



Bidirectional relationship between visual perception and mathematics performance in Chinese kindergartners

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Abstract

In this longitudinal study, 64 kindergartners (mean age at T1 = 4.69 ± 0.33 years; 34 girls) were tested on visual perception skills (T2 and T3) and mathematics performance (T1 to T3) with 6-month intervals between the three testing waves. Cross-lagged path analysis showed a bidirectional relationship between visual perception and mathematics performance from T2 to T3. Specifically, children's visual perception at T2 significantly predicted their mathematics performance at T3 ($B = 0.30$, $SE = 0.14$, $p = 0.03$, $\beta = 0.19$). Children's mathematics performance at T1 accounted for unique variance in visual perception at T2 ($B = 0.79$, $SE = 0.11$, $p < 0.001$, $\beta = 0.68$) and visual perception at T3 ($B = 0.27$, $SE = 0.12$, $p = 0.02$, $\beta = 0.32$). Their mathematics performance at T2 also significantly predicted visual perception at T3 ($B = 0.21$, $SE = 0.10$, $p = 0.04$, $\beta = 0.28$). Totally, they explained 61% of the variance in mathematics performance and 39% of the variance in visual perception at T3. The results highlight the developmental courses as well as the reciprocal facilitations between visual perception and mathematics performance in the kindergarten period.

Keywords Children · Longitudinal study · Mathematics performance · Visual perception · Reciprocal

The purpose of the current study was to address the bidirectional relationship between visual perception and mathematics performance in Chinese kindergartners. Some studies have established the relationship between visuospatial skills and mathematics performance (Cheng et al., 2020; Cheng & Mix, 2014; Hubbard et al., 2005; Mix et al., 2016; Simmons et al., 2012; Van Der Ven et al., 2013). Most previous research has focused on spatial skills, such as visuospatial working memory (Meyer

et al., 2010; Passolunghi & Mammarella, 2010; Sella et al., 2016), spatial attention (Geary et al., 2021), and spatial visualization (Durand et al., 2005; Yang et al., 2020), in relation to mathematics performance, but few of them have paid attention to the importance of visual perception in mathematics performance.

In recent years, studies have revealed that visual perception not only contributes to children's lower level math abilities, such as numerosity estimation and magnitude comparison (Cui et al., 2017), but also supports children's arithmetic fluency (Zhang et al., 2019). However, these studies emphasized the vitally unidirectional role of visual perception in mathematics performance. Mathematic activities were found to provide opportunities for children to practice basic cognitive skills, such as visual perception and visuomotor integration skills (Cameron et al., 2019; Guarino et al., 2013; Kim et al., 2018). Thus, we assume that mathematics performance may also have a bidirectional relationship with visual perception. This bidirectional relationship, however, has been sparsely investigated (see only Fung et al., 2020). In the present study, we tested visual perception and mathematics performance in kindergartners to determine whether longitudinal bidirectionality exists.

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Visual Perception and Mathematics Performance

Previous studies linking visuospatial skills with mathematics performance have focused mainly on spatial visualization or visuospatial working memory using complicated visual-spatial tasks, emphasizing the contributions of mental rotation (Gunderson et al., 2012) or visuospatial working memory (Allen et al., 2019; Dumontheil & Klingberg, 2012) to children's mathematics performance. For example, Mix and his colleague found that children and adults with better mental rotation skills also had better mathematics performance, such as structured counting and mental arithmetic (Cheng & Mix, 2014; Mix et al., 2016). Gunderson et al. (2012) also revealed that 5-year-olds' performance in mental rotation predicted their arithmetic skills three years later. Van de Weijer-Bergsma et al. (2015) investigated the relationship between visual-spatial working memory and mathematics performance at different ages during primary school. They found a significant predictive role of visual-spatial working memory in children's mathematics performance. However, these studies all used complex visuospatial tasks and mathematics measures, which makes the specific role of visual perception in mathematics very ambiguous.

Visual perception, as an important aspect of children's basic visuospatial process, refers to the ability to identify an object based on the structural relationships among its elements (Linn & Petersen, 1985; Zhang, 2016; Zhang et al., 2019). Existing studies have shown a positive relationship between visual perception and mathematics performance. For example, Cui et al. (2017) found that visual perception played a crucial role in teenagers' numerosity comparison, digit comparison, and exact computation. Zhou and his colleague (Cheng et al., 2020; Zhou & Cheng, 2015; Zhou et al., 2015) further proposed that visual perception was one of the possible reasons for the close relation between approximate number system acuity and symbolic mathematics performance. Zhang and Lin (2017) also demonstrated that the growth rate in visual perception significantly predicted preschoolers' mathematics performance measured with an arithmetic story problems test.

One explanation of the correlation between visual perception and mathematics performance is based on the processing of mathematics problems. Mathematics problems involve the rapid processing of complex visual stimuli, symbols, and signs. Visual perception reflects the ability to process relations between visual forms regardless of interference information. Visual perception is beneficial for children's mathematics performance through the mental number line that enables them to more effectively mentally represent and manipulate numerical information

(Gunderson et al., 2012; Thompson et al., 2013). In addition, visual perception may play the role of a "mental blackboard" that allows children to visualize numerical relations (Hawes & Ansari, 2020). Then, children can further perform and solve arithmetic problems. This explanation is also supported by neuroimaging evidence. Hubbard et al. (2005) revealed that similar neural circuits are activated in the performance of spatial perception tasks and numerical tasks and argued that magnitude processing relies on mental representation in a visual form.

Recently, an increasing number of studies have focused on investigating the relationship between visual perception and mathematics performance. However, most studies have focused mainly on primary and secondary school students (Cui et al., 2017; Zhang et al., 2019) and showed that the bidirectional relationship between visual perception and mathematics remains unclear. For example, Cameron and his colleague (Cameron et al., 2019; Kim et al., 2018) measured American children's mathematics performance with the Woodcock-Johnson Tests of Achievement and tested children's visuomotor integration, which included visual perception and fine motor skills. The results demonstrated longitudinal reciprocity between mathematics and visuomotor integration during kindergarten. In contrast, Fung et al. (2020) assessed Chinese children's mathematics, executive function, and visual-spatial skills (comprising visual perception and visual spatial skills) during their transition from kindergarten to primary school. They found that children's mathematics performance at prior time failed to predict their later executive function and visual-spatial skills.

The only relevant studies with younger children (Zhang, 2016; Zhang & Lin, 2017) have emphasized that visual perception contributes to younger children's mathematics performance. Only one longitudinal study (i.e., Fung et al., 2020) with Chinese kindergarten children examined the predictive role of mathematics performance in visual perception. However, the results failed to reveal the bidirectionality between visual perception and mathematics performance (Fung et al., 2020). Thus, more studies are needed to further reveal the relations between visual perception and mathematics performance, especially to determine the bidirectional relationship.

The Current Study

The present study mainly investigated the bidirectionality between visual perception and mathematics performance in Chinese kindergartners across three-time waves. It was hypothesized that a reciprocal association between visual perception and mathematics performance would be observed in kindergartners (Fig. 1). An arithmetic story problem task was used to measure younger children's mathematics performance at T1, T2, and T3 at six-month intervals. Arithmetic

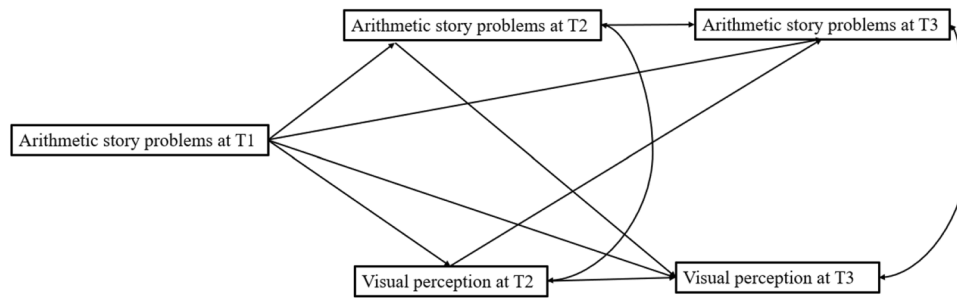


Fig. 1 A conceptual model of the cross-lagged relationships between children’s visual perception and mathematics performance with age and gender statistically controlled. *Note.* The model would conduct

with controlling for age and gender, which did not represent in the model for simplification; Children’s mathematics performance was measured by arithmetic story problems task

story problems involve the oral presentation of simple stories that require arithmetic solutions to children. To solve these problems, children have to understand the story and manipulate mental arithmetic schema with the present story (Yang & McBride, 2020). This task has been widely used (Fuchs et al., 2006; Yang & McBride, 2020).

In addition, visual perception has been usually measured with the adopted subtest of visual-perceptual skills from the Test of Visual-Perceptual Skills-Revised (Gardner’s, 1996). In each trial of the task, there are five simultaneously presented figures with identical configuration, which are combinations of multiple parts in the task. Children are required to identify the figure that was different in orientation from the other four. This visual perception task emphasizes children’s ability to process spatial relations between visual forms in spite of distracting information and does not involve transformations or manipulations, which is different from other complex spatial skills, such as spatial visualization or mental rotation (Zhang et al., 2019). Thus, it has been consistently used in young children to assess their ability of visual perception (Cui et al., 2017; Yang et al., 2021).

Methods

Participants

The participants were 68 Chinese-speaking children (34 girls). The mean age at the first assessment (in the autumn of K2) was 4.69 ± 0.33 years. The participants were recruited from a kindergarten in Jiangsu Province, China. All children were typically developing, and most of them came from middle-SES families. Informed consent was obtained from the children’s parents.

In the spring of K2 (T2), a total of 68 children (34 girls) participated in the second assessment. In the autumn of K3 (T3), 4 children (2 girls) did not participate in the study because they had transferred to other kindergartens. As a result, the total sample included 64 children (32 girls) who participated in the project completely.

Measures

Arithmetic Story Problems This task was used to measure children’s mathematics ability (Jordan et al., 2009; Yang & McBride, 2020). There were six addition and six subtraction story problems. The experimenter orally presented the questions. The children were asked to answer each question without time restrictions. For example, the experimenter said, “*Xiaoming has one apple, and Xiaoqing gives her two more apples. How many apples does Xiaoming have now?*” The children could take their time to arrive at the answer: “*Xiaoming has three apples now.*” The test was stopped when a child had four consecutive incorrect answers. The reliability coefficients for this task were 0.80 for T1, 0.75 for T2, and 0.77 for T3.

Visual Perception The adopted subtest of visual-perceptual skill from the Test of Visual-Perceptual Skills Revised (Gardner, 1996; Yang et al., 2020) was used to tap children’s visual perception ability. This subtest includes five black-and-white line drawings for each item. The children were asked to distinguish one picture that was different from the other four (see Fig. 2). When a child had five consecutive incorrect answers, the test was stopped. At the T2 wave, the task included 20 test items, which were arranged by difficulty level. At the T3 wave, there were 20 test items, including the last seventeen items from T2 and three more difficult item. The reliability coefficients for this task were 0.73 for T2 and 0.74 for T3.

Procedures

The participants were tested individually in a quiet room by one trained experimenter with a master’s degree. Performance on arithmetic story problems was measured at three waves from T1 to T3. Visual perception was tested at the T2 wave and the T3 wave. Visual perception at T1 was not tested because many children could not understand our instruction for most items at that time wave. The order of the testing was balanced. It took approximately ten minutes to

Fig. 2 One sample item of the visual perception task



finish all measures at T1 and fifteen minutes at T2 and T3. The children received a small gift after the testing.

Data Analysis

A cross-lagged model was conducted with Mplus 8.3 (Muthén & Muthén, 2010). The parameters of the models were estimated using robust maximum likelihood estimation and multiple imputation to handle missing data. The residuals of visual perception and performance on arithmetic story problems were set to correlate at each testing time.

The goodness of fit of the model was evaluated with five indicators: the chi-square statistic, comparative fit index (CFI), Tucker-Lewis index (TLI), root mean square error of approximation (RMSEA), and standardized root mean square residual (SRMR). A model is considered to have good fit when the chi-square statistic is not significant, the CFI and TLI are equal to or greater than 0.95, the SRMR is equal to or less than 0.08, and the RMSEA is equal to or less than 0.06 (Hu & Bentler, 1999).

Results

Correlations among Children’s Gender, Age, Mathematics Performance, and Visual Perception

Table 1 shows the descriptive statistics and correlations of all measures. Arithmetic story problems at T1 were significantly related to visual perception at T2 and visual perception at T3. In addition, significant correlations of arithmetic story problems with visual perception were observed at T2 and T3.

Children’s Performance on Mathematics Performance and Visual Perception

To investigate whether children’s performance on arithmetic story problems task and visual perception task would change over time, a repeated ANOVA with the time wave as an independent variable and children’s performance on the arithmetic story problem task as the dependent variable was conducted. The results showed a significant main effect of the time wave, $F(2, 62) = 46.43, p < 0.001, \eta^2 = 0.60$. That is, children performed significantly better on the arithmetic story problem task at T3 than that at T2 ($p < 0.001$). Meanwhile, children performed significantly better on the arithmetic story problem task at T2 than that at T1 ($p < 0.001$). In addition, a paired *t*-test with time waves as an independent variable and children’s performance on the visual perception task as the dependent variable was conducted. The results showed a significant main effect of the time wave, $t(63) = 15.03, p < 0.001$. Specifically, children performed significantly better on the visual perception task at T3 than that at T2 ($p < 0.001$). These results showed that there was a significant increase in children’s performance on arithmetic story problems from T1 to T3 and a significant increase in children’s visual perception from T2 to T3.

Bidirectional Relationship between Children’s Visual Perception and Mathematics Performance

We examined the cross-lag relations between children’s mathematics performance and visual perception when the covariate variable (i.e., age) was considered. Arithmetic

Table 1 Descriptive statistics and correlations for all variables

	Skewness	Range	<i>M</i> ± <i>SD</i>	1	2	3	4	5	6	7
1 Gender -		=	-	1						
2 Age1	0.21	=	4.69 ± 0.33	0.06	1					
3 SP1	1.31	0–10	2.30 ± 2.14	-0.02	0.34**	1				
4 VP2	-0.45	7–15	11.93 ± 1.89	-0.05	0.27*	0.34*	1			
5 SP2	0.82	0–12	4.14 ± 2.47	-0.04	0.34**	0.68***	0.39**	1		
6 VP3	-0.12	11–20	15.78 ± 1.82	-0.11	0.14	0.54***	0.39**	0.54***	1	
7 SP3	0.22	0–12	5.28 ± 2.96	0.05	0.36**	0.55***	0.46***	0.76***	0.52***	1

N = 64; Age 1 = age at T1; SP1 = Arithmetic story problems at T1; VP2 = Visual perception at T2; SP2 = Arithmetic story problems at T2; VP3 = Visual perception at T3; SP3 = Arithmetic story problems at T3. *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$

story problems at the three time waves were regressed on age. Similarly, visual perception at both times was also regressed on age. Gender was not included as a covariate variable because no significant correlations were found among gender, arithmetic story problems, and visual perception. This model shown in Fig. 3 demonstrated a good fit to the data, $\chi^2(2, N = 64) = 2.56, p = 0.28, CFI = 0.99, TLI = 0.97, RMSEA = 0.06$ (90% CI = 0.24–0.54), SRMR = 0.04.

Results revealed that the cross-lagged relationships were significant between T2 and T3. For the covariate, the age explained was significantly associated with arithmetic story problems at T1 ($B = 2.23, SE = 0.77, p < 0.01, \beta = 0.34$). Moreover, visual perception at T2 significantly predicted arithmetic story problems at T3 ($B = 0.30, SE = 0.14, p = 0.03, \beta = 0.19$). Arithmetic story problems at T2 accounted for unique variance in visual perception at T3 ($B = 0.21, SE = 0.10, p = 0.04, \beta = 0.28$). In addition, arithmetic story problems at T1 also significantly predicted arithmetic story problems at T2 ($B = 0.79, SE = 0.11, p < 0.001, \beta = 0.68$), visual perception at T2 ($B = 0.26, SE = 0.11, p = 0.02, \beta = 0.30$), and visual perception at T3 ($B = 0.27, SE = 0.12, p = 0.02, \beta = 0.32$). Besides, arithmetic story problems at T2 explained unique variance in arithmetic story problems at T3 ($B = 0.80, SE = 0.13, p = 0.004, \beta = 0.67$). In total, the model explained 61% of the variance in arithmetic story problems at T3 ($p < 0.001$) and 39% of the variance in visual perception at T3 ($p < 0.001$).

Discussion

The present study investigated the bidirectionality between visual perception and mathematics performance among Chinese kindergarten children. The result revealed that

children’s arithmetic story problem solving ability at T1 accounted for unique variance in their visual perception at T2. Moreover, children’s visual perception and their arithmetic story problem solving were reciprocally associated with each other from T2 to T3. The results not only revealed the unique role of the domain-specific cognitive skill (i.e., mathematics) in the domain-general cognitive skill (i.e., visual perception), but also highlight the reciprocal facilitations between visual perception and mathematics performance in the kindergarten period.

Bidirectional Relationship between children’s Visual Perception and Mathematics Performance

The current findings revealed that children with higher-level visual perception ability at T2 were more capable of solving arithmetic story problem at T3. Visual perception measures children’s ability to process the spatial relation between visual forms (Zhang et al., 2019). Arithmetic story problem solving includes the perception of numbers, an understanding of number relations, and arithmetic manipulation using a “mental blackboard” (Fuchs et al., 2006; Jordan et al., 2009; Yang & McBride, 2020). Many mental processes involving arithmetic story problem solving require visual perception. For instance, when listening to teachers’ presentation of arithmetic problems, such as two apples plus one apple, children must imagine this equation, possibly with mental written Arabic numerals on their “mental blackboards” (Zhang & Lin, 2015).

Specifically, recognizing the Arabic code of numbers requires visual perception (Dehaene, 1992). The basis of arithmetical computation that involves the extraction of numerical information and structural relationships requires visual perception (Wang et al., 2016; Zhang et al., 2019).

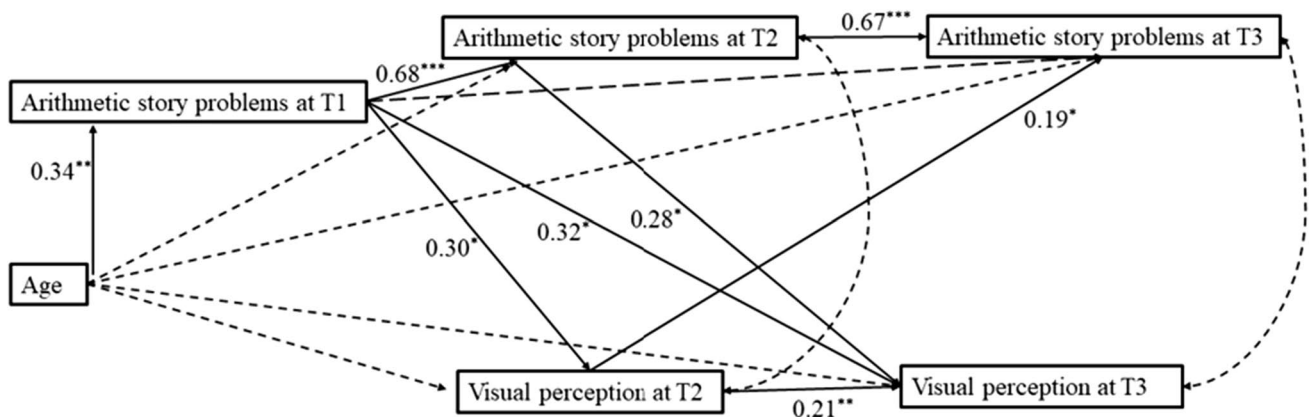


Fig. 3 The cross-lagged panel model of children’s arithmetic story problems and visual perception. Note. Standardized path estimates of the cross-lagged model. Solid lines represent significant paths. Dashed lines represent nonsignificant paths. The model fit is sat-

isfactory, $\chi^2(2, N = 64) = 2.56, p = 0.28, CFI = 0.99, TLI = 0.97, RMSEA = 0.06$ (90% CI = 0.24–0.54), SRMR = 0.04. *** $p < 0.001, ** p < 0.01, * p < 0.05$

Zhang and his colleague also indicated that early variations in visual perception was associated with preschool children's later variations in number competence, such as number comparison, non-symbolic arithmetic, written arithmetic, and word problems (Zhang, 2016; Zhang & Lin, 2015, 2017). They proposed explanations from a space-number relation perspective. Specifically, visual perception contributes to the recognition of a spatial layout of numbers despite a representational model of numbers, which could in turn aid children in understanding the numerical relations in arithmetic story problems. More importantly, this finding expands the existing literature by emphasizing the facilitative role of visuospatial skills in children's mathematics performance (Allen et al., 2019; Critten et al., 2018; Holmes et al., 2008; Lowrie et al., 2017; Zhang & Lin, 2015), especially showing that even very basic visual-spatial skills play vital roles in children's mathematics performance.

Importantly, our findings suggested that children's mathematics performance at each time point could significantly contribute to their visual perception at the next time point. Besides, children's mathematics performance at T1 was significantly associated with their visual perception at T3. There are two possible explanations. On the one hand, children with higher mathematics scores in early kindergarten have more math manipulation and learning experience than those with lower mathematics scores (Guarino et al., 2013; Kim et al., 2018). They have more practice distinguishing visual elements and identifying structural relationships. On the other hand, brain plasticity studies have shown that formal education modifies brain function and structure (Karmarkar & Dan, 2006). Basic cognitive skills become more fluent and consolidated with frequent and deliberate practice (Lin et al., 2016). Noble et al. (2007) found that activities (i.e., mathematical story problem solving) in day-care or preschool account for significant variance in children's visual skills and provide evidence of plasticity of visual skills. Children's visual perception is strengthened to meet the demand for solving arithmetic problems. Thus, arithmetic problem-solving experiences in kindergarten provide a routine practice that influences children's visual perception.

Furthermore, the common neural network underlying the association of visual perception with arithmetic problem solving also supports the present findings. Neuroimaging evidence has shown that understanding the nature of numbers and processing numbers require the visual cortex, which is also an area responsible for visual perception (Rinsveld et al., 2020). Dumontheil and Klingberg (2012) showed that children's activities in the intraparietal sulcus (IPS) during numerical relationship representation predicted their mathematics performance, which has also been implicated in visuospatial processes. In line with these findings, arithmetic story problem solving involves number processing and the

representations of numerical relations, which will promote children's visual perception skill in early kindergartners.

There exist several possible limitations in the current study. First, children's visual perception and mathematics performance were each only assessed with a single measure. Although the two measures were selected because they are widely used to tap each corresponding skill, the use of a single measure might not have fully tested the construct of each given variable. Second, other possible confounding factors, such as intelligence, language, and processing speed, should have been statistically controlled to determine the unique relationship between visual perception and mathematics performance. Third, considering the sample size of this study is quite small with very young children, a larger number of participants are suggested to be included to validate the findings while involving other control variables. Lastly, children's visual perception at T1 was not measured in the present study because most participants at that time could not understand the task. Future work is needed to develop more suitable measures for children at younger ages.

Conclusions and Implications

Nevertheless, by longitudinally tracking kindergarten children in mainland China across different periods, our findings revealed the reciprocal relationship between visual perception and children's mathematics and expanded the understanding of the developmental courses of visual perception and Chinese children's mathematics performance. This study contributes to the existing literature on the linkage between fundamental cognitive skills and higher-level cognitive skills, and clarifies previous arguments about how visual perception is associated to mathematics developmentally (e.g., Cui et al., 2017; Fung et al., 2020). Practically, the results suggest that the use of visual perception to retrieve the computation problems from stories may be very important for the latter's development and encourage us to consider the possible effects of story problem solving on the acquisition of visual perception. Moreover, the reciprocal promotions of visual perception and mathematics skills keep stable, indicating the reciprocal facilitations between visual perception and mathematics performance in the kindergarten period.

Author Contributions Yu and Chen were mainly responsible for data analysis and writing the paper. Xie contributed to data collection. Yang led the project and also made revision to the paper.

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Data Availability The datasets generated during the current study are available from the corresponding author on reasonable request.

Declarations

Ethical Approval All procedures were approved by the Academic Ethics Committee of the University.

Informed Consent Written informed consent was obtained from each child's parents.

Conflict of Interest All authors declare that there is no conflict of interest.

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