal of Experimental Child Psychology, 115*, 137–149.

Liu, C. N., & Georgiou, G. (2016, February). Examining the relationship between sound–symbol learning and rapid automatized naming. Poster presented at the fourth annual meeting of the Asia Joint Symposium on Reading and Spelling, Seoul, Korea.

Mazzocco, M. M., Feigenson, L., & Halberda, A. J. (2011). Preschoolers' precision of the approximate number system predicts later school mathematics performance. *PLoS One, 6*(9), e23749.

Mazzocco, M. M., & Grimm, K. J. (2013). Growth in rapid automatized naming from Grades K to 8 in children with math or reading disabilities. *Journal of Learning Disabilities, 46*, 517–533.

Mazzocco, M. M., & Myers, G. F. (2003). Complexities in identifying and defining mathematics learning disability in the primary school-age years. *Annals of Dyslexia, 53*, 218–253.

Miller, K. F., Kelly, M., & Zhou, X. (2005). Learning mathematics in China and the United States. In J. Campbell (Ed.), *Handbook of mathematical cognition* (pp. 163–178). New York: Psychology Press.

Miller, K., Major, S. M., Shu, H., & Zhang, H. (2000). Ordinal knowledge: Number names and number concepts in Chinese and English. *Canadian Journal of Experimental Psychology, 54*, 129–140.

Miller, K. F., & Stigler, J. W. (1987). Counting in Chinese: Cultural variation in a basic cognitive skill. *Cognitive Development, 2*, 279–305.

Miura, I. T., Okamoto, Y., Kim, C. C., Chang, C. M., Steere, M., & Fayol, M. (1994). Comparisons of children's cognitive representation of number: China, France, Japan, Korea, Sweden, and the United States. *International Journal of Behavioral Development, 17*, 401–411.

Moll, K., Göbel, S. M., Gooch, D., Landerl, K., & Snowling, M. J. (2016). Cognitive risk factors for specific learning disorder: Processing speed, temporal processing, and working memory. *Journal of Learning Disabilities, 49*, 272–281.

Naglieri, J. A., & Das, J. P. (1997). *Cognitive assessment system*. Itasca, IL: Riverside.

Ng, S. S. N., & Rao, N. (2010). Chinese number words, culture, and mathematics learning. *Review of Educational Research, 80*, 180–206.

Papadopoulos, T. C., Spanoudis, G., & Georgiou, G. (2016). How is RAN related to reading fluency? A comprehensive examination of the prominent theoretical accounts. *Frontiers in Psychology, 7*. http://dx.doi.org/10.3389/fpsyg.2016.01217.

Park, J., Hebrank, A., Polk, T. A., & Park, D. C. (2012). Neural dissociation of number from letter recognition and its relationship to parietal numerical processing. *Journal of Cognitive Neuroscience, 245*, 39–50.

Passolunghi, M. C., Cargnelutti, E., & Pastore, M. (2014). The contribution of general cognitive abilities and approximate number system to early mathematics. *British Journal of Educational Psychology, 84*, 631–649.

Pauly, H., Linkersdörfer, J., Lindberg, S., Woerner, W., Hasselhorn, M., & Lonnemann, J. (2011). Domain-specific rapid automatized naming deficits in children at risk for learning disabilities. *Journal of Neurolinguistics, 24*, 602–610.

Powell, D., Stainthorp, R., Stuart, M., Garwood, H., & Quinlan, P. (2007). An experimental comparison between rival theories of rapid automatized naming performance and its relationship to reading. *Journal of Experimental Child Psychology, 98*, 46–68.

Rodic, M., Zhou, X., Tikhomirova, T., Wei, W., Malykh, S., Ismatulina, V., et al (2015). Cross-cultural investigation into cognitive underpinnings of individual differences in early arithmetic. *Developmental Science, 18*, 165–174.

Schneider, M., Beeres, K., Coban, L., Merz, S., Susan-Schimdt, S., Stricker, J., & De Smedt, P. (in press). Associations of non-symbolic and symbolic numerical magnitude processing with mathematical competence: A meta-analysis. Developmental Science, doi:10.1111/desc.12372.

Siegler, R. S., & Mu, Y. (2008). Chinese children excel on novel mathematics problems even before elementary school. *Psychological Science, 19*, 759–763.

Simmons, F. R., & Singleton, C. (2008). Do weak phonological representations impact on arithmetic development? A review of research into arithmetic and dyslexia. *Dyslexia, 14*, 77–94.

Stanovich, K. E., & West, R. F. (1989). Exposure to print and orthographic processing. *Reading Research Quarterly, 24*, 402–433.

Stevenson, H. W., Lee, S. Y., Chen, C., Lummis, M., Stigler, J., Fan, L., et al (1990). Mathematics achievement of children in China and the United States. *Child Development, 61*, 1053–1066.

Stigler, J. W., Lee, S. Y., & Stevenson, H. W. (1986). Digit memory in Chinese and English: Evidence for a temporally limited store. *Cognition, 23*, 1–20.

Swanson, H. L. (2004). Working memory and phonological processing as predictors of children's mathematical problem solving at different ages. *Memory & Cognition, 32*, 648–661.

Swanson, H. L. (2011). Working memory, attention, and mathematical problem solving: A longitudinal study of elementary school children. *Journal of Educational Psychology, 103*, 821–837.

Swanson, H. L., & Kim, K. (2007). Working memory, short-term memory, and naming speed as predictors of children's mathematical performance. *Intelligence, 35*, 151–168.

Swanson, H. L., & Sachse-Lee, C. (2001). Mathematical problem solving and working memory in children with learning disabilities: Both executive and phonological processes are important. *Journal of Experimental Child Psychology, 79*, 294–321.

Temple, C. M., & Sherwood, S. (2002). Representation and retrieval of arithmetical facts: Developmental difficulties. *Quarterly Journal of Experimental Psychology A, 55*, 733–752.

van den Bos, K. P., Zijlstra, B. J. H., & van den Broeck, W. (2003). Specific relations between alphanumeric-naming speed and reading speeds of monosyllabic and multisyllabic words. *Applied Psycholinguistics, 24*, 407–430.

van der Sluis, S., de Jong, P. F., & van der Leij, A. (2004). Inhibition and shifting in children with learning deficits in arithmetic and reading. *Journal of Experimental Child Psychology, 87*, 239–266.

van Marle, K., Chu, F. W., Li, Y. R., & Geary, D. C. (2014). Acuity of the approximate number system and preschoolers' quantitative development. *Developmental Science, 17*, 492–505.

Vanbinst, K., Ghesquière, P., & De Smedt, B. (2015). Does numerical processing uniquely predict first graders' future development of single-digit arithmetic? *Learning and Individual Differences, 37*, 153–160.

Vukovic, R. K., & Siegel, L. S. (2010). Academic and cognitive characteristics of persistent mathematics difficulty from first through fourth grade. *Learning Disabilities Research & Practice, 25*, 25–38.

Warmington, M., & Hulme, C. (2012). Phoneme awareness, visual–verbal paired-associate learning, and rapid automatized naming as predictors of individual differences in reading ability. *Scientific Studies of Reading, 16*, 45–62.

Wei, W., Lu, H., Zhao, H., Chen, C., Dong, Q., & Zhou, X. (2012). Gender differences in children's arithmetic performance are accounted for by gender differences in language abilities. *Psychological Science, 23*, 320–330.

Wei, W., Yuan, H., Chen, C., & Zhou, X. (2012). Cognitive correlates of performance in advanced mathematics. *British Journal of Educational Psychology, 82*, 157–181.

Willburger, E., Fussenegger, B., Moll, K., Wood, G., & Landerl, K. (2008). Naming speed in dyslexia and dyscalculia. *Learning and Individual Differences, 18*, 224–236.

Wise, J. C., Pae, H. K., Wolfe, C. B., Sevcik, R. A., Morris, R. D., Lovett, M., et al (2008). Phonological awareness and rapid naming skills of children with reading disabilities and children with reading disabilities who are at risk for mathematics difficulties. *Learning Disabilities Research & Practice, 23*, 125–136.

Xue, J., Shu, H., Li, H., Li, W., & Tian, X. (2013). The stability of literacy-related cognitive contributions to Chinese character naming and reading fluency. *Journal of Psycholinguistic Research, 42*, 433–450.

Zago, L., Pesenti, M., Mellet, E., Crivello, F., Mazoyer, B., & Tzourio-Mazoyer, N. (2001). Neural correlates of simple and complex mental calculation. *Neuroimage, 13*, 314–327.

Zhang, Y., Tardif, T., Shu, H., Li, H., Liu, H., McBride-Chang, C., et al (2013). Phonological skills and vocabulary knowledge mediate socioeconomic status effects in predicting reading outcomes for Chinese children. *Developmental Psychology, 49*, 665–671.

Zhou, X., Chen, Y., Chen, C., Jiang, T., Zhang, H., & Dong, Q. (2007). Chinese kindergartners' automatic processing of numerical magnitude in Stroop-like tasks. *Memory & Cognition, 35*, 464–470.

Zhou, X., Wei, W., Zhang, Y., Cui, J., & Chen, C. (2015). Visual perception can account for the close relation between numerosity processing and computational fluency. *Frontiers in Psychology, 6*. http://dx.doi.org/10.3389/fpsyg.2015.01364.