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Visual form perception is fundamental for both reading comprehension and arithmetic computation

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ABSTRACT

Visual perception has been found to be a critical factor for reading comprehension and arithmetic computation in separate lines of research with different measures of visual form perception. The current study of 1099 Chinese elementary school students investigated whether the same visual form perception (assessed by a geometric figure matching task) underlies both reading comprehension and arithmetic computation. The results showed that visual form perception had close relations with both reading comprehension and arithmetic computation, even after controlling for age, gender, and cognitive factors such as processing speed, attention, working memory, visuo-spatial processing, and general intelligence. Results also showed that numerosity comparison's relations with reading comprehension and arithmetic computation were fully accounted for by visual form perception. These results suggest that reading comprehension and arithmetic computation might share a similar visual form processing mechanism.

1. Introduction

Reading comprehension and arithmetic computation have both common and distinct neural and cognitive mechanisms (e.g., Butterworth, Cappelletti, & Kopelman, 2001; Dehaene, Spelke, Pinel, Stanescu, & Tsivkin, 1999; Eger, Sterzer, Russ, Giraud, & Kleinschmidt, 2003; Thioux, Pesenti, Costes, De Volder, & Seron, 2005). In terms of distinct mechanisms, reading comprehension mainly relies on the processing of semantics (e.g., Li et al., 2017; Tong & Mcbride, 2017), orthography (e.g., Abbott et al., 2016; Tighe & Schatschneider, 2016), and phonology (e.g., Tong & Mcbride, 2017; Vaknin-Nusbaum, Sarid, Raveh, & Nevo, 2016), whereas mathematics is more closely related to spatial processing (e.g., Boonen, Wesel, Jolles, & Schoot, 2014; Burte, Gardony, Hutton, & Taylor, 2017; Cheng & Mix, 2014; Dehaene et al., 1999; Molko et al., 2003; Reuhkala, 2001; van der Ven, van der Maas, Straatemeier, & Jansen, 2013; Wei, Yuan, Chen, & Zhou, 2012, and also see reviews from Nieder & Dehaene, 2009; Uttal, Miller, & Newcombe, 2013), working memory (e.g., Kyttälä, Aunio, Lepola, & Hautamäki, 2014; Swanson, Jerman, & Zheng, 2008; Träff, Olsson, Skagerlund, & Östergren, 2018; Zheng, Swanson, & Marcoulides, 2011) and symbolic number processing (e.g., Bugden & Ansari, 2011; Kolkman, Kroesbergen, & Leseman, 2013; Landerl, Bevan, & Butterworth, 2004; Rodic et al., 2015; and see a meta-analysis from Schneider et al., 2017). In terms of shared cognitive mechanisms, visual perception has emerged as an important factor for both reading comprehension (e.g., Casco & Prunetti, 1996; Meng, Cheng-Lai, Zeng, Stein, & Zhou, 2011; Vidyasagar & Pammer, 1999) and arithmetic computation (e.g., Anobile, Stievano, & Burr, 2013; Cui, Zhang, Cheng, Li, & Zhou, 2017; Tibber et al., 2013; Zhou & Cheng, 2015; Zhou, Wei, Zhang, Cui, & Chen, 2015) in separate lines of research. However, because these studies examined either reading comprehension or arithmetic computation but not both, and used different measures of visual perception, it is not clear whether reading comprehension and arithmetic computation share a similar visual perceptual mechanism. Using a geometric figure matching task (e.g., Basso, Capitani, Luzzatti, Spinnler, & Zanobio, 1985; van Strien, Licht, Bouma, & Bakker, 1989; Zhou &

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Cheng, 2015; Zhou et al., 2015), the current study explored whether reading comprehension and arithmetic computation would share a similar visual perceptual mechanism.

1.1. Visual perception and reading comprehension

A close relation between visual perception and language processing (especially reading comprehension) has been supported by studies on children with dyslexia, typically-developing children, and patients. First, children with dyslexia have been found to show deficits in visual perception (e.g., Eden et al., 1996; O'Neill & Stanley, 1976; Sperling, Lu, Manis, & Seidenberg, 2005). For example, O'Neill and Stanley (1976) presented children with dyslexia and healthy controls with pairs of identically-oriented (from zero to 90°) and spatially-overlapping straight lines and asked them to judge whether they saw one or two lines. Children with dyslexia had longer reaction time or needed longer stimulus exposures for detection than did the controls. Recently, Wang et al. (2014) used a texture discrimination task (i.e., to judge the orientation of target bars) to examine visual perceptual learning in Chinese children with developmental dyslexia. Results showed that, whereas healthy controls showed a steady decline in threshold SOA (stimulus-to-mask onset asynchrony) across the five days of perceptual learning, children with dyslexia did not show a significant decrease in threshold SOA. Children with dyslexia also showed deficits in dynamic visual perception as measured with a coherent motion detection task (Conlon, Sanders, & Wright, 2009; Talcott et al., 2000; Witton et al., 1998).

Second, visual perception has also been associated with the reading comprehension ability of typically-developing children (e.g., Conlon et al., 2009; Conlon, Sanders, & Zapart, 2004; Talcott et al., 2000). For example, using the same coherent motion detection task mentioned above, Talcott et al. (2000) showed that English-speaking children's sensitivity to dynamic visual stimuli explained unique variance of children's ability to discriminate real words from pseudohomophones (e.g., "rain" vs. "rane") after controlling for intelligence and word reading skill measured with subscales of British Abilities Scales.

Third, neuropsychological evidence from patients also suggests that visual form perception was critical to processing printed word forms, which is an integral part of reading comprehension. For example, Leff et al. (2001) found that a patient with pure alexia could not recognize integrated words because he could not map all the visual letters into the representation of the whole word form. He could only read letter-by-letter. Miozzo and Caramazza (1998) showed another case of a patient with alexia who could not identify the orthographic structure of words and hence did not know the meanings of visually presented words, although the patient had no problem with words orally spelled out.

1.2. Visual perception and arithmetic computation

Compared with the many studies linking visual perception to reading comprehension, relatively fewer studies have been conducted to investigate the role of visual perception in mathematical processing. Nevertheless, studies on both children with dyscalculia and typically-developing children showed the importance of visual perception in arithmetic computation (e.g., Anobile et al., 2013; Kurdek & Sinclair, 2001; Rosner, 1973; Rourke & Finlayson, 1978; Sigmundsson, Anholt, & Talcott, 2010; Tibber et al., 2013; Zhou & Cheng, 2015; Zhou et al., 2015).

Children with disabilities in arithmetic computation exhibited lower visual-perceptual and visual-spatial abilities (Rourke & Finlayson, 1978; Sigmundsson et al., 2010). For example, Sigmundsson et al. (2010) found that such children were less sensitive than controls to visually coherent motion, even though they performed similarly on a global form coherence task (requiring participants to detect a coherent signal, such as imaginary concentric circles defined by many static short line segments and embedded in randomly oriented line segments). Zhou and Cheng (2015) found that 41 children with dyscalculia had a deficit in visual form perception measured with a geometric figure matching task, after controlling for the scores of choice reaction time, mental rotation, visual-tracing, and Raven's Progressive Matrices. In terms of typically-developing children, Rosner (1973) found that visual perception was significantly correlated with arithmetic computational fluency after controlling for auditory perception score. Kurdek and Sinclair (2001) showed that preschoolers' visuomotor integration (as well as verbal skills) predicted later mathematical achievement in the fourth grade (assessed by Ohio proficiency-based assessments, CTB/McGraw-Hill, 1999) after controlling for age. Recently, Zhou et al. (2015) have shown that visual form perception (based on the geometric figure matching task) was significantly related to computational fluency as well as numerosity comparison (or the approximate number system, ANS) after controlling for general IQ, spatial processing, visual tracing, working memory, and processing speed. In fact, the well-demonstrated association between the ANS and computational fluency was completely accounted for by visual form perception.

1.3. The association between reading comprehension and arithmetic computation

Another reason to expect that reading comprehension and arithmetic computation share common cognitive mechanisms such as visual form perception is their association with each other. An earlier review already pointed out such an association (Aiken, 1971). Later studies have shown that children with dyscalculia often have reading comprehension difficulties (Jordan, Hanich, & Kaplan, 2003). Similarly, children with dyslexia also often exhibit more errors and longer reaction time in multiplication task (e.g., de Smedt & Boets, 2010). A neuroimaging study found that children with dyslexia showed different patterns of brain activations during addition and subtraction tasks as compared to their healthy peers (Evans, Flowers, Napoliello, Olulade, & Eden, 2014). Studies of typically-developing children also show a close relation between reading comprehension and arithmetic computation (e.g., Fedorenko, Gibson, & Rohde, 2007; Swanson & Beebe-Frankenberger, 2004; Träff, 2013).

This close association is most evident in patients with "visual form agnosia". Such patients have difficulties in perceiving simple forms including geometric figures, letters, numbers, mathematical signs, and even numerosity (e.g., Cavina-Pratesi, Large, & Milner, 2015; Efron, 1969; Milner et al., 1991). For example, patient DF suffered from a profound and enduring visual form agnosia, and she could not distinguish simple geometric shapes or single alphanumeric characters (Milner et al., 1991). DF's visual numerosity performance was perfect when only 1 dot was presented but quickly dropped when the number of dots increased, with an accuracy of 33% for 2 dots and 0% for 3–5 dots. The problem could not be attributed to her counting ability, because she could correctly count up to 6 auditory taps. Thus, impaired ability of visual numerosity may be related to deficits in visual form perception.

1.4. The current study

Previous studies as reviewed above have shown a close association between visual form perception and both reading comprehension and arithmetic computation, but they were based on separate lines of research using different measures of visual form perception. The current study aimed to address the question of whether reading comprehension and arithmetic computation shared a similar visual form perception mechanism (assessed by a geometric figure matching task, as used in Basso et al., 1985; van Strien et al., 1989).

Three hypotheses were proposed in the current study:

First, we hypothesized that visual form perception would have similar associations with reading comprehension and arithmetic computation, even after controlling for general cognitive abilities. Given

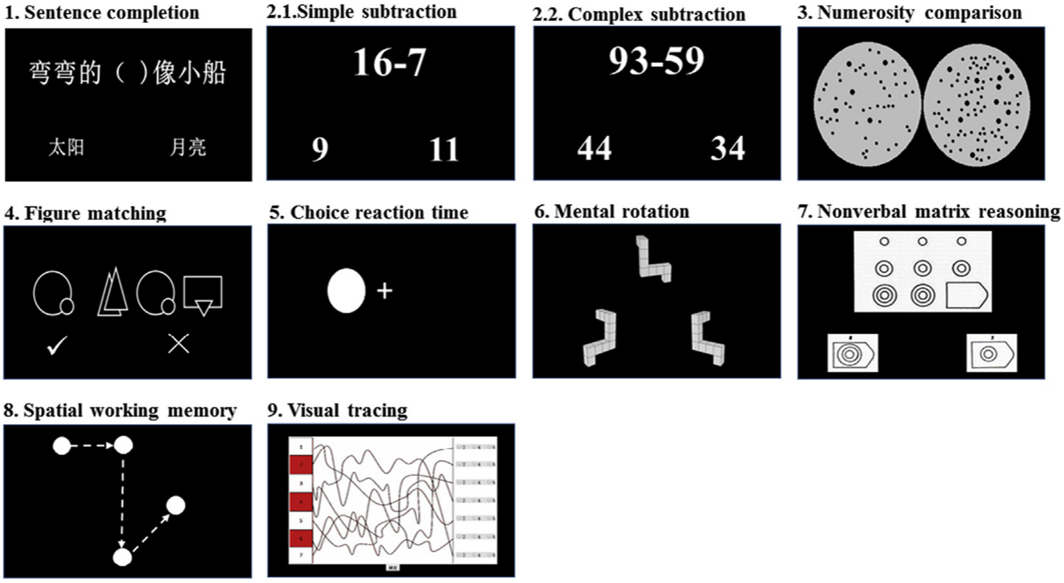

Fig. 1. Display of a sample item of each test used in the current study.

that geometric figure discrimination (structured by lines) is similar to visual processing of symbolic forms in reading comprehension and arithmetic computation (e.g., letters, characters, Arabic digits, mathematical signs), it could be considered as a proper tool to test visual form perception and it should make similar contributions to reading comprehension and arithmetic computation, because both involve visual form processing.

Second, we expected that the ANS would have similar associations with reading comprehension and arithmetic computation, but those associated would be accounted by visual form perception. Previous research has showed that symbolic number processing is correlated with exact computation (Cui et al., 2017; Rodic et al., 2015; Wei, Lu, et al., 2012), approximate computation (Cui et al., 2017), and mathematical reasoning (i.e., number series completion task, Wei, Lu, et al., 20122; Zhang, Chen, Liu, Cui, & Zhou, 2016). However, one of the unsolved questions in the cognitive mechanisms of mathematics is the role of ANS in mathematics (Schneider et al., 2017). As mentioned earlier, our previous studies showed that visual form perception accounted for the close relation between the ANS and computational fluency (Zhou & Cheng, 2015; Zhou et al., 2015), and to our knowledge there have been only two previous studies reporting a significant zero-order correlation between ANS and reading comprehension (Cheng, Xiao, Chen, Cui, & Zhou, 2018; Träff, 2013). However, these two studies did not control for potential confounds such as general cognitive factors. The ANS has been associated with visual form perception (e.g., Cavina-Pratesi et al., 2015; Efron, 1969; Milner et al., 1991; Zhou & Cheng, 2015; Zhou et al., 2015), and also with spatial processing (e.g., Cui et al., 2017; Wei, Yuan, et al., 2012; Zhang et al., 2016). Therefore, it could be expected that ANS ability is also closely linked to reading comprehension. Considering that both visual form perception and ANS required rapid processing of visuo-spatial materials during discrimination and judgment, visual form perception may account for the ANS's significant relation with reading comprehension and arithmetic computation (Cheng et al., 2018; Träff, 2013).

Third, we expected that, with increasing grade level, visual form perception (similarly the ANS acuity) would have stronger associations with both arithmetical computation and reading comprehension. The rationale for this hypothesis is that the fluency of reading comprehension and arithmetical computation increases with increasing grade level, and fluency has been demonstrated to strengthen the association between visual form perception (similarly the ANS acuity) and mathematics (Wang, Sun, & Zhou, 2016).

In this study, reading comprehension and arithmetic computation were assessed using the sentence completion and subtraction tasks, respectively. These two tasks are comparable because both tasks involve the integration of basic elements (i.e., numbers, letters, words) based on certain principles (i.e., arithmetic laws in arithmetic and syntax in reading comprehension) to generate meaningful results.

2. Methods

2.1. Participants

Participants of this study were 1099 third, fourth and fifth graders in elementary schools. There were 171 male and 187 female third graders (mean age: 103.3 ± 4.7 months), 210 male and 194 female fourth graders (114.8 ± 5.5 months), and 189 male and 148 female fifth graders (125.2 ± 5.5 months). The sample size for each subgroup met the requirement for running multiple correlations (Green, 1991). According to Green (1991), the number of participants needed for partial correlations should be no less than the sum of 104 and number of predictors (nine in this study), i.e., 104 + 9 = 113. All children were recruited from urban and suburban primary schools in Beijing. They typically came from families of middle-level socioeconomic backgrounds. All children were native Mandarin speakers. They had normal or corrected-to-normal vision. Parental consent was obtained prior to classroom-based testing.

2.2. Tasks

A total of nine tasks were used. All of them have been reported previously (Cui et al., 2017; Wei, Lu, et al., 2012; Zhou et al., 2015). All the tasks were computerized using web-based applications in the "Online Psychological Experiment System (OPES)" (www.dweipsy.com/lattice). Fig. 1 shows a schematic representation of the nine tasks. Each task has two sessions: practice session and formal testing session. All tasks have shown acceptable half-split reliabilities, ranging from 0.80 to 0.96 according to previous studies (Wei, Lu, et al., 2012; Wei, Yuan, et al., 2012; Zhou et al., 2015).

2.2.1. Sentence completion

This task was similar to the one used by previous researchers (So & Siegel, 1997) and was used to measure reading comprehension (e.g., Elbeheri, Everatt, Mahfoudhi, Al-Diyar, & Taibah, 2011; Träff et al., 2018). Materials for the task were adapted from the test materials used in primary, middle, and high schools in China (from first to ninth grade). For each trial, a sentence was presented in the middle of the computer screen with a word missing. Participants needed to select one of two candidate words presented beneath the sentence to complete the sentence. There were 120 problems, ordered from easy to difficult, and participants were asked to complete as many trials as possible and to choose their answer for each trial as quickly and accurately as possible. The formal testing of this task was limited to 5 min.

Adjusted number of correct trials was used to control for the effect of guessing in multiple choice tests. The score was calculated by subtracting the number of incorrect responses from the number of correct responses following the Guilford correction formula "$S = R - W/(n - 1)$" (S: the adjusted number of items that the participants can actually perform without the aid of chance. R: the number of right responses, W: the number of wrong responses. n: the number of alternative responses to each item) (Guilford, 1936). This correction procedure has been utilized recently in studies of mathematical cognition (Cirino, 2011; Wei, Lu, et al., 2012; Zhou et al., 2015) and cognition in general (Hedden & Yoon, 2006; Putz, Gaulin, Sporter, & McBurney, 2004; Salthouse, 1994).

2.2.2. Arithmetic computation

There were two arithmetic computation tasks: simple and complex subtraction. The scores for both subtraction tasks were adjusted numbers of correct trials (see the sentence completion test), and scores of the two tasks were averaged as the score of arithmetic computation. Time-limited arithmetic computation tasks have been utilized in previous studies to assess computational fluency (e.g., Geary, 1996; Geary, Saults, Liu, & Hoard, 2000; Zhou et al., 2015).

2.2.2.1. Simple subtraction. The task consisted of 92 single-digit subtraction problems. For each trial, a subtraction problem (e.g., 9–2) was presented on the top part of the screen, with two candidate answers presented on the bottom. Each problem's minuend ranged from 2 to 18, and an answer ranging from 2 to 9. The false candidate answer deviated from true answer by plus or minus 1 to 3 (i.e., ± 1, ± 2, or ± 3). The formal testing was limited to 2 min.

2.2.2.2. Complex subtraction. There were 95 problems, with each problem involving double-digit numbers for both operands. Borrowing was required for most problems. In each trial, a subtraction problem (e.g., 64–27) was presented on the top part of the screen, with two candidate answers presented on the bottom. The differences between false and true answers were either 1 or 10. The formal testing for the task was also limited to 2 min.

2.2.3. Numerosity comparison

The numerosity comparison test was used to assess approximate number sense (ANS) (Wei, Lu, et al., 2012; Zhou et al., 2015). Each trial consisted of two dot arrays presented for 200 ms. Each dot array included 11, 14, 17, 20, 23, 26, or 29 dots, presented in a grey circle with a visual angle of 6.8°. The two dot arrays for each trial were horizontally aligned and extended to a visual angle of about 14°. The participants were asked to fixate at the blank center (no fixation sign) of the screen in the beginning of the task. Participants were asked to choose the dot array with more dots, while ignoring all visual properties such as total surface area, envelope area, diameter, and circumference. They responded by pressing the key "Q" for the left dot array or "P" for the right one on a computer keyboard. The test included 120 trials, administered in three 40-trial sessions. The dot arrays were created following a common procedure to control for continuous quantities in non-symbolic numerical discrimination (e.g., Agrillo, Piffer, & Adriano, 2013; Halberda, Mazzocco, & Feigenson, 2008). For half of the trials, the two dot arrays had the same total combined area, whereas for the other half, the two arrays had the same average area of all dots. The ratios between the numbers of dots in the two dot arrays ranged from 1.2 to 2.0. The dots in a dot array were randomly distributed within a circle, and the dots' sizes varied. The envelope area/convex hull varied little from trial to trial.

Gebuis and Reynvoet (2011) proposed that five visual properties of the numerosity comparison task could affect numerosity comparison: total surface area, envelope area or convex hull, item size, density, and circumference. Density is defined as the number of items per unit area (Anobile et al., 2013; Anobile, Cicchini, & Burr, 2014; Tinelli et al., 2015). Zhou et al. (2015) showed that the numerosity comparison task was still ratio-dependent after the five visual properties of dot arrays were controlled. To confirm previous finding, the current investigation would also examine the effects of visual properties on task performance.

The median reaction time and accuracy (percentage of correct trials) were used.

2.2.4. Figure matching

The figure matching test was used to measure the ability of visual perception (Zhou & Cheng, 2015; Zhou et al., 2015). There were 120 trials, each containing one target picture on the left side and three candidate pictures on the right side. The pictures were constructed from 150 abstract line figures. The four pictures were presented simultaneously for 200 ms, following a 1000-ms blank. Participants were asked to judge whether the picture on the left side also appeared on the right side. Participants should press the key "Q" if the target picture was the same as one of the candidate pictures, or else press the key "P". The 120 trials were grouped into three 40-trial sessions. The median reaction time and accuracy (percentage of correct trials) were used.

2.2.5. Choice reaction time

A basic reaction time task was employed in order to control for the effect of manual response and mental processing speed (cf., Butterworth's [2003] "Dyscalculia Screener", which included a reaction time task). Each trial presented a fixation cross in the center of the screen and a white dot, either to the left or to the right of the fixation cross. Participants were asked to press the "Q" key when the dot was on the left or pressed the "P" key when the dot was on the right. There were 30 trials. The interval between responses and stimuli was randomly chosen between 1500 ms and 3000 ms.

The median reaction time and error rate were recorded, but the gross mean error rate for the choice reaction time task was very low (4.72%) and hence was not further analyzed.

2.2.6. Mental rotation

The mental rotation test was adapted from Vandenberg and Kuse (1978). The revised version had only two choices and was limited to 3 min. There were three three-dimensional images in each trial: one at the top and the other two at the bottom. Participants were asked to judge which of the two candidates at the bottom was the same as the top one, after mentally rotating one of the images. The correct image was rotated from the original, with a rotation angle ranging from 15° to 345° (with intervals of 15°). The other image was a mirror image of the target. Participants pressed the key "Q" if their choice was on the left side, or "P" if it was on the right side. Adjusted number of correct trials was used (see the sentence completion test).

2.2.7. Nonverbal matrix reasoning

Nonverbal matrix reasoning was utilized to assess abstract reasoning ability, which has been correlated with mathematical performance (e.g., Kyttälä & Lehto, 2008; Rohde & Thompson, 2007). The task was adapted from Raven's Progressive Matrices (Raven, 2000). The original version had 4–6 choices, whereas the current version was simplified with only two candidate answers for each question. One of the two answers is the correct answer and the other one is the most similar one (out of the 4–6 choices on the original test) to the correct one. Participants were asked to find the missing segment of a figure according to the rules underlying the figure. The participants were instructed to press "Q" with their left forefinger if the missing segment was on the left or "P" with their right forefinger if it was on the right. Due to the limited time allotted for this study, we had to shorten the task to 80 items, including 44 items from Standard Progressive Matrices (12 items from first set and eight items from each of the other four sets) and 36 items from Advanced Progressive Matrices. The formal test was limited to 4 min. Similarly shortened versions of Raven's test have been used in previous studies (e.g., Bors & Vigneau, 2001; Bouma, Mulder, & Lindeboom, 1996; Vigneau, Caissie, & Bors, 2006; Wei, Lu, et al., 2012). The shortened version had convergent validity, as shown by its high correlation with a number series completion task that measures a type of reasoning in mathematics (Wei, Lu, et al., 2012).

Adjusted number of correct trials (see the sentence completion test) was used.

2.2.8. *Spatial working memory*

This test was adapted from the Corsi Blocks Task (Corsi, 1972). In each trial, several dots were sequentially presented in an implicit 3 × 3 lattice on the screen. The number of dots ranged from three to nine, increasing with correct responses. Each dot was presented for 1000 ms, with an interval of 1000 ms between dots. After the presentation of all dots of a trial, participants used a mouse to click the positions of dots on the screen according to the order they were presented.

The score of this test was calculated as accuracy, utilizing the following formula: $\text{Accuracy} = 100 - |\text{response} - \text{standard answer}|/(\text{standard answer} + |\text{response} - \text{standard answer}|) \times 100$. ("Response" refers to the participants' answer, and "standard answer" refers to the correct answer.) Deviation of the participants' answer from the standard answer is divided by the sum of the standard answer and the deviation, which gives the degree of deviation from the standard value. The formula returns values from 0 to 100.

2.2.9. *Visual tracing*

The visual tracing test was adapted from the task designed by Groffman (1966) to assess the oculo-motor coordination ability, which has been associated with dyslexia (Groffman, 1994) and mathematical disability (Fischer, Gebhardt, & Hartnegg, 2008; Groffman, 2009). In each trial, there were several interweaving curved lines presented within a square, starting from the left side of the square and ending on the right side. Participants were asked to track a particular line (the number that indicates the line is marked by red color) from beginning to end only by "eyeing" (i.e., they were not allowed to use a finger, the cursor, or an object to trace) and then to mark the correct end point by clicking the left mouse. The difficulty of the task increased as the total number of lines increased. There were 36 trials. This task was limited to 4 min. The number of correct trials was used.

2.3. *Procedure*

The battery of tasks was administered in two 40-min sessions. Computerized tasks were administered to students (one class at a time) in a computer classroom. Each class was monitored by two or three experimenters, as well as the teacher of that class. The experimenters explained the instruction with slides for each task. The teacher was present only for the purpose of discipline (e.g., maintaining silence during the formal testing). After all students finished one test, the experimenter started to administer the next test. For each test, the students were first given instructions and then completed a practice session, followed by the formal test. The practice test included four to six trials, which were similar to those used in the formal test. The feedback in the practice session for all cognitive tasks was "Correct! Can you go faster?" for correct answers, and was "It is wrong. Try again." for incorrect answers. During the practice session, the children could ask the experimenters any questions related to the testing. The formal test began after the children had finished the practice session. Only when all students understood the procedure during practice, could they begin the formal test. After the main experimenter said "Start!", all children in the computer classroom pressed a key to begin the formal test. All students performed the tasks in the same order.

Participants' responses and reaction times were automatically recorded and transmitted over the Internet to a server located in a laboratory at Beijing Normal University. The data collection for the current investigation was administered from July to December of 2013.

2.4. *Data analysis*

Descriptive statistics and intercorrelations (with Bonferroni correction) for all tasks were first obtained. A series of hierarchical regression analyses were then conducted to examine the independent contributions of ANS and visual form perception to both reading comprehension and arithmetic computation, after controlling for age (the variations in months within an age group), gender, and all other five types of general cognitive processes (choice reaction time, mental rotation, non-verbal matrix reasoning, spatial working memory, and visual tracing). A path model that integrated all key variables was also used.

3. Results

Table 1 shows the means and standard deviations of scores for all nine tasks in the current investigation. Table 2 displays the Pearson's intercorrelational coefficients among all the scores, with Bonferroni correction. A Bonferroni correction was used to maintain the p-value < 0.05 across the 55 correlations in Table 2. Thus, a conservative p-value of < 0.00091 ($=0.05/55$) was considered

Table 1
Means and standard deviations of all the measures by age.

Tasks	Grade 3 M(SD)	Grade 4 M(SD)	Grade 5 M(SD)	Index
Sentence completion	18.4(8.8)	22.7(9.1)	25.4(9.1)	Adj. No. of correct response
Arithmetic computation	48.6(12.6)	53.0(13.0)	57.9(12.7)	Adj. No. of correct response
Simple subtraction	35.9(8.4)	38.2(8.2)	40.2(9.7)	Adj. No. of correct response
Complex subtraction	11.5(8.4)	14.2(8.5)	17.1(7.7)	Adj. No. of correct response
Numerosity comparison (ACC)	70.6(11.2)	71.7(11.4)	73.6(11.1)	Accuracy (%)
Numerosity comparison (RT)	581(157)	545(143)	546(141)	Reaction time (Millisecond)
Figure matching(ACC)	60.9(10.6)	65.9(12.1)	68.5(11.5)	Accuracy (%)
Figure matching (RT)	855(409)	892(342)	904(310)	Reaction time (Millisecond)
Choice reaction time	463(89)	419(82)	408(79)	Reaction time (Millisecond)
Mental rotation	15.7(9.8)	17.1(9.9)	17.7(9.3)	Adj. No. of correct response
Non-verbal matrix reasoning	14.8(8.4)	15.1(8.1)	16.3(8.3)	Adj. No. of correct response
Spatial working memory	76.6(5.5)	79.7(5.0)	80.5(5.0)	Accuracy (%)
Visual tracing	11.4(5.4)	14.2(5.7)	15.9(5.2)	No. of correct response

Note: Adj.: adjusted, No.: number. ACC: accuracy; RT: reaction time (calculated as the mean of all participants' median reaction time).

Table 2
Intercorrelations of all measures.

Task	1	2	3.1	3.2	4.1	4.2	5	6	7	8
1 Sentence completion	–									
2 Arithmetic computation	0.45*	–								
3.1 Numerosity comparison (ACC)	0.31*	0.36*	–							
3.2 Numerosity comparison (RT)	0.13*	0.14*	0.62*	–						
4.1 Figure matching (ACC)	0.38*	0.44*	0.49*	0.32*	–					
4.2 Figure matching (RT)	0.25*	0.30*	0.51*	0.50*	0.61*	–				
5 Choice reaction time	−0.14*	−0.16*	−0.04	0.26*	−0.16*	0.07	–			
6 Mental rotation	0.14*	0.19*	0.14*	0.01	0.15*	0.08	−0.11*	–		
7 Non-verbal matrix reasoning	0.21*	0.26*	0.26*	0.14*	0.23*	0.16*	−0.02	0.21*	–	
8 Spatial working memory	0.30*	0.35*	0.23*	−0.02	0.34*	0.18*	−0.20*	0.22*	0.19*	–
9 Visual tracing	0.20*	0.28*	0.17*	−0.05	0.27*	0.07	−0.30*	0.24*	0.19*	0.35*

* $p < .05$, Bonferroni-corrected. ACC: accuracy; RT: reaction time.

statistically significant.

The Steiger z test (Steiger, 1980) was used to examine the differences in correlations. Results showed that the correlation between figure matching and arithmetic computation was the highest among all the correlations with arithmetic computation. For example, the correlation coefficient for accuracy rate of figure matching (0.44) was significantly larger than the second-largest one (0.35, the correlation coefficient between spatial working memory and arithmetic computation), Z = 2.92, $p < .01$. Similarly, the correlation between figure matching and sentence completion was the highest among all the correlations with sentence completion. For example, the correlation coefficient for accuracy rate of figure matching (0.38) was significantly larger than the second-largest one (0.30, the correlation coefficient between spatial working memory and sentence completion), Z = 2.51, $p < .05$.

Fig. 2 shows the scatter plots of reading comprehension and arithmetic computation over visual form perception after controlling for age, gender, and five cognitive factors (including choice reaction time, mental rotation, non-verbal matrix reasoning, spatial working memory, and visual tracing). Visual form perception made significant unique contributions to both reading comprehension and arithmetic computation.

Twelve hierarchical regression analyses were conducted to examine the contributions of various cognitive factors to reading comprehension and arithmetic computation. With Bonferroni correction, the adjusted significance alpha of 0.05 corresponded to 0.004 before correction (=0.05/12) for each regression table.

Table 3 shows unique contribution of ANS and visual form perception made to reading comprehension and arithmetic computation after controlling for age (the variations in months within an age group), gender, and five types of general cognitive factors (including choice reaction time, mental rotation, non-verbal matrix reasoning, spatial working memory, and visual tracing). The three panels show consistent results from children in Grades 3, 4, and 5, respectively.

Table 4 shows the contributions of visual form perception to reading comprehension and arithmetic computation, for each grade, after controlling for age (the variations in months within an age group) and gender, as well as the other five types of cognitive factors (including choice reaction time, mental rotation, non-verbal matrix reasoning, spatial working memory, and visual tracing). The three panels show consistent results from children in Grades 3, 4, and 5, respectively.

The regression results in Tables 3 and 4 showed that both ANS and

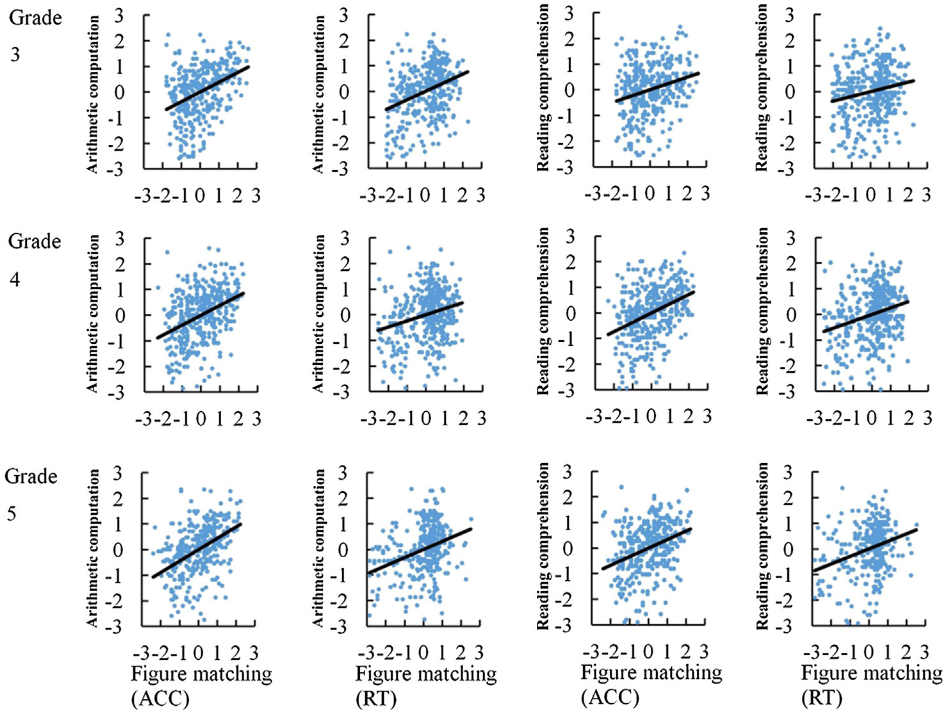

Fig. 2. Scatter plots of standardized Z scores of figure matching (visual form perception) and standardized Z scores of reading comprehension and arithmetic computation. ACC: accuracy, RT: reaction time.

Table 3
Hierarchical regression models predicting reading comprehension and arithmetic computation from age, gender, general cognitive processing, numerosity comparison, and figure matching.

Grade	Predictors	Sentence completion				Arithmetic computation			
		Step 1 B(SE)	Step 2 B(SE)	Step 3 B(SE)	Step 4 B(SE)	Step 1 B(SE)	Step 2 B(SE)	Step 3 B(SE)	Step 4 B(SE)
3	Age(months)	0.11(0.05)	0.09(0.05)	0.09(0.05)	0.08(0.05)	0.11(0.07)	0.08(0.07)	0.06(0.06)	0.06(0.06)
	gender	4.7(0.9)*	4.7(0.9)*	4.4(0.9)*	4.3(0.9)*	4.2(1.3)*	4.7(1.3)*	3.8(1.3)	3.3(1.2)
	Choice reaction time	–	−0.00(0.01)	−0.00(0.01)	0.00(0.01)	–	−0.01(0.01)	−0.01(0.01)	−0.01(0.01)
	Mental rotation	–	0.02(0.05)	0.01(0.05)	0.01(0.05)	–	0.13(0.07)	0.11(0.07)	0.10(0.06)
	Non-verbal matrix reasoning	–	0.10(0.06)	0.08(0.06)	0.07(0.06)	–	0.17(0.08)	0.10(0.08)	0.08(0.08)
	Spatial working memory	–	0.23(0.09)	0.21(0.09)	0.16(0.09)	–	0.41(0.12)*	0.37(0.12)	0.22(0.12)
	Visual tracing	–	0.13(0.09)	0.12(0.09)	0.11(0.09)	–	0.31(0.12)	0.28(0.12)	0.25(0.12)
	Numerosity comparison (ACC)	–	–	0.09(0.06)	0.06(0.06)	–	–	0.23(0.08)	0.14(0.08)
	Numerosity comparison (RT)	–	–	−0.00(0.00)	−0.00(0.00)	–	–	0.00(0.01)	−0.00(0.00)
	Figure matching (ACC)	–	–	–	0.10(0.06)	–	–	–	0.16(0.08)
	Figure matching (RT)	–	–	–	0.00(0.00)	–	–	–	0.00(0.00)
		$R^2 = 0.081^{*}$	$\Delta R^2 = 0.056^{*}$	$\Delta R^2 = 0.007$	$\Delta R^2 = 0.010$	$R^2 = 0.033^{*}$	$\Delta R^2 = 0.120^{*}$	$\Delta R^2 = 0.038^{*}$	$\Delta R^2 = 0.039^{*}$
4	Age(months)	0.09(0.07)	0.05(0.06)	0.05(0.06)	0.05(0.06)	0.29(0.09)*	0.19(0.09)	0.19(0.08)	0.19(0.08)
	gender	3.7(0.9)*	3.5(0.9)*	2.6(0.9)	2.1(0.09)	4.3(1.3)*	3.7(1.2)*	2.6(1.2)	1.9(1.1)
	Choice reaction time	–	−0.00(0.01)	−0.01(0.01)	−0.00(0.01)	–	−0.01(0.01)	−0.01(0.01)	−0.01(0.01)
	Mental rotation	–	0.09(0.05)	0.07 (0.05)	0.07(0.05)	–	0.05(0.06)	0.03(0.06)	0.03(0.06)
	Non-verbal matrix reasoning	–	0.15(0.06)	0.10(0.05)	0.09(0.05)	–	0.37(0.07)*	0.32(0.07)*	0.30(0.07)*
	Spatial working memory	–	0.30(0.09)*	0.23(0.09)	0.20(0.09)	–	0.63(0.12)*	0.54(0.12)*	0.50(0.12)*
	Visual tracing	–	0.02(0.08)	0.01(0.08)	−0.03(0.08)	–	0.25(0.11)	0.22(0.11)	0.17(0.11)
	Numerosity comparison (ACC)	–	–	0.19(0.05)*	0.13(0.05)	–	–	0.24(0.07)*	0.16(0.07)
	Numerosity comparison (RT)	–	–	0.00(0.00)	0.00(0.00)	–	–	0.00(0.01)	−0.00(0.01)
	Figure matching (ACC)	–	–	–	0.16(0.00)*	–	–	–	0.22(0.06)*
	Figure matching (RT)	–	–	–	0.00(0.00)	–	–	–	0.00(0.01)
		$R^2 = 0.045^{*}$	$\Delta R^2 = 0.079^{*}$	$\Delta R^2 = 0.061^{*}$	$\Delta R^2 = 0.031^{*}$	$R^2 = 0.048^{*}$	$\Delta R^2 = 0.182^{*}$	$\Delta R^2 = 0.040^{*}$	$\Delta R^2 = 0.032^{*}$
5	Age(months)	−0.02(0.06)	−0.01(0.05)	−0.01(0.05)	−0.01(0.05)	0.05(0.08)	0.08(0.08)	0.07(0.07)	0.06(0.07)
	gender	5.0(1.0)*	4.7(0.9)*	4.1(0.9)*	3.9(0.9)*	3.5(1.4)	3.2(1.3)	2.0(1.3)	1.7(1.3)
	Choice reaction time	–	−0.01(0.01)	−0.01(0.01)	−0.01(0.01)	–	0.00(0.01)	0.01(0.01)	0.01(0.01)
	Mental rotation	–	0.09(0.05)	0.08(0.05)	0.07(0.05)	–	0.19(0.08)	0.17(0.07)	0.14(0.07)
	Non-verbal matrix reasoning	–	0.22(0.06)*	0.17(0.06)	0.16(0.06)	–	0.24(0.08)	0.15(0.08)	0.12(0.08)
	Spatial working memory	–	0.29(0.10)	0.24(0.10)	0.21(0.06)	–	0.36(0.14)	0.29(0.14)	0.20(0.13)
	Visual tracing	–	0.01(0.10)	−0.02(0.10)	−0.03(0.10)	–	0.21(0.14)	0.13(0.14)	0.08(0.13)
	Numerosity comparison (ACC)	–	–	0.13(0.06)	0.09(0.06)	–	–	0.32(0.08)*	0.22(0.08)
	Numerosity comparison (RT)	–	–	0.01(0.00)	0.00(0.01)	–	–	0.00(0.01)	−0.01(0.01)
	Figure matching (ACC)	–	–	–	0.08(0.05)	–	–	–	0.31(0.07)*
	Figure matching (RT)	–	–	–	0.00(0.00)	–	–	–	0.00(0.00)
		$R^2 = 0.078^{*}$	$\Delta R^2 = 0.115^{*}$	$\Delta R^2 = 0.047^{*}$	$\Delta R^2 = 0.016$	$R^2 = 0.018$	$\Delta R^2 = 0.119^{*}$	$\Delta R^2 = 0.071^{*}$	$\Delta R^2 = 0.060^{*}$

* $p < .05$, Bonferroni-corrected. ACC: accuracy; RT: reaction time.

visual form perception played unique roles in reading comprehension and arithmetic computation, after controlling for age, gender, and general cognitive factors (including choice reaction time, mental rotation, non-verbal matrix reasoning, spatial working memory, and visual tracing).

The contribution of ANS could be explained by visual form perception–that is, when numerosity comparison was added to the regression (in the fourth step), it made no significant contributions to reading comprehension or arithmetic computation for any age group of children. However, the reverse was not the case–that is, the unique role of visual form perception was not explained by ANS. Moreover, as shown in Tables 3 and 4, the amounts of contributions (ΔR^2) of visual form perception and ANS to reading comprehension and arithmetic computation appeared to increase with grade: mean $\Delta R^2 = 0.034$, 0.048, and 0.068 for third, fourth and fifth grade, respectively.

As would be expected, test scores of reading comprehension ($F(2, 1096) = 53.711$, $p < .001$, $\eta_p^2 = 0.089$) and arithmetic computation ($F(2,1096) = 44.904$, $p < .001$, $\eta_p^2 = 0.076$) differed significantly by grade level. For the sentence completion task, the difference between Grades 3 and 4 [*Mean Difference* = −4.25, *SD* = 0.65, $t\,(760) = 6.54$, $p = 1.1 \times 10^{-10}$, Cohen's $d = -0.48$] was much larger than that between Grades 4 and 5 [*Mean Difference* = −2.75, *SD* = 0.66, $t\,(739) = 4.10$, $p = 3.7 \times 10^{-5}$, Cohen's $d = -0.297$], independent samples *t*-test [$t\,(739) = 2.24$, $p = .026$, Cohen's $d = 0.17$]. For the arithmetic computation task, the difference between Grades 3 and 4 [*Mean Difference* = −4.35, *SD* = 0.93, $t\,(760) = 4.67$, $p = 3.2 \times 10^{-6}$, Cohen's $d = -0.344$] was similar as that between Grades 4 and 5 [*Mean Difference* = −4.86, *SD* = 0.94, $t\,(739) = 5.11$, $p = 3.2 \times 10^{-7}$, Cohen's $d = -0.381$], independent samples *t*-test [$t\,(739) = -0.48$, $p = .632$, Cohen's $d = -0.035$].

Tables 5 and 6 show the contributions of visual form perception and ANS to simple and complex arithmetic computation for children in Grades 3, 4, and 5, after controlling for the same factors in Tables 3 and 4. Scores of both subtraction tests were similarly related to ANS ability, which also could be explained by visual form perception test. Moreover, the contribution (ΔR^2) of visual form perception and ANS to both subtraction appeared to increase with grade: mean $\Delta R^2 = 0.037$, 0.039, and 0.076 for third, fourth and fifth grade, respectively. In other words, the two subtraction tests showed very similar results, perhaps because both tests measured arithmetic fluency. Visual form perception and ANS appeared to make greater contributions to complex subtraction ($\Delta R^2 = 0.072$) than to simple subtraction ($\Delta R^2 = 0.029$).

The regression analyses shown in Tables 3–6 were conducted separately for sentence comprehension and arithmetic computation. The following regression analyses were conducted on the covariance between reading comprehension and arithmetic computation to show that figure matching accounted for similar variance of both tasks. We first computed the covariance between the residuals of reading compression and the residuals of arithmetic computation after controlling for age, gender and general cognitive processes (including non-verbal matrix

Table 4
Hierarchical regression models predicting reading comprehension and arithmetic computation from figure matching and numerosity comparison.

Grade	Predictors	Sentence completion				Arithmetic computation			
		Step 1 B(SE)	Step 2 B(SE)	Step 3 B(SE)	Step 4 B(SE)	Step 1 B(SE)	Step 2 B(SE)	Step 3 B(SE)	Step 4 B(SE)
3	Age(months)	0.11(0.05)	0.09(0.05)	0.08(0.05)	0.08(0.05)	0.11(0.07)	0.08(0.07)	0.06(0.06)	0.06(0.06)
	gender	4.7(0.9)*	4.7(0.9)*	4.5(0.9)*	4.3(0.9)*	4.2(1.3)*	4.7(1.3)*	3.6(1.2)	3.3(1.2)
	Choice reaction time	–	−0.00(0.01)	−0.00(0.01)	−0.00(0.01)	–	−0.01(0.01)	−0.01(0.01)	−0.01(0.01)
	Mental rotation	–	0.02(0.05)	0.01(0.05)	0.01(0.05)	–	0.13(0.07)	0.11(0.06)	0.10(0.06)
	Non-verbal matrix reasoning	–	0.10(0.06)	0.08(0.06)	0.07(0.06)	–	0.17(0.08)	0.10(0.08)	0.08(0.08)
	Spatial working memory	–	0.23(0.09)	0.17(0.09)	0.16(0.09)	–	0.41(0.12)*	0.23(0.12)	0.22(0.12)
	Visual tracing	–	0.13(0.09)	0.11(0.09)	0.11(0.09)	–	0.31(0.12)	0.27(0.12)	0.25(0.12)
	Figure matching (ACC)	–	–	0.11(0.06)	0.10(0.06)	–	–	0.18(0.08)	0.16(0.08)
	Figure matching (RT)	–	–	0.00(0.00)	0.00(0.00)	–	–	0.01(0.00)	0.00(0.00)
	Numerosity comparison (ACC)	–	–	–	0.06(0.06)	–	–	–	0.14(0.08)
	Numerosity comparison (RT)	–	–	–	−0.00(0.00)	–	–	–	−0.00(0.01)
		$R^2 = 0.081$*	$\Delta R^2 = 0.056$*	$\Delta R^2 = 0.015$	$\Delta R^2 = 0.003$	$R^2 = 0.033$*	$\Delta R^2 = 0.120$*	$\Delta R^2 = 0.069$*	$\Delta R^2 = 0.007$
4	Age(months)	0.09(0.07)	0.05(0.06)	0.06(0.06)	0.05(0.06)	0.28(0.09)*	0.19(0.09)	0.20(0.08)	0.19(0.08)
	gender	3.7(0.9)*	3.5(0.9)*	2.4(0.9)	2.1(0.9)	4.3(1.3)*	3.7(1.2)*	2.3(1.2)	1.9(1.2)
	Choice reaction time	–	−0.00(0.01)	−0.00(0.01)	−0.00(0.01)	–	−0.01(0.01)	−0.01(0.01)	−0.01(0.01)
	Mental rotation	–	0.09(0.05)	0.08(0.05)	0.07(0.05)	–	0.05(0.06)	0.04(0.06)	0.03(0.06)
	Non-verbal matrix reasoning	–	0.15(0.06)	0.11(0.05)	0.09(0.05)	–	0.37(0.07)*	0.32(0.07)*	0.30(0.07)*
	Spatial working memory	–	0.30(0.09)*	0.24(0.09)	0.20(0.09)	–	0.63(0.12)*	0.55(0.12)*	0.50(0.12)*
	Visual tracing	–	0.02(0.08)	−0.03(0.08)	−0.03(0.08)	–	0.25(0.11)	0.17(0.11)	0.17(0.11)
	Figure matching (ACC)	–	–	0.18(0.05)*	0.15(0.05)*	–	–	0.25(0.06)*	0.22(0.06)*
	Figure matching (RT)	–	–	0.00(0.00)	0.00(0.00)	–	–	0.00(0.00)	0.00(0.00)
	Numerosity comparison (ACC)	–	–	–	0.13(0.05)	–	–	–	0.16(0.07)
	Numerosity comparison (RT)	–	–	–	0.00(0.00)	–	–	–	−0.00(0.01)
		$R^2 = 0.045$*	$\Delta R^2 = 0.079$*	$\Delta R^2 = 0.075$*	$\Delta R^2 = 0.018$	$R^2 = 0.048$*	$\Delta R^2 = 0.182$*	$\Delta R^2 = 0.062$*	$\Delta R^2 = 0.010$
5	Age(months)	−0.02(0.06)	−0.01(0.05)	−0.01(0.05)	−0.01(0.05)	0.05(0.08)	0.08(0.08)	0.07(0.07)	0.06(0.07)
	gender	5.0(0.9)*	4.7(0.9)*	4.1(0.9)*	3.9(0.9)*	3.5(1.4)	3.2(1.3)	2.1(1.3)	1.7(1.3)
	Choice reaction time	–	−0.01(0.01)	−0.01(0.01)	−0.01(0.01)	–	0.00(0.01)	0.00(0.01)	0.01(0.01)
	Mental rotation	–	0.09(0.05)	0.07(0.05)	0.07(0.05)	–	0.19(0.08)	0.15(0.07)	0.14(0.07)
	Non-verbal matrix reasoning	–	0.22(0.06)*	0.18(0.06)*	0.16(0.06)	–	0.24(0.08)	0.15(0.08)	0.12(0.08)
	Spatial working memory	–	0.29(0.10)	0.22(0.10)	0.21(0.10)	–	0.36(0.14)	0.20(0.14)	0.20(0.13)
	Visual tracing	–	0.01(0.10)	−0.01(0.09)	−0.03(0.10)	–	0.21(0.14)	0.13(0.13)	0.08(0.13)
	Figure matching (ACC)	–	–	0.11(0.05)	0.08(0.05)	–	–	0.34(0.07)*	0.31(0.07)*
	Figure matching (RT)	–	–	0.00(0.00)	0.00(0.00)	–	–	0.00(0.00)	0.00(0.00)
	Numerosity comparison (ACC)	–	–	–	0.09(0.06)	–	–	–	0.22(0.08)
	Numerosity comparison (RT)	–	–	–	0.00(0.01)	–	–	–	−0.01(0.01)
		$R^2 = 0.078$*	$\Delta R^2 = 0.115$*	$\Delta R^2 = 0.052$*	$\Delta R^2 = 0.011$	$R^2 = 0.018$	$\Delta R^2 = 0.119$*	$\Delta R^2 = 0.114$*	$\Delta R^2 = 0.016$

* $p < .05$, Bonferroni-corrected. ACC: accuracy; RT: reaction time.

reasoning, mental rotation, choice RT, visual tracing and spatial working memory). The covariance was defined as the uniquely explained component of the residuals of arithmetic computation by the residuals of reading comprehension. The contribution of figure matching to the covariance was significant, 4.4% ($p < .001$). When the covariance was defined as the uniquely explained component of the residuals of reading comprehension by the residuals of arithmetic computation (controlling for age, gender and general cognitive processes), the contribution of figure matching to the covariance was also significant, 7.7% ($p < .001$). The significant contributions suggest that figure matching can influence both reading comprehension and arithmetical computation.

Finally, Fig. 3 shows the path model on the structural relationships among all main variables. The latent variable "Achievement" had the two manifest measures (reading comprehension and arithmetic computation). Thus, the general achievement stands for the shared component for arithmetic computation and sentence completion. The hypothesized model was a good fit for the data, χ^2 (20) = 28.34, $p = .102$, *RMSEA* = 0.02, *CFI* = 0.99, and *SRMR* = 0.00. The model showed that numerosity comparison did not have any significant association with achievement (arithmetic computation and reading comprehension), but it had significant association with visual form perception. Visual form perception had a significant load (0.42) to the general achievement. Non-verbal matrix reasoning, spatial working memory, gender and age also had significant direct associations with achievement. Spatial working memory and age had significant associations with visual form perception. Non-verbal matrix reasoning, spatial working memory, and gender had significant associations with numerosity comparison. The significance level of path coefficients in the path model was Bonferroni-corrected, set to 0.05, corresponding to original alpha 0.002 (0.05/24 links).

4. Discussion

The aim of this study was to investigate whether visual form perception made substantial contributions to both reading comprehension and arithmetic computation. As expected, visual form perception had close relations with both reading comprehension and arithmetic computation for fourth and fifth graders after controlling for age, gender, and cognitive factors such as processing speed, attention, working memory, and general intelligence. Also as expected, numerosity comparison's relations with reading comprehension and arithmetic computation were fully accounted for by visual form perception. These results suggest that reading comprehension and arithmetic computation might share a similar visual form processing mechanism.

4.1. *Visual form perception has similar associations with reading comprehension and arithmetic computation*

By using unusual and meaningless combinations of simple geometric figures, the geometric figure matching task is mostly measuring the ability to process visual form information, whereas tasks using

Table 5
Hierarchical regression models predicting simple and complex arithmetic computation from age, gender, general cognitive processing, numerosity comparison, and figure matching.

Grade	Predictors	Simple subtraction				Complex subtraction			
		Step 1 B(SE)	*Step 2 B(SE)*	*Step 3 B(SE)*	*Step 4 B(SE)*	*Step 1 B(SE)*	*Step 2 B(SE)*	*Step 3 B(SE)*	*Step 4 B(SE)*
3	Age(months)	0.13(0.05)	0.11(0.04)	0.10(0.04)	0.10(0.04)	0.11(0.05)	0.09(0.04)	0.08(0.04)	0.08(0.04)
	gender	2.57(0.88)	2.94(0.84)	2.45(0.84)*	2.38(0.85)	2.90(0.88)*	3.22(0.85)*	2.75(0.86)*	2.46(0.85)
	Choice reaction time	–	0.00(0.00)	0.00(0.00)	0.00(0.00)	–	0.00(0.00)	0.00(0.00)	0.00(0.00)
	Mental rotation	–	0.11(0.04)	0.10(0.04)	0.10(0.04)	–	0.07(0.04)	0.06(0.04)	0.60(0.04)
	Non-verbal matrix reasoning	–	0.15(0.05)	0.12(0.05)	0.11(0.05)	–	0.13(0.05)	0.08(0.05)	0.07(0.05)
	Spatial working memory	–	0.27(0.08)	0.20(0.08)*	0.21(0.08)	–	0.18 (0.08)	0.18(0.08)	0.07(0.08)
	Visual tracing	–	0.16(0.08)	0.15(0.08)	0.14(0.08)	–	0.18(0.08)	0.17(0.08)	0.15(0.08)
	Numerosity comparison (ACC)	–	–	0.06(0.05)	0.03(0.06)	–	–	0.09(0.05)	0.03(0.06)
	Numerosity comparison (RT)	–	–	0.00(0.00)	0.00(0.00)	–	–	0.00(0.00)	0.00(0.00)
	Figure matching (ACC)	–	–	–	0.06(0.06)	–	–	–	0.12(0.05)
	Figure matching (RT)	–	–	–	0.00(0.00)	–	–	–	0.00(0.00)
		$R^2 = 0.042^*$	$\Delta R^2 = 0.125^*$	$\Delta R^2 = 0.022$	$\Delta R^2 = 0.013$	$R^2 = 0.043^*$	$\Delta R^2 = 0.083^*$	$\Delta R^2 = 0.028^*$	$\Delta R^2 = 0.040^*$
4	Age(months)	0.12(0.06)	0.07(0.06)	0.06(0.06)	0.05(0.06)	0.16(0.06)	0.12(0.06)	0.12(0.06)	0.13(0.06)
	gender	2.78(0.81)*	2.71(0.78)*	2.20(0.78)	1.88(0.78)	2.05(0.84)	1.67(0.81)	1.15(0.81)	0.68(0.80)
	Choice reaction time	–	0.00(0.00)	0.00(0.00)	0.00(0.01)	–	0.00(0.00)	0.00(0.00)	0.00(0.01)
	Mental rotation	–	0.08(0.04)	0.08(0.04)	0.08(0.04)	–	0.01(0.04)	0.00(0.04)	0.00(0.04)
	Non-verbal matrix reasoning	–	0.12(0.05)	0.09 (0.05)	0.08(0.05)	–	0.21(0.05)*	0.18(0.05)*	0.17(0.05)*
	Spatial working memory	–	0.35(0.08)*	0.29(0.08)*	0.27(0.08)*	–	0.33(0.08)*	0.29(0.08)*	0.27(0.08)*
	Visual tracing	–	0.14(0.07)	0.13(0.07)	0.11(0.07)	–	0.13(0.08)	0.12(0.07)	0.08(0.07)
	Numerosity comparison (ACC)	–	–	0.14(0.04)*	0.11(0.05)*	–	–	0.08(0.05)	0.12(0.04)
	Numerosity comparison (RT)	–	–	0.00(0.00)	0.00(0.00)	–	–	0.00(0.00)	0.00(0.00)
	Figure matching (ACC)	–	–	–	0.12(0.04)	–	–	–	0.02(0.05)
	Figure matching (RT)	–	–	–	0.00(0.00)	–	–	–	0.00(0.00)
		$R^2 = 0.038^*$	$\Delta R^2 = 0.123^*$	$\Delta R^2 = 0.025^*$	$\Delta R^2 = 0.018$	$R^2 = 0.031^*$	$\Delta R^2 = 0.116^*$	$\Delta R^2 = 0.029^*$	$\Delta R^2 = 0.042^*$
5	Age(months)	0.04(0.06)	0.04(0.06)	0.04(0.06)	0.04(0.06)	0.04(0.05)	0.07(0.05)	0.06(0.04)	0.06(0.04)
	gender	2.45(1.07)	2.20(1.05)	1.67(1.05)	1.47(1.04)	2.06(0.85)	1.95(0.83)	1.25(0.81)	0.96(0.77)
	Choice reaction time	–	−0.01(0.01)	0.00(0.01)	0.00(0.01)	–	0.01(0.01)	0.01(0.01)	0.01(0.01)
	Mental rotation	–	0.09(0.06)	0.07(0.06)	0.06(0.06)	–	0.09(0.05)	0.08(0.04)	0.06(0.04)
	Non-verbal matrix reasoning	–	0.17(0.07)	0.13(0.07)	0.12(0.07)	–	0.12(0.05)	0.06(0.05)	0.04(0.05)
	Spatial working memory	–	0.24(0.11)	0.21(0.11)	0.17(0.11)	–	0.21(0.09)	0.16(0.08)	0.10(0.08)
	Visual tracing	–	0.05(0.11)	0.00(0.11)	−0.01(0.11)	–	0.06(0.09)	0.03(0.08)	0.00(0.08)
	Numerosity comparison (ACC)	–	–	0.19(0.07)*	0.14(0.07)	–	–	0.14(0.04)	0.06(0.04)
	Numerosity comparison (RT)	–	–	0.00(0.00)	0.00(0.00)	–	–	0.01(0.00)	0.00(0.00)
	Figure matching (ACC)	–	–	–	0.11(0.06)	–	–	–	0.20(0.04)*
	Figure matching (RT)	–	–	–	0.00(0.00)	–	–	–	0.00(0.00)
		$R^2 = 0.016$	$\Delta R^2 = 0.075^*$	$\Delta R^2 = 0.027$	$\Delta R^2 = 0.023$	$R^2 = 0.018$	$\Delta R^2 = 0.079^*$	$\Delta R^2 = 080^*$	$\Delta R^2 = 0.086^*$

* $p < .05$, Bonferroni-corrected. ACC: accuracy; RT: reaction time.

characters and digits would measure the processing of visual form, phonological, and semantic information. The tasks could share the similar visual form processing.

Both reading comprehension and arithmetic computation are symbolic systems (letters or characters and digits) that involve spatial layouts of lines, not unlike those used in the geometric figure matching task (Basso et al., 1985; van Strien et al., 1989). Szwed, Cohen, Qiao, and Dehaene (2009) showed that the vertices of lines were one of the invariant visual features for line drawing of objects and symbols. The form perception for both reading comprehension and arithmetic computation might be associated with the orthographic processing of Chinese characters during reading comprehension or that of mathematics symbols during arithmetic computation (Grainger, Dufau, & Ziegler, 2016).

Reading Chinese might involve greater form perception than reading alphabetic languages because Chinese characters have ideographic origin and are consisted of intricate strokes. The Chinese character form (the combination of strokes, not unlike geometric figures) is the main information source during reading comprehension (e.g., Shen & Jiang, 2013; Wang et al., 2013) and hence orthographic awareness and general visual perceptual skills have been found to play an important role in the development of Chinese language abilities (e.g., Meng, Zhou, Zeng, Kong, & Zhuang, 2002; Kuo et al., 2014). Cross-linguistic behavioral studies have further found that visual skills are more predictive of reading ability in Chinese than in English readers (Huang & Hanley, 1995; Mcbride-Chang et al., 2005). Finally, cross-linguistic meta-analyses of neuroimaging data have revealed that Chinese readers show greater recruitment of their right inferior occipital and posterior fusiform regions than do English readers, suggesting that Chinese reading requires more visual processing (Bolger et al., 2005; Tan, Laird, Li, & Fox, 2005). The greater reliance to the processing of Chinese character forms for Chinese samples might extend to the processing of mathematics that is expressed with symbols. The possible cross-cultural difference in the reliance of form perception for reading comprehension and arithmetic computation should be directly investigated in future studies.

Previous studies have found the visual word form area (VWFA) is involved in language processing and the number form area (NFA) in numerical processing (Fernandes, Moscovitch, Ziegler, & Grady, 2005; Fias, Lammertyn, Caessens, & Orban, 2007; Grotheer, Ambrus, & Kovács, 2016; Grotheer, Herrmann, & Kovács, 2016; Shum et al., 2013; Thesen et al., 2012). These two brain regions' partial overlap in the ventral occipito-temporal cortex might underlie the significant correlations among arithmetic computation, reading comprehension, and visual form perception.

4.2. The nature of ANS acuity and its relation to visual form perception

In this study, we found that ANS acuity was correlated with arithmetic fluency after controlling for age, gender, and cognitive factors

Table 6

Hierarchical regression models predicting simple and complex arithmetic computation from age, gender, general cognitive processing, figure matching, and numerosity comparison.

Grade	Predictors	Simple subtraction				Complex subtraction			
		Step 1 *B(SE)*	*Step 2* *B(SE)*	*Step 3* *B(SE)*	*Step 4* *B(SE)*	*Step 1* *B(SE)*	*Step 2* *B(SE)*	*Step 3* *B(SE)*	*Step 4* *B(SE)*
3	Age(months)	0.13(0.05)	0.11(0.04)	0.10(0.04)	0.10(0.04)	0.13(0.05)	0.11(0.04)	0.10(0.04)	0.10(0.04)
	gender	2.57(0.88)	2.94(0.84)	2.45(0.84)*	2.38(0.85)	2.57(0.88)	2.94(0.84)	2.45(0.84)*	2.38(0.85)
	Choice reaction time	–	0.00(0.00)	0.00(0.00)	0.00(0.00)	–	0.00(0.00)	0.00(0.00)	0.00(0.00)
	Mental rotation	–	0.11(0.04)	0.10(0.04)	0.10(0.04)	–	0.11(0.04)	0.10(0.04)	0.10(0.04)
	Non-verbal matrix reasoning	–	0.15(0.05)	0.12(0.05)	0.11(0.05)	–	0.15(0.05)	0.12(0.05)	0.11(0.05)
	Spatial working memory	–	0.27(0.08)	0.20(0.08)*	0.21(0.08)	–	0.27(0.08)	0.20(0.08)*	0.21(0.08)
	Visual tracing	–	0.16(0.08)	0.14(0.08)	0.14(0.08)	–	0.16(0.08)	0.14(0.08)	0.14(0.08)
	Figure matching (ACC)	–	–	0.07(0.06)	0.06(0.06)	–	–	0.07(0.06)	0.06(0.06)
	Figure matching (RT)	–	–	0.00(0.00)	0.00(0.00)	–	–	0.00(0.00)	0.00(0.00)
	Numerosity comparison (ACC)	–	–	–	0.03(0.05)	–	–	–	0.03(0.05)
	Numerosity comparison (RT)	–	–	–	0.00(0.00)	–	–	–	0.00(0.00)
		$R^2 = 0.042$*	$\Delta R^2 = 0.125$*	$\Delta R^2 = 0.030$*	$\Delta R^2 = 0.005$	$R^2 = 0.043$*	$\Delta R^2 = 0.083$*	$\Delta R^2 = 0.066$*	$\Delta R^2 = 0.002$
4	Age(months)	0.12(0.06)	0.07(0.06)	0.06(0.06)	0.05(0.06)	0.16(0.06)	0.12(0.06)	0.13(0.06)	0.13(0.06)
	gender	2.78(0.81)*	2.71(0.78)*	2.09(0.78)	1.88(0.78)	2.05(0.84)	1.67(0.81)	0.73(0.79)	0.68(0.80)
	Choice reaction time	–	0.00(0.00)	0.00(0.00)	0.00(0.01)	–	0.00(0.00)	0.00(0.00)	0.00(0.01)
	Mental rotation	–	0.08(0.04)	0.08(0.04)	0.08(0.04)	–	0.01(0.04)	0.00(0.04)	0.00(0.04)
	Non-verbal matrix reasoning	–	0.12(0.05)	0.10(0.05)	0.08(0.05)	–	0.21(0.05)*	0.17(0.05)*	0.17(0.05)*
	Spatial working memory	–	0.35(0.08)*	0.31(0.08)*	0.27(0.08)*	–	0.33(0.08)*	0.28(0.08)*	0.27(0.08)*
	Visual tracing	–	0.14(0.07)	0.11(0.07)	0.11(0.07)	–	0.13(0.08)	0.08(0.07)	0.08(0.07)
	Figure matching (ACC)	–	–	0.14(0.04)*	0.12(0.04)*	–	–	0.13(0.04)*	0.12(0.04)
	Figure matching (RT)	–	–	0.00(0.00)	0.00(0.00)	–	–	0.00(0.00)	0.00(0.00)
	Numerosity comparison (ACC)	–	–	–	0.11(0.05)	–	–	–	0.02(0.05)
	Numerosity comparison (RT)	–	–	–	0.00(0.00)	–	–	–	0.00(0.00)
		$R^2 = 0.038$*	$\Delta R^2 = 0.123$*	$\Delta R^2 = 0.032$*	$\Delta R^2 = 0.011$	$R^2 = 0.031$*	$\Delta R^2 = 0.116$*	$\Delta R^2 = 0.070$*	$\Delta R^2 = 0.001$
5	Age(months)	0.04(0.06)	0.04(0.06)	0.05(0.06)	0.04(0.06)	0.04(0.05)	0.07(0.05)	0.06(0.04)	0.06(0.04)
	gender	2.45(1.07)	2.20(1.05)	1.68(1.04)	1.47(1.04)	2.06(0.85)	1.95(0.83)	1.09(0.77)	0.96(0.77)
	Choice reaction time	–	−0.01(0.01)	−0.01(0.01)	0.00(0.01)	–	0.01(0.01)	0.01(0.01)	0.01(0.01)
	Mental rotation	–	0.09(0.06)	0.07(0.06)	0.06(0.06)	–	0.09(0.05)	0.06(0.04)	0.06(0.04)
	Non-verbal matrix reasoning	–	0.17(0.07)	0.13(0.07)	0.12(0.07)	–	0.12(0.05)	0.05(0.05)	0.04(0.05)
	Spatial working memory	–	0.24(0.11)	0.17(0.11)	0.17(0.11)	–	0.21(0.09)	0.10(0.08)	0.10(0.08)
	Visual tracing	–	0.05(0.11)	0.03(0.11)	−0.01(0.11)	–	0.06(0.09)	0.02(0.08)	0.00(0.08)
	Figure matching (ACC)	–	–	0.11(0.06)	0.11(0.06)	–	–	0.21(0.04)*	0.20(0.04)*
	Figure matching (RT)	–	–	0.00(0.00)	0.00(0.00)	–	–	0.00(0.00)	0.00(0.00)
	Numerosity comparison (ACC)	–	–	–	0.14(0.07)	–	–	–	0.06(0.05)
	Numerosity comparison (RT)	–	–	–	−0.01(0.01)	–	–	–	0.00(0.00)
		$R^2 = 0.016$	$\Delta R^2 = 0.075$*	$\Delta R^2 = 0.036$*	$\Delta R^2 = 0.014$	$R^2 = 0.018$	$\Delta R^2 = 0.079$*	$\Delta R^2 = 0.160$*	$\Delta R^2 = 0.005$

* $p < .05$, Bonferroni-corrected. ACC: accuracy; RT: reaction time.

such as processing speed, attention, working memory, and general intelligence and that the above association was accounted for by visual form perception. These results replicated previous investigations (e.g., Cui et al., 2017; Wang et al., 2016; Zhou & Cheng, 2015; Zhou et al., 2015). More importantly, the current investigation also found that the ANS acuity was correlated with reading comprehension after controlling for the same factors mentioned above and again the association was fully explained by visual form perception. The two lines of evidence suggest the ANS acuity is not a domain-specific numerical ability but a domain-general perceptual ability.

Dot layouts in the ANS task is a type of visual form defined by the number of dots and their relations to one another. Indeed, the dots in dot arrays are similar to the vertices, which is the critical information for visual form perception (Szwed et al., 2009). Interestingly, some studies have shown that the close association between ANS and arithmetic computation persists even after controlling for visuospatial processes that involve visual form perception (e.g., Halberda et al., 2008; Keller & Libertus, 2015; Matthews, Lewis, & Hubbard, 2016; Zhang et al., 2016). For example, Halberda et al. (2008) controlled for various visuospatial processing tasks including visual working memory, visual motor integration, and spatial reasoning, and still observed a correlation between non-verbal number acuity and mathematical achievement. Zhang et al. (2016) observed a close correlation between ANS acuity and arithmetical computation even after controlling for spatial processing (as-measured by mental rotation task), as well as processing speed and intelligence. This inconsistency in results may be due to the varied degree of the involvement of visual form perception in visuospatial processing tasks. For example, the tasks for visual short-term memory and visual attention are highly dependent on visual form perception (e.g., Anobile et al., 2013; Zhou et al., 2015), whereas visuospatial tasks that focus on traits such as size, color, brightness, or location, are typically not correlated with ANS acuity or mathematical achievement (e.g., Piazza et al., 2010; Tibber, Greenwood, & Dakin, 2012; Zhou & Cheng, 2015). As shown in Tables 5 and 6, complex subtraction depends more on visual form perception and ANS than simple subtraction for each grade. The reason might be that complex subtraction has much complex visual presentation and relies more on visual perception.

4.3. *Visual form perception (similarly the ANS acuity) in developmental arithmetical computation and reading comprehension*

Although there was a close relation between visual form perception and achievement (reading comprehension and arithmetic computation) for fourth and fifth graders in the current investigation, the third graders showed a slightly different pattern: The scores for figure matching and numerosity comparison were correlated with scores of arithmetic computation but not with those of reading comprehension. One possible explanation is that the skill in reading comprehension is critical for the close relation between visual form perception and achievement

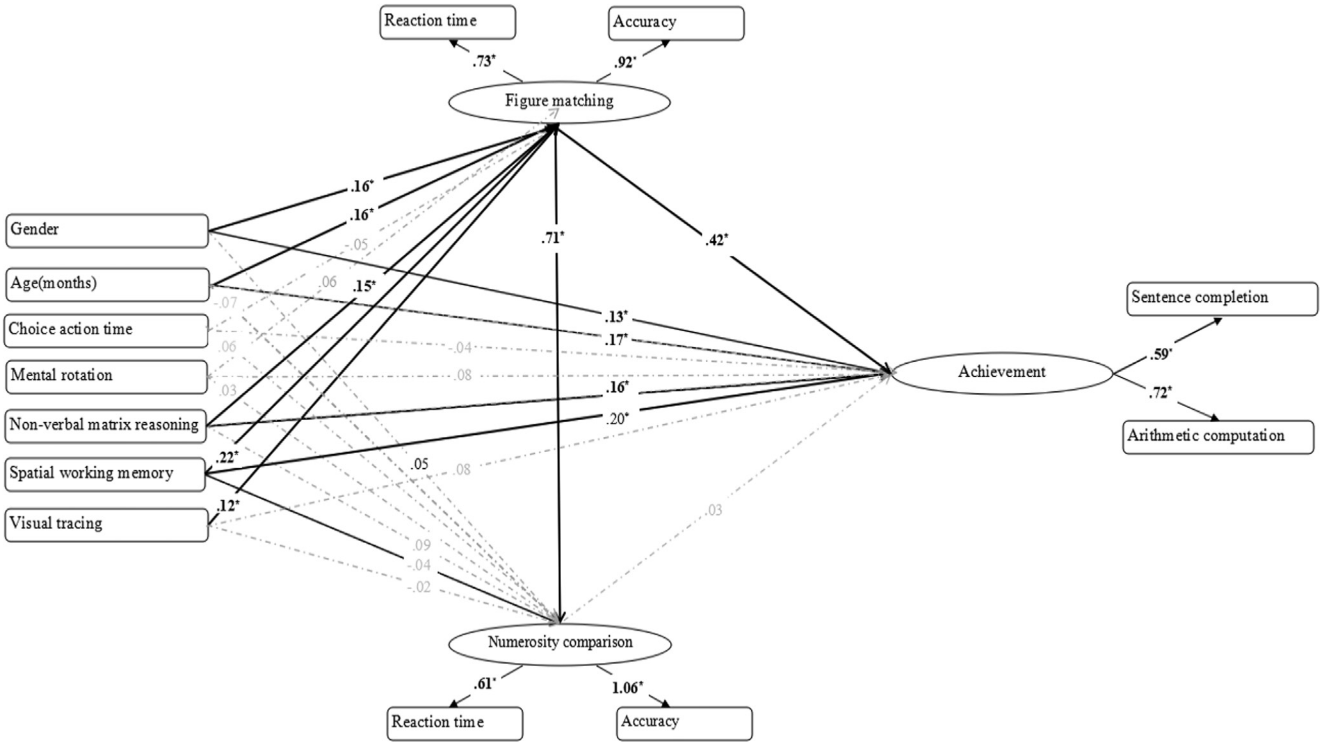

Fig. 3. Path model (path coefficients are standardized, N = 1099). $^*p < .05$, with Bonferroni correction.

(reading comprehension and arithmetic computation). Third graders were not skillful at reading as shown by the larger difference in reading comprehension between Grades 3 and 4 than the difference between Grades 4 and 5, so the third graders spent more time on reading comprehension and could not rely on rapid form perception.

Previous studies of younger children also did not show an association between ANS acuity and language processing for younger children, but those of older children did. Specifically, studies of children in kindergartens or lower grades of primary school did not show a significant correlation between ANS acuity and language processing (e.g., Anobile et al., 2013; Praet, Titeca, Ceulemans, & Desoete, 2013). For example, Anobile et al. (2013) found no significant relationship between Weber fraction of numerosity comparison and errors of text reading in 68 8–11-year-old children ($r = -0.008$, $p = .516$). Studies of children in Grade 3 or higher, however, found an association between ANS acuity and language ability (Träff, 2013; Wei, Lu, et al., 2012; Zhang et al., 2016). For instance, Träff (2013) showed a significant relation between ANS processing (subitizing and dot counting) and reading comprehension in students in Grades 4–6. Wei, Lu, et al. (2012) and Zhang et al. (2016) both showed a significant relation between numerosity comparison and word rhyming in children in Grades 3–6.

4.4. Limitations

Some limitations of the current investigation need to be discussed.

First, the figure matching task used to measure form perception might involve some other cognitive processes that were not sufficiently controlled for, such as processing speed and visuospatial attention. According to Cattell-Horn-Carroll (CHC) model (Schneider & Mcgrew, 2012), processing speed refers to the ability to perform simple repetitive cognitive tasks quickly and fluently. CHC model proposed several types of processing speed, including perceptual speed, rate-of-test-taking, number facility, reading speed, and writing speed. Perceptual speed refers to "speed at which visual stimuli can be compared for similarity or difference" (p. 119, Schneider & Mcgrew, 2012). Figure matching can measure the perceptual speed of form, which is assumed to be a shared mechanism for figure matching, numerosity comparison, reading comprehension, and arithmetic computation. However, general processing speed might also be the shared factor. Although we controlled for choice reaction time, it is considered as reaction and decision speed, different from processing speed in CHC model. Future work should use other tasks to assess general processing speed. In addition, this study only emphasized the perceptual speed of form, so it will be useful to assess and control for the perceptual speed of color, brightness, or size in future studies.

We did not directly control for visuospatial attention in the current investigation, although we probably controlled for it indirectly by including spatial short-term memory and visual tracing, both which involve visuospatial attention. In future studies, visuospatial attention can be directly measured with a visual search task (Franceschini, Gori, Ruffino, Pedrolli, & Facoetti, 2012).

Second, we used only one task each to measure reading comprehension and arithmetic computation. More tasks fully covering the two areas should be applied in future studies. For example, we can add paragraph comprehension to our sentence complete task. Paragraph comprehension is used more widely than sentence completion in the literature (e.g., Binder, Lee, & College, 2012; Träff, 2013; Träff et al., 2018). For example, Träff (2013) used a reading task with 12 short stories (20–150 words in length) and required children in grades 4–6 to read stories as fast and accurately as possible and then to answer a number of multiple-choice comprehension questions in relation to each story. Arithmetic computation was measured with subtraction in this study. Future studies should consider including addition, multiplication, and division. The different operations might elicit different mental processes (e.g.,Chiarelli, Menichelli, Zadini, & Semenza, 2011; Li et al., 2018; Zhou et al., 2006, 2007).

Third, the current study was correlational and hence cannot address the question of causality. To our knowledge, there has been little research to address the effects of short- or long-term instruction of visual form perception on either reading comprehension or arithmetic computation, which could be an important line research in the future.

Relatedly, previous studies involving the training of ANS have been shown to promote arithmetic performance (e.g., Obersteiner, Reiss, & Ufer, 2013; Park & Brannon, 2013). It is possible that an intervention involving visual processing could be helpful for the development of arithmetic ability, especially for children with developmental dyscalculia who have been found to show poor performance in visual form perception (Cheng et al., 2018; Zhou & Cheng, 2015).

4.5. Conclusion

In sum, this study found that reading comprehension and arithmetic computation may share a similar domain-general visual form perception. Due to its link to visual form perception, the ANS acuity could be a domain-general perceptual process that makes similar contributions to both reading comprehension and arithmetic computation.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cognition.2019.03.014.

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