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Chinese kindergarteners skilled in mental abacus have advantages in spatial processing and attention

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A R T I C L E I N F O

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Spatial ability
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A B S T R A C T

Previous studies have demonstrated that mental abacus learning could be helpful in improving mathematical skills. We hypothesized that kindergarteners skilled in mental abacus would have advantages in arithmetic and related visuospatial abilities. This investigation examined two large matched samples of preschool kindergarteners aged 5–6 years who showed the same baseline accuracy and speed measures. A total of 221 kindergarteners skilled in mental abacus (i.e., those who passed the test for Level 7 on the Standard Mental Abacus Test) and 221 age-matched peers with no experience using a physical or mental abacus were compared. We found that the mental abacus group achieved better performance than matched peers in subtraction, a two-dimensional mental rotation task, and a geometric form searching task, even after controlling for other cognitive abilities such as intelligence, reaction and decision speed, and non-symbolic number sense. These findings suggest that mental abacus learning in kindergarteners is associated with good performance in arithmetic, spatial, and attentional abilities.

1. Introduction

In China and other Asian countries, it is common for children to learn to use a "mental abacus"—that is, the mental image of an abacus—to perform arithmetic operations. It can be used as a tool to train student's arithmetic, and even general cognitive, abilities. Educators, teachers, and parents are interested to know whether this tool can promote arithmetic and general cognitive processing (Cui et al., 2020; Wang, Geng, Yao, Weng, & Chen, 2015). The national mathematics syllabus in China asserts that the abacus should be introduced for the lower grades in primary schools (Huang & Huang, 2009).

Previous research suggested that students should acquire the basic abacus, or even mental abacus skills, in the mathematics course (Gueudet & Poisard, 2019). The studies on outcomes of cognitive abilities in abacus learning can provide empirical evidence for the design of abacus courses. To become skilled in using the mental abacus, learners initially learn to operate a physical abacus with one or both hands and afterwards to carry out calculations in their mind by imagining a mental abacus, which may, or may not be, accompanied by explicit finger movements. In an abacus, numbers are represented via their positions using beads aligned in columns.

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Each column represents a place value, increasing from right to left (Li, 1959). Separated by a horizontal bar, the beads are divided into "earth" beads (beads below the horizontal bar) and "heaven" beads (beads above). Each "earth" bead represents "1," whereas each "heaven" bead represents "5." (See Fig. 1 and Appendix A).

Almost all studies have found a positive effect on arithmetic skills after abacus learning (Barner et al., 2016, 2017; Chen et al., 2006; Donlan & Wu, 2017; Huang et al., 2015; Na, Lee, Park, Jung, & Ryu, 2015; Stigler, Chalip, & Miller, 1986; Wu et al., 2009). This suggests that abacus learning could induce a transfer effect from non-symbolic arithmetic to symbolic arithmetic. However, whether a transfer effect exists from non-symbolic arithmetic to cognitive processing remains inconclusive.

Studies have reported that abacus learning can have transfer effects on general cognitive abilities. Previous studies found that adult abacus experts had higher verbal short-term memory (i.e., digit span) than controls (Hatano & Osawa, 1983; Tanaka, Michimata, Kaminaga, Honda, & Sadato, 2002). Recent studies have focused more on attention and visuospatial processing. For example, children or adults skilled in using the mental abacus have shown high-level visual attention ability (Liu & Sun, 2017). In a recent study, Wang et al. (2015) investigated the effect of mental abacus on 7-year-old children's arithmetic and visuospatial ability. The results showed that children receiving long-term mental abacus learning performed better than their peers in calculation and visual space performance. Another study showed that short-term training in the mental abacus could improve verbal short-term memory (i.e., letter span) and visuospatial working memory (i.e., visuospatial n-back task) in college students (Dong et al., 2016). These findings suggest that mental abacus learning can improve general cognitive abilities.

However, several studies failed to find the transfer effects of mental abacus on general abilities. For example, second grade students who received three years of mental abacus training outperformed controls on arithmetic tasks, but showed no difference in basic cognitive abilities such as mental rotation and spatial working memory (Barner et al., 2016). Similarly, after one year of mental abacus instruction, neither first graders nor second graders exhibited an advantage in cognitive abilities (i.e., spatial working memory, reasoning, and go/no-go) or arithmetic ability, relative to the control group (Barner et al., 2017). Frank and Barner (2012) found that the abacus expert and novice groups showed a similar pattern in visual working memory performance, which suggests that mental abacus does not increase working memory capacity.

This inconsistency may be because the participants in these studies were school-age children and adolescents. They had received academic learning that could interact with the mental abacus learning. Therefore, the current study examined the cognitive abilities in kindergarteners skilled in mental abacus but without academic learning experience. Additionally, a large sample study suggested that when the samples are large enough, the results would persist (Paap, 2015). In this study, we employed a cross-sectional design to examine the cognitive abilities of a large sample of 442 kindergarteners (aged 5–6 years) from 11 cities in China who had equal baseline measures of accuracy and speed. One group was experienced in abacus and one group consisted of age-matched peers with no

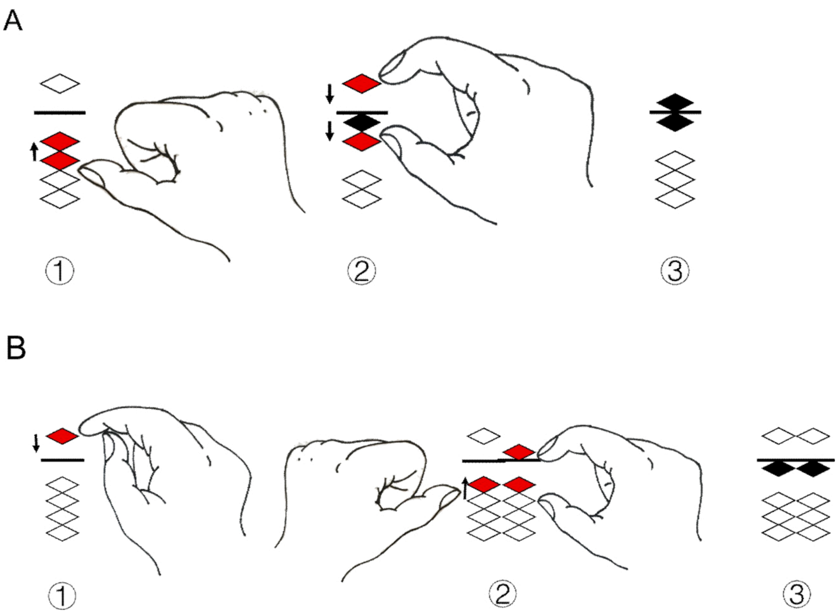

Fig. 1. An example using an abacus to calculate "2 + 4" (A) and "5 + 6." (B).
A: 2 + 4. The first step is to enter the number "2". Use the thumb of your right hand to move two earth beads toward the horizontal bar. The second step is to enter "+4". Use the thumb of your right hand to remove one earth bead away from the horizontal bar, while using the index finger of the right hand to move a heaven bead towards the horizontal bar. At last, get the number six.
B: 5 + 6. The first step is to enter the number "5". Use the index finger of the right hand to move a heaven bead towards the horizontal bar. The second step is to enter "+6". Use the thumb of your right hand to move one earth bead towards the horizontal bar while using the index finger of the right hand to move a heaven bead away from the horizontal bar, Meanwhile, use the thumb of your left hand to move a earth bead towards the horizontal bar.
At last, Get the number eleven.

experience in abacus. The kindergarteners skilled in abacus passed Level 7 on the Standard Mental Abacus Test.

This study focused on whether mental abacus was associated with general cognitive abilities such as visuospatial ability in kindergarteners. We hypothesized that the kindergarteners skilled in mental abacus could have an advantage in spatial ability and attention. The rationale for this hypothesis was, first, because previous studies suggested that children or adults skilled in mental abacus showed an advantage in verbal short-term memory (Tanaka et al., 2002) and visuospatial processing (Dong et al., 2016; Liu & Sun, 2017), the two groups would differ in mental rotation and geometrical form searching as they are typical cognitive tests that assess spatial processing and visual attention. It was expected that the two groups would differ in mental rotation and geometrical form searching as these are typical cognitive tests that assess spatial processing and visual attention, and are suitable to administer to young children in kindergarten. Second, we hypothesized that mental abacus learners could transfer digits into beads aligned in an imagined abacus, which involves manipulation and storage of the spatial image of the abacus and concentration ability. Finally, we hypothesized that long-term abacus training could lead to better attention because children would not need to perform the tedious and lengthy non-symbolic arithmetic computation.

2. Methods

2.1. Participants

Four hundred and forty-two Chinese kindergarteners aged from 5.5–6.4 years old participated in this study. In the kindergarten system of China, there are also three "grades" or "levels" according to age, including junior class (from 3 years old), middle class (from 4 years old), and senior class (from 5 years old). After senior class, children enter formal school education. Thus, all participants were selected from senior classes. Half the children had experience in using the physical abacus and mental abacus (mental abacus group: N = 221, 125 boys and 96 girls; M_{age} = 73.74 months; *SD* = 4.25), while the other half were peers with no experience in abacus, who were matched in age, gender, and grade to those in the mental abacus group (matched peers: N = 221, 127 boys and 94 girls; M_{age} = 73.96 months; *SD* = 4.13). Kindergarteners learn abacus in off-campus education institutions (outside of kindergarten). Children generally attend half a year, one year, or several years of abacus courses in the off-campus education institutions, which are private. The hours of abacus practice vary across the institutions, from one hour to several hours per week. Children are asked to practice at home each day because it is necessary to acquire abacus or mental abacus skills. The main contents of the course typically include abacus and mental abacus (operating abacus in the mind). Only addition and subtraction are practiced in kindergarten. When the children achieve Level 7 on the Standard Mental Abacus Test developed by the Chinese Association of Abacus and Mental Calculation (Ni, 2007), the learning program may be ended according to the parents' preference. Appendix B provides a detailed description of the arithmetic problems for each level of this test. Level 7 requires learners to answer at least 8 out of 10 problems correctly within 5 min using only mental abacus. The lowest level was 10, and the highest level was 1 for the children. Each arithmetic problem at Level 7 has 6 operands (integers), including 1 three-digit integer, 2 two-digit integers, and 3 one-digit integers (e.g., 9 + 70 + 81 + 247 − 3 − 8).

All the children were recruited from kindergartens in 11 cities in China: Huizhou, Huaibei, Shenzhen, Tianjin, Chengdu, Fuzhou, Taiyuan, Chongqing, Handan, Quanzhou, and Yanbian. All the children were native Mandarin speakers and had normal or corrected-

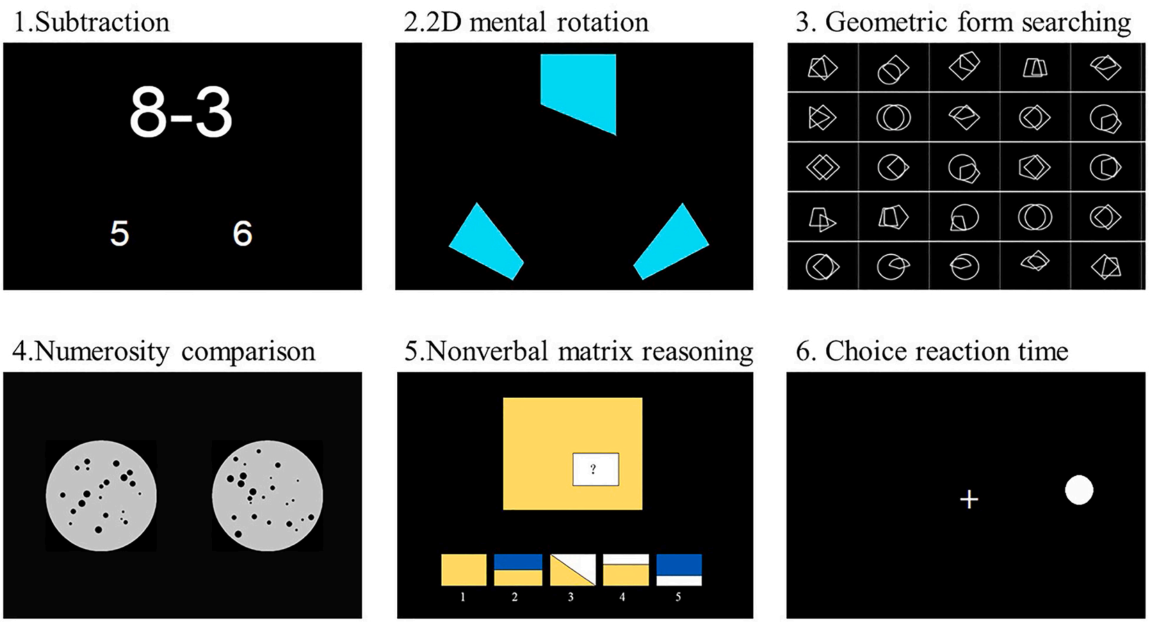

Fig. 2. Illustration of tests used in the current study.

to-normal vision. None of the children had been diagnosed with any intellectual, behavioral, sensory, or neurological deficits. The current study was approved by the Institutional Review Board of the authors' affiliated institution. Before the testing, the children's parents provided informed consent.

All the data were collected from March to August 2018. The participants used computers to complete six tests evaluating non-symbolic numerical acuity, arithmetic computation, and general cognitive abilities (2D mental rotation, geometric form searching, nonverbal matrix reasoning, and choice reaction time) in quiet rooms at local kindergartens. Prior to each test, the experimenter explained the instructions presented on the computer screen, and then participants performed a practice session to ensure that they fully understood the procedure. During the practice session, the children could ask the experimenters questions related to the tests. The mental abacus group also completed the mental abacus level test to identify their levels. The entire experiment lasted approximately 40 min. All participants completed the tests in the same order and had a 2-minute rest between each test.

2.2. Tests

There were six tests programmed in a web-based psychological experimental system (Cui et al., 2020; Wei et al., 2012). Examples of the trials in the tests are shown in Fig. 2.

2.3. Subtraction

This test was used to assess arithmetic ability (Cheng, Xiao, Chen, Cui, & Zhou, 2018; Cui, Zhang, Cheng, Li, & Zhou, 2017; Wei et al., 2012; Zhou, Wei, Zhang, Cui, & Chen, 2015). For each trial, a simple subtraction problem (e.g., $6 - 2$, $17 - 8$) was presented in the center of the computer screen. The minuend was never larger than 18, and all answers were single-digit numbers. Beneath each problem, two choices were presented. Participants were asked to press the "Q" key to select the answer on the left and the "P" key to select the answer on the right. Each incorrect choice was within three of the correct answer (i.e., ±1, ±2, or ±3). This test contained 92 trials in total, and children were allotted 2 min to complete as many problems as accurately as possible.

In the analysis, we used an adjusted number of correct trials to control for the effect of guessing (Cirino, 2011; Salthouse & Coon, 1994; Salthouse & Meinz, 1995). The adjusted number was calculated by subtracting the number of incorrect responses from the number of correct responses using the Guilford correction formula: $S = (R - W)/(n - 1)$ (where S is the adjusted number of items that the participants can correctly answer without the aid of chance; R is the number of correct responses; W is the number of incorrect responses; and n is the number of alternative responses to each item) (Guilford & Guilford, 1936). This correction procedure has been used in recent studies on mathematical cognition (Cirino, 2011; Wei et al., 2012; Zhou et al., 2015) and cognition in general (Hedden & Yoon, 2006; Putza, Sporter, & Mcburney, 2004; Salthouse & Coon, 1994).

2.4. Two-dimensional (2D) mental rotation

This test was used to assess spatial processing ability. It was adapted from Shepard and Metzler's (1971) mental rotation task, but rather than three-dimensional spatial ability, this test assessed two-dimensional (2D) spatial ability. In each trial, a 2D image was presented on the upper part of the computer screen and two more images were presented in the lower part of the screen. One of the two images presented in the lower part formed a complete rectangle with the figure in the upper part; participants were asked to press the "Q" key to choose the image on the left and the "P" key to choose the image on the right. The matching image could only be identified via mental rotation. This test was limited to 3 min. The adjusted number of correct trials was used as the index.

2.5. Geometric form searching

The geometric form searching test was adapted from a visual searching test (Mclean, Castles, Coltheart, & Stuart, 2010). It was used to assess sustained attentional ability. In each trial, 10 figures were simultaneously presented on the screen in a line until the participant responded. Each figure was a combination of two shapes randomly selected from an array of 150 simple line shapes. Participants were asked to use the mouse to click on the figure that comprised a square and a circle. The test contained 240 trials and participants were limited to 4 min. The adjusted number of correct trials was used in the analysis.

2.6. Numerosity comparison

This test was used to assess participants' ability to process non-symbolic numerical quantities. Two sets of dots of varying sizes were presented simultaneously on the computer screen, and participants were asked to judge which array contained more dots while ignoring the sizes of individual dots. Participants pressed the "Q" key if they thought that the array on the left contained more dots and the "P" key if they thought that the array on the right contained more dots. The number of dots in each set varied from 5 to 32. The two dot arrays for each trial were presented for 200 ms. After participants responded, a blank screen was presented for one second before the next trial. The test comprised 120 trials. Following the procedure used by Halberda, Mazzocco, and Feigenson (2008), the total combined area of all dots in each set was controlled to be the same for half of the trials, and the average area of all dots in each set was controlled to be the same for the other half of the trials. The ratios for the two dot arrays ranged from 1.2 to 2.0. The trials were administered across three sessions, with 40 trials for each session. The children were asked to complete all 120 trials. The adjusted number of correct trials was used as the index for analysis.

2.7. Nonverbal matrix reasoning

This test was similar to Raven's Progressive Matrices (Raven, 1998), a measure of general intelligence. In this test, participants were asked to identify the missing segment of a figure. Six possible answers were presented beneath each figure. Participants were asked to use the computer mouse to choose which of the items was suitable to complete the figure based on its inherent regularity. The participants completed five practice trials before completing the formal task, which contained 76 trials. The task was a time-limited (3-min) test.

2.8. Choice reaction time

A basic reaction time test was used as the baseline measure of accuracy and reaction times between the two samples (Cui et al., 2017; Zhou et al., 2015). In each trial of this test, a white dot was presented on a black screen either to the left or to the right of a fixation cross. The position of the dot was within 15° of the visual angle of the fixation cross. Participants were asked to press the "Q" key if the dot appeared on the left and the "P" key if the dot appeared on the right. The task comprised 30 trials in total (15 trials with the dot on the left and 15 trials with the dot on the right). The size of the dot appeared on the screen varied randomly across trials. The interstimulus interval also randomly varied between 1500 ms and 3000 ms. The median reaction time and accuracy (i.e., percentage of correct trials) were used in the analysis.

2.9. Data analyses

The index of measurement for each test is shown in Table 1. The means and standard deviations for the index were calculated for the tests. To test the effect of the site on group difference, hierarchical linear model (HLM) analysis was used to take the nesting of sites into account (Boyle & Willms, 2001; Mullola et al., 2012). The effect size of these comparisons was indicated with Cohen's d (Cumming, 2014). Analysis of covariance (ANCOVA) was conducted to examine group differences in test scores when age, gender, and other cognitive measures were treated as covariates. The major variables, including age and gender, served as covariates. We could not include factors such as the parents' income and predisposition for learning abacus. In China, parents choose abacus classes to promote their children's calculation abilities but not in order to advance their high-level working memory skills. To our knowledge, most other parents pursued other kinds of interests for their children, such as dancing, piano, and swimming classes, with a similar price to abacus classes. Finally, we also calculated partial correlations (controlling for age and gender) among the test scores in each group.

3. Results

Table 1 shows the mean and deviation of each test for the mental abacus group and the matched peers. The split-half reliability for each test was also listed, ranging from .73 to .93. The HLM analysis (see Table 1) showed that after taking the nesting of sites into account the mental abacus group performed significantly better than the control group on subtraction, $b = 11.39$, $t = 4.18$, $p = .004$; mental rotation, $b = 8.38$, $t = 4.89$, $p = .000$; and geometric form searching tasks, $b = 13.45$, $t = 4.63$, $p = .000$. The effect sizes between groups were $d = 0.58$ for subtraction, 0.48 for mental rotation, and 0.59 for geometric form searching. We observed no significant group differences for numerosity comparison, nonverbal matrix reasoning, and choice reaction time.

The ANCOVA demonstrated the following results after controlling for age, gender, and other cognitive measures (i.e., nonverbal matrix reasoning, choice reaction time (ACC) and choice reaction time (RT)): 1) the difference between groups for subtraction was still significant: $F\,(1, 434) = 40.18$, $p < .001$, $\eta^2 = .085$; 2) the difference between groups for 2D mental rotation was still significant: $F\,(1, 434) = 33.24$, $p < .001$, $\eta^2 = .071$; and 3) the difference between groups for geometric form searching was still significant: $F\,(1, 434) = 42.09$, $p < .001$, $\eta^2 = .088$.

The partial correlations (controlling for age and gender) among test scores are shown in Table 2. In both groups, subtraction scores were significantly correlated with scores in 2D mental rotation, numerosity comparison, nonverbal matrix reasoning, and choice reaction time.

Table 1
Descriptive statistics, analysis of variance (ANOVA) and hierarchical linear model (HLM) for the tests in the mental abacus group and the matched peers group.

Test	Index	Mental abacus *Mean (SD)*	Matched peers *Mean (SD)*	Split-half reliability	Cohen's *d*	*t*
Subtraction	Adj. No. of correct responses	21.10 (10.59)	15.16 (11.00)	.91	0.58	4.18**
2D Mental Rotation	Adj. No. of correct responses	21.33 (14.73)	14.68 (13.91)	.90	0.48	4.89***
Geometric Form Searching	Adj. No. of correct responses	44.77 (27.38)	31.41 (17.35)	.93	0.59	4.63***
Numerosity Comparison	Adj. No. of correct responses	7.37 (7.95)	7.90 (6.84)	.92	−0.07	1.96
Nonverbal Matrix Reasoning	Adj. No. of correct responses	11.35 (4.96)	11.61 (4.82)	.90	−0.05	1.88
Choice Reaction Time (ACC)	Accuracy	97.37 (3.92)	97.54 (3.80)	.91	−0.05	0.24
Choice Reaction Time (RT)	Reaction time (millisecond)	765 (231)	783 (209)	.73	−0.09	2.52

Note. $^{***}p < .001$, $^{**}p < .01$. 2D = two-dimensional; Adj.: adjusted, No.: number; ACC = accuracy; RT = reaction time.

Table 2
Partial correlations controlling for age and gender between test scores by group.

	Tests	1	2	3	4	5	6.1	6.2
Mental abacus group	1. Subtraction	–						
	2. 2D Mental Rotation	.20**	–					
	3. Geometric Form Searching	−.05	.40***	–				
	4. Numerosity Comparison	.26***	.24***	−.04	–			
	5. Nonverbal Matrix Reasoning	.22**	.42***	.29***	.29***	–		
	6.1 Choice Reaction Time (ACC)	.16*	.10	−.02	.15*	.08	–	
	6.2 Choice Reaction Time (RT)	−.24***	−.32***	−.24***	−.20**	−.22**	−.04	–
Matched peers group	1. Subtraction	–						
	2. 2D Mental Rotation	.27***	–					
	3. Geometric Form Searching	.28***	.19**	–				
	4. Numerosity Comparison	.25***	.29***	.22**	–			
	5. Nonverbal Matrix Reasoning	.24***	.45***	.26***	.37***	–		
	6.1 Choice Reaction Time (ACC)	.01	.04	−.02	.16*	.06	–	
	6.2 Choice Reaction Time (RT)	−.22**	−.15*	−.19**	−.10	−.14	.02	–

Note. *$p < .05$, **$p < .01$, ***$p < .001$. 2D = two-dimensional; ACC = accuracy; RT = reaction time.

4. Discussion

The aim of the current investigation was to explore whether kindergarteners experienced in mental abacus showed better general cognitive abilities than their matched peers. The kindergarteners skilled in mental abacus were found to perform much better in arithmetic, visual searching, and mental rotation tasks than their matched peers, and this difference remained significant after controlling for age, gender, and other general cognitive abilities. These findings suggest that mental abacus learning in kindergarten is associated with good performance in general abilities such as attentional and spatial processing.

Children in the mental abacus group outperformed in arithmetic ability, which is consistent with the findings of previous studies (Barner et al., 2016; Chen et al., 2006; Donlan & Wu, 2017; Huang et al., 2015; Na et al., 2015; Wu et al., 2009). When the kindergarteners in the present study achieved Level 7 on a standard test, they were able to do one- to three-digit addition or subtraction. Although this does not mean that they acquired an understanding of ordinal numbers and the cardinality of large numbers, the kindergarteners who learned abacus could complete complex calculations by means of the mental abacus. This implied that they possessed the prerequisites to learn numbers on the abacus. In China, schoolteachers and parents focus on children's ability to count and recognize numbers from kindergarten. In most abacus training institutions, the children receive abacus learning from approximately five years of age. During mental abacus learning, the mapping between non-symbolic beads and numbers is fundamental in the practice of physical and/or mental abacus. Individuals using the physical and/or mental abacus quasi-naturally practice mental arithmetic using an imaginary abacus coupled with actual finger movements, which are associated with arithmetic skill.

Additionally, children skilled in the mental abacus exhibited greater attention ability, here in geometric form searching, which is also consistent with previous findings (Na et al., 2015; Yamada, 1998). Although some researchers found that abacus-trained children showed improved performance in sustained attention tasks, they failed to show an effect in visual/auditory selective attention. The mental abacus-learning curriculum requires persistent attention to achieve the targeted high level, which requires building an association between a physical abacus and the imagined abacus. It is therefore suggested that attention plays an important role in mental abacus learning for kindergarteners.

The finding that kindergarteners skilled in mental abacus showed better performance in spatial processing is different from the finding that mental abacus learning did not show a transfer effect on visuospatial ability (Barner et al., 2016, 2017). Two factors may explain the inconsistent findings. First, the length of training time might be critical for the effect of abacus training. For example, Barner et al.'s (2017) study did not show a positive effect on arithmetic skills after abacus learning, which only lasted one year (three periods per week for 40 min each) in first- and second-grade students. They observed a positive effect on arithmetic skills in second-grade students with three years of weekly mental abacus training (3 h/week) (Barner et al., 2016). Second, there are different levels of mental abacus. In the present study, abacus learners all achieved a high level on the Standard Mental Abacus Test (Level 7 in the present study). Barner et al. (2016) employed abacus measures to examine any differences between the mental abacus group and control group, which is not clear what level the abacus learner has reached. Compared with abacus learning at schools, teachers in off-campus education institutions aimed to make learners reach a high level on the Standard Mental Abacus Test. However, the present study used a cross-sectional correlation design to examine the relevant factors that affect mental abacus. Based on previous randomized controlled trials that used a superior methodology (Barner et al., 2016, 2017), our future study would employ a randomized controlled trial design to overcome this limitation.

Compared to previous studies, the present study deepens our understanding of mental abacus learning. Previous studies typically focused on the effect of mental abacus learning in elementary school students (Liu & Sun, 2017; Wang et al., 2015; Wang, Geng, Hu, Du, & Chen, 2013). Here, mental abacus training could be affected by arithmetic learning in formal schools because abacus computation is different in procedure from ordinary arithmetic computation. The current study found that the kindergarteners skilled in mental abacus had advantages in arithmetic performance as well as attentional and spatial abilities. There are two possible reasons. First, mental abacus processing is similar to mapping between the approximate number system and performing arithmetic operation.

In mental abacus learning, children learn to conduct symbolic arithmetic in their minds by operating a mental abacus. This is consistent with the theory of two different number representation systems: a symbolic, exact number representation system and an analog, approximate number system (Dehaene & Cohen, 1991; Dietrich, Nuerk, Klein, Moeller, & Huber, 2019). The former is used to represent the numbers of individual objects and support exact calculations, and the latter is used to recognize and mentally manipulate numerosities. To achieve a high level of mental abacus skills, participants need to repeatedly practice mental imagery in the form of the abacus and build associations between form representations of beads, number symbols, and exact arithmetic. Second, mental abacus skills and specific cognitive abilities share a general cognitive mechanism such as visual form perception. Mental abacus learning involves transforming digits into beads aligned in an imagined abacus, which requires the manipulation of the perceived form perception of the abacus. During the tedious practice of mental abacus, the learner should maintain a high level of focus. Therefore, long-term mental abacus training could lead to better form perception associated with visuospatial skills and attention.

However, this study has some limitations. First, a pre-test at the very beginning of junior class when children were 3-year-olds and thus a longitudinal design would have been useful. However, the two large samples of 5- to 6-year-old children were comparable on baseline measures of accuracy and speed. Moreover, in samples over $N = 100$, bilingual advantages tend to disappear (Paap, 2015), so the result that an abacus advantage persists in the current large sample of 400+ participants speaks to the reliability of the results. Furthermore, in both groups, the correlation with speed was more important than with accuracy, most likely because the tasks were timed, which showed the comparability of the samples in the context of the current tasks. Second, we used only a mental rotation test and a geometric form-searching test to assess the visual attention and visuospatial abilities, respectively. These two tasks are typical assessment tests, and the senior kindergarten children were capable of performing these tasks. However, it would be better if future research employed two tests per domain to assess cognitive function.

In short, the two groups did not differ in baseline measures—accuracy and latencies—in a choice reaction time task, nor did they differ in a nonverbal matrix task, which served as a computerized proxy to the culture-fair Raven Progressive Matrices intelligence test. Thus, we may conclude that this large multi-city study showed that extra abacus classes in addition to regular preschool could produce a higher level of some visuospatial skills and arithmetic before formal schooling is even commenced.

Declaration of Competing Interest

The authors report no declarations of competing interest.

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Appendix A. The instructions of addition and subtraction on a Chinese abacus, based on the textbook

Arithmetic	Conditions
Addition	1. If there are more outer beads than the added (there are enough to add), move the beads toward the horizontal bar, such as 1 + 2. 2. If the sum of two numbers in the same place value is more than 4, but less than 10, move one “heaven” bead toward the horizontal bar, and move “earth” bead(s) toward or away from the horizontal bar depending on the magnitude of the addition, such as 2 + 4. 3. If the sum of two numbers in the same place value is more than 9, move the adjacent left column “earth” bead toward the horizontal bar, and move the current column’s bead away from the horizontal bar, such as 5 + 6.
Subtraction	1. If there are more inner beads than the subtrahend (there are enough to subtract), move beads away from the horizontal bar, such as 4 − 1. 2. If the minuend value is more than 4 (the difference value is less than 5), move the “heaven” bead away from the horizontal bar, and move the “earth” bead toward the horizontal bar, such as 5 − 1. 3. If the minuend value is more than 9 (the difference value is less than 5), move the adjacent left column “earth” bead away from the horizontal bar, and move the current column’s bead toward the horizontal bar, such as 11 − 7.

Note. Addition and subtraction with an abacus can be divided into three conditions, which are based on the calculation of the number of beads involved. Outer beads: the beads that are further away from the horizontal bar. Inner beads: the beads that are nearer to the horizontal bar.

Appendix B. Detailed illustration and examples from the Standard Mental Abacus Level Test for children

Level	No. of operands	No. of digits in operands				With decimals	Examples
		1	2	3	4		
10	3	3	0	0	0	No	5 − 3 + 9
9	4	3	1	0	0	No	7 + 6 − 3 + 64
8	5	3	2	0	0	No	40 + 84 − 5 + 2 + 7
7	6	3	2	2	0	No	9 + 70 + 81 + 247 − 3 − 8

(continued on next page)

(*continued*)

Level	No. of operands	No. of digits in operands				With decimals	Examples
		1	2	3	4		
6	7	3	3	1	0	No	69 + 258 + 47 + 25 + 2 + 8 + 1
5	7	2	3	2	0	Yes	0.71 − 0.59 + 1.48 + 0.05 − 0.01 + 0.14 + 6.93
4	8	2	3	2	1	Yes	708 + 5 + 4 − 19 + 31 + 42 + 4263 + 920
3	8	2	2	2	2	Yes	0.07 + 6.53 + 83.20 − 49.86 + 0.08 + 0.31 + 8.75 + 0.64
2	9	2	3	3	2	Yes	362 + 6473 + 39 + 8475 − 928 + 84 − 7 − 6 + 140 + 51
1	10	0	3	4	3	Yes	837 + 8271 + 93 + 9382 − 84 + 726 − 48 − 160 + 2615 + 759

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