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Short-term numerosity training promotes symbolic arithmetic in children with developmental dyscalculia: The mediating role of visual form perception

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Abstract

Studies have shown that numerosity-based arithmetic training can promote arithmetic learning in typically developing children as well as children with developmental dyscalculia (DD), but the cognitive mechanism underlying this training effect remains unclear. The main aim of the current study was to examine the role of visual form perception in arithmetic improvement through an 8-day numerosity training for DD children. Eighty DD children were selected from four Chinese primary schools. They were randomly divided into the intervention and control groups. The intervention group received training on an apple-collecting game, whereas the control group received an English dictation task. Children's cognitive and arithmetic performances were assessed before and after training. The results showed that the intervention group showed a significant improvement in arithmetic performance, approximate number system (ANS) acuity, and visual form perception, but not in spatial processing and sentence comprehension. The control group showed no significant improvement in any cognitive ability. Mediation analysis further showed that training-related improvement in arithmetic performance was fully mediated by the improvement in visual form perception. The results suggest that short-term numerosity training enhances the arithmetic performance of DD children by improving their visual form perception.

1 | INTRODUCTION

Developmental dyscalculia (DD) is a disorder in the development of mathematical abilities that afflicts approximately 5% of school-age children (Butterworth, Varma, & Laurillard, 2011). Children with DD are substantially below expectation in their arithmetical abilities given their chronological age, measured intelligence, and participation in age-appropriate education. They show a core deficit in the processing of numerosity or the approximate number system (ANS; Butterworth et al., 2011; Cheng, Xiao, Chen, Cui, & Zhou, 2018; De Smedt, Noël, Gilmore, & Ansari, 2013; Dehaene, Molko, Cohen, & Wilson, 2004; Landerl, Bevan, & Butterworth, 2004; Mazzocco, Feigenson, & Halberda, 2011; Mussolin, Mejias, & Noël, 2010; Piazza et al., 2010; Rousselle & Noël, 2007).

A number of studies have shown that numerosity-based training could improve arithmetic performance of healthy adults (Park & Brannon, 2013, 2014), typically developing children (Hyde, Khanum, & Spelke, 2014), and children with DD (Wilson, Revkin, Cohen, Cohen, & Dehaene, 2006). Specifically, Park and Brannon (2013, 2014) found that adults who received about 5 hours of training on non-symbolic approximate addition or subtraction showed improvements in both ANS acuity and symbolic arithmetic speed and accuracy. Park and Brannon (2013) further found that individual differences in arithmetic performance improvement were significantly correlated with individual differences in changes in ANS acuity. Hyde et al. (2014) administered a brief ANS training (e.g., a non-symbolic numerical comparison and addition task) with only 60 training trials to typically developing 6- to 7-year-old children. Their results demonstrated that the intervention was effective in reducing reaction time for exact arithmetic problems. Finally, in an earlier intervention study, Wilson et al. (2006) provided non-symbolic numerical comparison training to children with DD and found improvements in accuracy rates in subtraction.

Although the one intervention study targeting numerosity has proved its effectiveness for children with DD (Wilson et al., 2006), the cognitive mechanism underlying the training effect on arithmetic performance is still unclear. Based on research with typically developing children, there exist two perspectives. One viewpoint suggests that ANS and symbolic mathematics share a generalized magnitude system (Hyde et al., 2014; Landerl et al., 2004; Park & Brannon, 2014). The other viewpoint suggests that fundamental cognitive abilities underlie the representations of both symbolic mathematics and non-symbolic numbers (Cheng et al., 2018; Fuhs & McNeil, 2013; Holloway & Ansari, 2010; Zhou & Cheng, 2015). Visual form perception measured with a geometric figure matching task has emerged as a critical shared cognitive mechanism of non-symbolic numbers and symbolic arithmetic (Cui, Zhang, Cheng, Li, & Zhou, 2017; Wang, Sun, & Zhou, 2016; Zhou, Wei, Zhang, Cui, & Chen, 2015). For example, Zhou et al. (2015) showed that visual form perception could fully account for the association between ANS acuity and arithmetic performance. Cui et al. (2017) also found that ANS acuity was associated with symbolic number comparison and arithmetical computation, and that visual form perception was the cognitive mechanism responsible for this association. Finally, Cheng et al. (2018) and Zhou and Cheng (2015) found that children with DD had deficits in both visual form perception and ANS concurrently, and that the deficit in visual form perception accounted for the ANS deficit. Based on the above literature, the current study hypothesized that the low-level visual form perception is the cognitive mechanism underlying the effect of numerosity training on arithmetic performance in children with DD. Visual form perception, assessed by the figure matching task, is believed to reflect visual perceptual speed as a type of processing speed according to the Cattell–Horn–Carroll (CHC) model (Proctor, 2012).

Research Highlights

- Previous studies have demonstrated that children with developmental dyscalculia (DD) show a core deficit in the processing of numerosity or the approximate number system (ANS). The present study offers evidence that short-term numerosity training enhances arithmetic performance for DD children by improving visual perception.
- Compared to the control group (English dictation training), the numerosity-training group, who received training with a numerosity-based apple-collecting game, showed significant improvements in arithmetic performance, ANS acuity, and visual form perception. Further analysis showed that visual form perception could account for the improvement in symbolic arithmetic
- These findings suggest that non-symbolic numerosity training could improve the arithmetic performance of children with DD, and visual form perception is the underlying cognitive mechanism in this training effect.

Children with DD were identified from a large sample of elementary school children, and they were randomly assigned into two training conditions: numerosity training and English dictation training. The children were tested in arithmetic and cognitive performance before and after the 8-day training. If visual form perception plays an important role in the effect of numerosity training on symbolic arithmetic, we would expect the numerosity training to enhance visual form perception as well as symbolic arithmetic and ANS acuity. More importantly, we would expect that the expected improvement in visual form perception would account for the expected improvement in symbolic arithmetic and ANS acuity.

2 | METHODS

2.1 | Participants

A Web-based testing battery was used to select the participants from among third through fifth graders from four primary schools in Beijing and Shijiazhuang, China. These schools agreed to participate in the cognitive assessment project and subsequent training. According to the definition and screening criteria of dyscalculia (Butterworth et al., 2011; Landerl et al., 2004), children with DD were defined as having scores lower than the 7th percentile (−1.50 *SD*) in arithmetic performance but above the 25th percentile (−0.67 *SD*) in Raven's Progressive Matrices. Eighty children were selected, and their parents agreed to allow them to participate in the current study. All participants were native Chinese speakers, with normal or corrected-to-normal vision and hearing. They had no neurological or psychiatric disorders.

Following previous studies of cognitive training with children with DD (Layes, Lalonde, Bouakkaz, & Rebai, 2018; Looi et al., 2017), the present study employed a randomized controlled design. Participants were randomly divided into two groups: the intervention group (n = 40) receiving numerosity training with an apple-collecting game and the control group (n = 40) receiving English dictation training. After excluding data that were beyond three standard deviations from the mean, the final sample for the intervention group included 38 participants (22 males and 16 females, mean age = 9.53 years, SD = 0.73 years). No participant was excluded from the control group (27 males and 13 females, mean age = 9.55 years, SD = 0.85 years). The current investigation was approved by the State Key Laboratory of Cognitive Neuroscience and Learning at Beijing Normal University.

2.2 | Training program

Following the principles of the constructionist pedagogical theory (Laurillard, 2016) that emphasize the foundational concepts and principles about the structural properties of numbers, the numerosity training specifically targeted the core deficit identified in the neuroscience of dyscalculia (Butterworth et al., 2011), by training the mental representation of numerosities, the relationship among numerosities, and their relationship with numerical symbols.

As mentioned earlier, previous training studies targeting numerosity have been effective for both typically developing children (Hyde et al., 2014) and children with DD (Wilson et al., 2006). Because some studies have shown that only in the rapidly presented numerosity paradigm does numerosity processing have a close association with arithmetic performance (Halberda, Ly, Wilmer, Naiman, & Germine, 2012; Lourenco, Bonny, Fernandez, & Rao, 2012; Wei, Yuan, Chen, & Zhou, 2012), the training program in the present study used a computerized apple-collecting game (see Figure 1) that was modeled closely after the rapid non-symbolic numerosity (i.e., dots) comparison task (Cheng et al., 2018; Cui et al., 2017; Halberda, Mazzocco, & Feigenson, 2008; Wang et al., 2016; Zhou et al., 2015).

FIGURE 1 The computerized apple-collecting game used as the intervention. The player was asked to manipulate the mouse to move a pig in the screen to catch as many apples as possible, regardless of their size. To get the highest score, participants needed to quickly determine which bunch contained more apples and avoided the bombs. There were 12 levels of difficulty. After the player received a preset target score at a given level, he or she would be allowed to play at the next level

In the training program on an apple-collecting game, the target stimuli are similar to dot arrays presented rapidly. There were apples mixed in with bombs (i.e., distractors) falling randomly from the apple tree at the top of the computer screen. The apples fell in bunches, ranging from a single apple to 12 apples in a bunch. The apple bunches were drawn in a similar way as dot arrays, ranging from 1 to 12 (corresponding to 1 to 12 dots). There were two types of bunches; one type had the same total area of all apples in the same bunch combined, and the other had apples whose average size (area) was the same (see Panel (a) and (b) in Figure 2). The procedure used to control for the total and average areas was the same as that for dot arrays in previous studies (Cheng et al., 2018; Cui et al., 2017; Halberda et al., 2008; Wang et al., 2016; Zhou et al., 2015). The apples were either yellow or red; yellow apples were worth 30 points each, and red apples were worth 10 points each. Each bomb would cost 100 points. There was auditory feedback: a "bing" for getting the apples and a score gain (shown at the upper left of the screen), and a "bong" for hitting a bomb and a score loss. The participants' task was to use the mouse to move a pig to collect as many apples as possible, regardless of their size. That way, the participants would focus on the target bunches with a greater number of apples and try to avoid the bombs, instead of randomly moving the mouse. The falling apple bunches that are similar to dot arrays should have

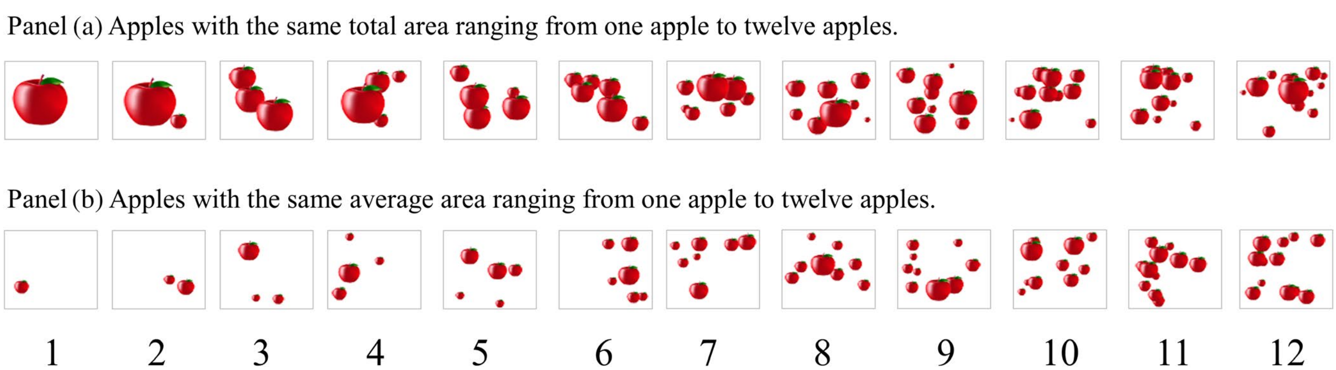

FIGURE 2 The sample bunches of apples for the apple-collecting game. There were two types of bunches; one set had the same total area of all apples in the same bunch combined (Panel a), and the other had apples whose average area was the same (Panel b)

encouraged participants' rapid processing of numerosity. There were 12 levels of difficulty (Level 1 as the easiest and Level 12 as the most difficult) as a function of the number of apples falling, their speed, and the preset score to pass each level.

For the control group, the participants performed an English dictation task, in which they were asked to listen to English sentences that omitted a word, and found the correct word to fill in the blank. All words used in this English training came from primary school textbooks.

The trainings were programmed using applications available on the Web-based system www.dweipsy.com/lattice (Cheng et al., 2013; Wei, Lu, et al., 2012). Participants' responses, including the total score for the apple-collecting game and accuracy in English dictation, were automatically recorded.

2.3 | Pre- and post-intervention tasks

Cognitive tasks, including mental rotation, sentence completion, simple subtraction, numerosity comparison, and figure matching, were administered before and immediately after the intervention (see the stimulus examples in Figure 3).

The *mental rotation* task was adapted from a previously described task (Vandenberg & Kuse, 1978). The task was used to measure visuospatial processing ability. Previous studies have shown that visuospatial processing is critical for mathematical performance (Verdine et al., 2014). We wanted to control for spatial processing in order to observe the effect of training on visual form perception. The task has been used in previous studies (Wei, Yuan, et al., 2012), with split-half reliabilities from 0.87 to 0.91. On each trial, one three-dimensional image was presented on the upper part of the screen, and two more were presented on the lower portion of the screen. Participants were asked to choose which image from the bottom of the screen matched the image at the top after rotation. The non-matching image was a rotated mirror image of the target. Participants pressed the "Q" key to choose the image on the left and the "P" key to choose the image on the right. The mental rotation test consisted of 180 trials. This was a time-limited (3 min) test. The rotation angles of the matching images ranged from 15° to 345°, in intervals of 15°. On each trial, the stimuli remained on the screen until the participant responded by pressing the "P" or "Q" keys.

The *sentence completion* task was used to measure sentence comprehension (Wei, Yuan, et al., 2012) and to examine if the numerosity training had a domain-specific effect on the arithmetic. The task has been used in previous studies, with split-half reliabilities from 0.90 to 0.92. The materials used in this task were adapted from the textbooks used in primary schools, 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 it. The stimulus remained on the screen until the participants responded.

Simple subtraction was used to measure arithmetic performance. We used simple subtraction to assess arithmetic ability for several reasons. Because this was a training study involving repeated testing, we had to select a brief test. Of the four arithmetic operations (addition, subtraction, multiplication, and division), multiplication and division involve rote memory of the multiplication table so they are not the ideal operations to use to assess calculation fluency (Zhou et al., 2007). Moreover, they are somewhat difficult for the younger participants included in this study (third graders). Indeed, other studies of children of similar age have used addition and subtraction to assess arithmetic ability (Landerl et al., 2004; Rousselle & Noël, 2007). Because addition and subtraction share a common mechanism of visuospatial memory (Zhou & Cheng, 2015) and are highly correlated with each other in previous studies (Artemenko, Pixner, Moeller, & Nuerk, 2018; Cui et al., 2016) as well as in our own unpublished results (r = .77, Cui et al., Submitted), we needed only one of the two operations. Finally, we selected subtraction over addition because the former is most frequently included in previous studies of children with DD (Geary, Saults, Fan, & Hoard, 2000; Kucian et al., 2011; Landerl et al., 2004; Mussolin et al., 2010; Rousselle & Noël, 2007; Wilson et al., 2006). The simple subtraction task has been used in previous studies, with split-half reliabilities ranging from 0.93 to 0.96 (Wei, Lu, et al., 2012). It included 92 simple subtraction problems (e.g., 6 – 2, 17 – 8); the minuends were 18 or smaller, and the differences were single-digit numbers. Two candidate answers were presented beneath each problem. The participants were asked to press the "Q" key to choose the answer on the left and the "P" key

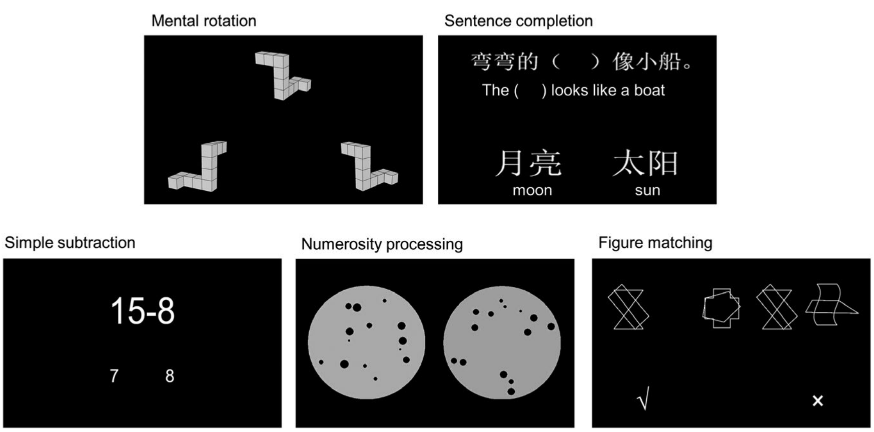

FIGURE 3 Illustration of pretest and posttest tasks used in the experiment: mental rotation, sentence completion, simple subtraction, numerosity processing, and figure matching

to choose the answer on the right. For this task, each incorrect candidate answer was within the range of the correct answer plus or minus 3 (i.e., 1, 2, or 3). This was a time-limited (2 min) task.

The *numerosity comparison* task was used to assess the ability to process non-symbolic number quantities. Two sets of dots of varying sizes were presented simultaneously on the screen, and participants were asked to judge which array contained more dots while ignoring the sizes of individual dots. Participants pressed "Q" if they thought the array on the left contained more dots, and "P" if they thought the array on the right contained more dots. The number of dots in each set varied from 5 to 32. The two dot arrays for each trial were presented for 200 ms. After the participants responded, there was a 1-second blank screen before the next trial. The test consisted of 120 trials. For half of the trials, the total combined area of all dots in each set was controlled to be the same. For the other half of the trials, the average area of all dots in each set was controlled to be the same. This procedure of controlling the total and average areas was similar to that used by Halberda et al. (2008). The ratios for the two dot arrays ranged from 1.2 to 2.0. The trials were tested in three sessions, with 40 trials for each session. The children were asked to complete all trials.

The *figure matching* task was adapted from the identical picture test in the Manual for the Kit of Factor-Referenced Cognitive Tests (Ekstrom, French, Harman, & Dermen, 1976). According to the CHC model (Proctor, 2012) and relevant empirical data (Mclean, Stuart, Coltheart, & Castles, 2013), visual figure matching is the ideal task to assess perceptual speed. The task has been used in previous studies, with split-half reliabilities ranging from 0.86 to 0.96 (Zhou et al., 2015). There were 120 trials, each containing one target picture on the left side and three candidate pictures on the right. Each picture consisted of two simple geometric figures constructed from 150 abstract line figures. For each trial, four pictures were presented simultaneously for 400 ms. Each picture had horizontal and vertical visual angles of 2.8°. The four pictures extended to a visual angle of about 15°. The participants were asked to fixate at the center of the screen in the beginning of the experiment, although no fixation sign was presented. The participants were asked to judge whether the picture on the left side was the same as any of the pictures on the right side. The task included 120 trials with 60 matched trials and 60 non-matched trials, which were grouped into three 40-trial sessions. The participants were asked to complete all trials.

For all cognitive tasks, we calculated corrected scores by subtracting the number of incorrect responses from the number of correct responses in order to control for the effect of guessing (Cirino, 2011). All the tasks were administered using a Web-based psychological system (Cheng et al., 2013; Wei, Yuan, et al., 2012).

2.4 | Procedure

All data were collected from October 2013 to June 2014. All participants were tested and given the daily training in a computer classroom at their respective schools. The classroom was monitored by two or three experimenters. Instructions were given and a practice session was completed before each formal testing. The tasks were administered in the same order for all children. Students' responses were automatically recorded and sent over the Internet to a server located in the laboratory at Beijing Normal University.

Participants were assigned randomly to the intervention and control conditions. The intervention group completed the apple-collecting game training, whereas the control group completed English dictation. After completing 30-s practice trials, all participants were given the formal training task. Similar to other short-term training studies (Hyde et al., 2014; Looi et al., 2017), we ensured that the training was intensive enough for it to show effectiveness. The training session lasted for 15 min and was carried out once per day for 8 days during school hours (i.e., no training on the weekends). Therefore, the participants in each group were trained in eight different sessions that took place within a 2-week period.

2.5 | Data analysis

Data were analyzed using three-way ANOVA with task (mental rotation, sentence completion, simple subtraction, numerosity comparison, and figure matching) and testing phase (pretest before intervention and posttest after intervention) as the within-subjects variables, and group (intervention vs. control) as the between-subjects variable. All p values for the main effects and interactions were corrected using the Greenhouse–Geisser method. Significant effects were followed up by pairwise contrasts. The effect size indexed by Cohen's d was used (Cumming, 2013).

We then conducted a mediation analysis with the bootstrapping method (Preacher & Hayes, 2008) to investigate the contribution of improvement in visual form perception in mediating the relation between numerosity training (Yes/No) and improvement in symbolic arithmetic.

3 | RESULTS

Figure 4 shows the results from the different tests by group and by testing phase. The three-way ANOVA showed a significant main effect of task and testing phase, F (4, 304) = 39.13, $p < .001$, $\eta^2 = 0.340$; F (1, 76) = 19.22, $p < .001$, $\eta^2 = 0.202$. The main effect of group attained marginal significance, F (1, 76) = 3.85, $p = .053$, $\eta^2 = 0.048$. We also found a significant task × testing phase interaction, F (4, 304) = 3.93, $p < .01$, $\eta^2 = 0.049$, a significant testing phase × group interaction, F (1, 76) = 9.24, $p < .01$, $\eta^2 = 0.108$, and a significant task × testing phase × group interaction, F (4, 304) = 2.62, $p < .05$, $\eta^2 = 0.033$. Further analysis revealed that the intervention group showed a significant interaction of task and phase, F (4, 304) = 6.17, $p < .001$. Simple effect analysis showed that the intervention group showed significant improvements in subtraction, F (1, 76) = 9.67, $p < .01$, numerosity comparison, F (1, 76) = 10.46, $p < .01$, and figure matching, F (1, 76) = 19.51, $p < .001$. The effect sizes between the pre- and post-intervention test were

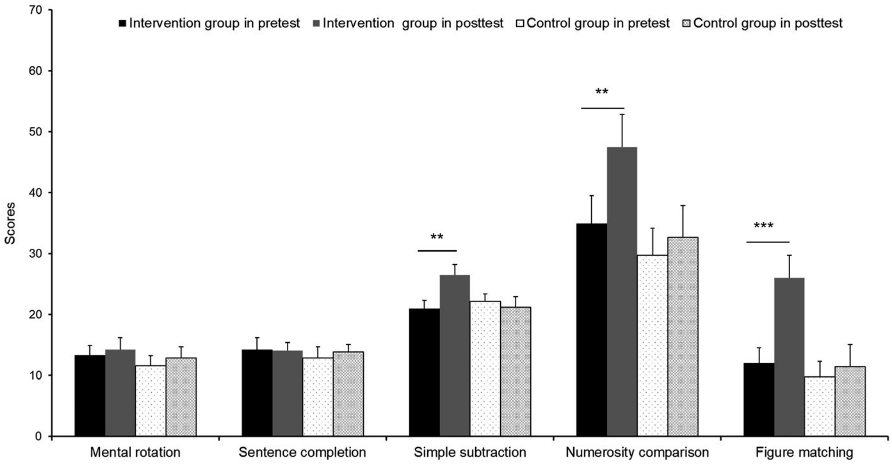

FIGURE 4 The scores of cognitive tasks in pretest and posttest for the intervention group and control group

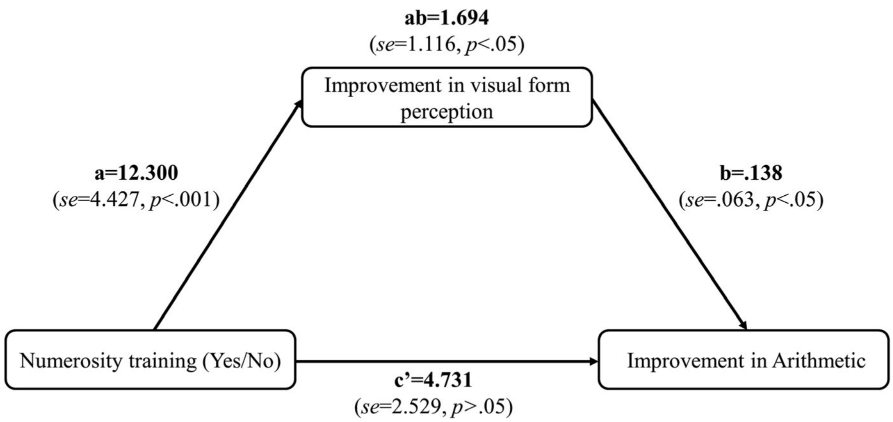

FIGURE 5 Improvement in visual perception mediated the training effect on symbolic arithmetic

d = 0.60 for subtraction, 0.39 for numerosity comparison, and 0.70 for figure matching. The intervention group had similar scores between the pre- and post-intervention tests for two other tasks: F (1, 76) = 0.30, p = .588, for mental rotation; and F (1, 76) = 0.02, p = .962, for sentence completion. For the control group, there was no significant interaction of task and phase: F (4, 304) = 0.28, p = .891.

For the mediation analyses, we tested whether the improvement in figure matching mediated the relation between numerosity training (Yes/No) and improvement in symbolic arithmetic. It showed that the training-related improvement in symbolic arithmetic was fully mediated by the improvement in figure matching (see Figure 5).

4 | DISCUSSION

The present study examined whether numerosity training could improve arithmetic performance in children with DD, and whether visual form perception was the cognitive mechanism involved in the training effect. The findings indicated that the intervention group receiving training with the numerosity-based apple-collecting game significantly improved arithmetic performance, ANS acuity, and visual form perception. Mediation analysis showed that the improvement in visual form perception mediated the training-related improvements in arithmetic performance. These results suggest that non-symbolic numerosity training could improve arithmetic fluency in children with DD, and visual form perception is the underlying cognitive mechanism in the training effect.

Non-symbolic numerosity training enhanced arithmetic ability, suggesting a causal relationship between numerosity processing and symbolic arithmetic performance in children with DD. Previous evidence has suggested that a deficit in numerosity processing is the crucial cognitive characteristic of children with DD (Butterworth & Kovas, 2013; Butterworth et al., 2011; Cheng et al., 2018; Zhou et al., 2015). Some researchers (2015) found that numerosity processing was significantly correlated with arithmetic ability among children with DD. The present findings move beyond the findings of correlational studies to provide experimental evidence that training the primitive system of approximate number representation can enhance symbolic arithmetic performance in children with DD. This suggests that numerosity processing plays a causal role in the performance of symbolic arithmetic among children with DD.

Furthermore, the training-related improvement in symbolic arithmetic was fully mediated by the improvement in figure matching. This result is consistent with the view that visual form perception is the shared component of numerosity processing and arithmetic performance (Cui et al., 2017; Wang et al., 2016; Zhou &

Cheng, 2015; Zhou et al., 2015), or even the domain-general mechanism underlying both arithmetic and reading performance (Cheng et al., 2018). If this conjecture proves to be true, the current intervention may even be helpful for other visual form-related learning disorders such as dyslexia (Zhao, Qian, Bi, & Coltheart, 2014). Indeed, two previous studies showed that visual perceptual training was effective in children with dyslexia (Sandro et al., 2013; Wang et al., 2014).

It should be mentioned that other mechanisms may be involved. An alternative domain-general mechanism may be the inhibitive process, which has been found to mediate the relationship between non-symbolic numerical processing and symbolic arithmetic (Fuhs & McNeil, 2013; Gilmore, Mccarthy, & Spelke, 2010). Another alternative domain-general mechanism is visual attention. The apple-collecting game included various elements (numerosity, colors, bombs, and auditory feedback), some or all of which might attract the participants' attention and hence the cognitive/attentional demands may also be part of the training. Future studies are required to validate the effect of numerosity-targeted training or even direct visual form perception training on arithmetic fluency by controlling for inhibition and visual attention for DD children.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author (Xinlin Zhou, PhD, E-mail: zhou_xinlin@bnu.edu.cn) upon reasonable request.

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