Wei et al. BMC Psychology (2024) 12:466
https://doi.org/10.1186/s40359-024-01965-6

BMC Psychology

RESEARCH

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Affective and cognitive factors associated with Chinese and Italian children's arithmetic performance

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Abstract

Background This study aimed to investigate the cognitive and affective factors associated with cross-cultural differences in arithmetic tasks.

Methods A total of 404 third- and fourth- graders were recruited from China and Italy to complete exact arithmetic, arithmetic estimation and cognitive tasks (i.e., short-term memory, executive functions, and fluid reasoning). Their mathematical anxiety was also measured.

Results The results showed that Chinese children performed better than Italian children in both arithmetic tasks and in shifting task. Italian children performed better in visuospatial updating task and reported higher levels of mathematical anxiety than their Chinese peers. Multi-group path analyses showed that the patterns of relations among cognitive factors (i.e., short-term memory, inhibition and shifting), mathematical anxiety, and arithmetic performance were similar across groups. The only exception was that visuospatial updating uniquely predicted arithmetic estimation for Chinese but not for Italian children.

Conclusions Chinese children outperformed their Italian peers in the exact arithmetic task, likely due to the greater emphasis on arithmetic fluency in Chinese mathematics education, both in schools and at home. They also had a slight advantage than Italian peers in the arithmetic estimation task. The unique link between updating and arithmetic estimation found in Chinese children but not Italian children suggests that, although arithmetic estimation is not emphasized in the curricula of either country, instruction and practice in exact arithmetic may enhance Chinese children's efficiency in solving arithmetic estimation problems.

Keywords Cross culture, Arithmetic, Estimation, Short-term memory, Executive functions, Mathematical anxiety

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Background

Eastern-Western disparities in mathematical ability are well-documented in international surveys with children and adolescents from East Asian countries outperforming their Western peers [1, 2]. Arithmetic ability is a fundamental aspect of mathematical proficiency, which children develop progressively during their school years. Numerous studies have consistently shown that East Asian children's superiority in arithmetic skills [3–7]. All these studies convey results in what literature defines as "*exact arithmetic*", which pertains to the ability to calculate the precise answer to an arithmetic problem [8]. The variations in exact arithmetic performance are believed to underlie differences in more general mathematics education across cultures [3, 7, 9].

While previous research has predominantly focused on exact arithmetic tasks to assess arithmetic ability, the role of arithmetic estimation — the ability to calculate an approximate answer to an arithmetic problem [8] — has been undervalued in mathematics education across many countries [10, 11]. Thus, the primary aim of the present study was to investigate the cultural differences in exact arithmetic and arithmetic estimation skills among school-aged children from two countries: China and Italy, representing Eastern and Western cultures, respectively. Moreover, prior studies have indicated that both cognitive factors – such as working memory [12] and executive functions [13, 14] – and affective factors, such as mathematical anxiety [15, 16], are related to individual differences in children's arithmetic performance [17]. Hence, the second objective of the study was to investigate potential variations in the patterns of relations between these cognitive and affective aspects concerning different types of arithmetic abilities among Chinese and Italian children.

Definitions and types of arithmetic

Arithmetic can be defined by the increasing use of efficient procedures over the course of learning that become automatic with practice during the school years [8]. To progress in mathematical learning, in addition to understanding concepts and principles, children must be able to quickly recognize numerical symbols, learn the counting sequence, and through the repetitive co-occurrence of operands and answers, and memorize arithmetic facts. These acquired facts then serve as automated support when tackling more complex arithmetic problems [8].

Arithmetic problems typically yield exact answers; however, in many real-life situations, it is sufficient to produce approximate answers rather than exact ones to arithmetic problems. For example, one might need to estimate their monthly expenses or the time required to finish a particular task. The process of producing an approximate answer to an arithmetic problem is called arithmetic estimation [8]. Efficient arithmetic estimation requires a range of conceptual knowledge, including an understanding of the goal to produce an answer reasonably close in magnitude to the correct answer, and the ability to choose a strategy that can be used quickly and accurately [18–20]. Effective estimation also requires procedures for generating approximate numbers, for example, rounding the operands to simplify calculations and using decomposition methods to compensate for rounding errors [19, 21, 22]. Altogether, when properly acquired, the main advantage of arithmetic estimation is that it requires less time and attentional resources than exact calculation, making it appropriate for circumstances where time or attention resources are limited [23].

Cognitive factors on arithmetic performance

Understanding the role of cognitive factors in arithmetic performance is crucial, as evidenced by a wealth of correlational and longitudinal studies have consistently demonstrated the involvement of working memory and executive functions in overall mathematics achievement [12, 24, 25]. Working memory represents a limited capacity system that enables temporary storage and processing of information during complex cognitive activities [26, 27]. Dual-task experimental studies found that when participants were asked to perform both arithmetic and working memory tasks simultaneously, children's [28, 29] and adults' [30] performance on exact arithmetic and arithmetic estimation decreased as working memory difficulty increased. A meta-analysis found that increases in working memory load can lead to a decrease in arithmetic problem-solving by 7–19% [31].

Executive functions also play a role in arithmetic performance [25, 32]. From many theories regarding executive functions [33, 34], we selected the widely cited classic model proposed by Miyake et al. [35]. The three core processes of executive functions in Miyake et al.'s model are updating, inhibition and shifting. All three components, albeit in different remarks, support the arithmetic process. Updating, which involves constant monitoring and rapid addition/deletion of working memory content, might assist in holding relevant partial results during complex arithmetic processing [36, 37]. Inhibition, the ability to deliberately inhibit dominant, automatic responses when required, may suppress inappropriate arithmetic strategies or irrelevant information [38–40]. Finally, shifting, the ability to switch between tasks or mental sets to adjust to changed priorities, may help in switching between operations [41], solution strategies [42], and calculation steps [43]. Altogether, the involvement of different components of executive functions support various aspects of arithmetic processing.

Affective factor (mathematical anxiety) on arithmetic performance

Research has consistently shown how emotional states and beliefs may deeply impact learning and performance in mathematics [44–46]. Among these, the most extensively studied aspect is the experience of unpleasant emotions associated with the execution of numerical and arithmetic tasks [45, 47]. This negative feeling, defined by researchers as mathematical anxiety [15], often interferes with mathematical performance beginning in the early school years, highlighting a moderate negative stable correlation [17, 48]. From a developmental perspective, the negative relation between mathematical anxiety and math performance may increase through the course of schooling [49–51]. Following this trend, it is unsurprising that results of the 2022 Programme for International Student Assessment (PISA) survey indicated that, among 15-years-old students, a one-point increase in the measure of mathematical anxiety corresponded with an 18-point decrease in mathematical achievement [2]. Previous studies have found that mathematical anxiety disrupts working memory functioning, leading to poor math performance [15, 17, 52–58]. Therefore, it is crucial to account for mathematical anxiety when investigating the associations between cognitive abilities and children's arithmetic performance.

The current study: cultural differences

As already anticipated, an extensive body of research has investigated cross-cultural differences in exact arithmetic performance, consistently showing that Chinese primary students outperform their western peers [3–7]. Education has been posited as an important factor in these cultural differences in mathematical abilities [3, 7, 9]. Specifically, in comparison to Western countries, there is a greater emphasis on arithmetic fluency as a foundation for developing a comprehensive grasp of conceptual knowledge [59–62]. Moreover, in China, a strand mathematics curriculum is implemented, focusing on introducing a limited number of topics with in-depth instructions, with each topic building upon the mastery acquired in preceding topics [63]. In contrast, in many Western countries, including Italy, a spiral curriculum is implemented, introducing a broad range of topics each year and revisiting them multiple times across grades [64]. Consequently, children may not have adequate time to master arithmetic fluency [64]. The impact of mathematics curriculum on children's arithmetic performance has not been studied.

In addition to the differences in school curricula, the home learning environment also varies between China and Western countries. Compared to Western parents, Chinese parents have higher expectations for their children's mathematical performance [65, 66], which may lead them to spend more time on home numeracy activities. Cross-cultural studies have found that Chinese parents of school-aged children spend more time on mathematics, use more formal teaching methods, and expect their children to complete more mathematics homework [67, 68].

Our study aimed to delve deeper into the role of education by comparing arithmetic estimation—a skill less emphasized in formal schooling [10, 11]—against the more emphasized exact arithmetic. We recruited third and fourth graders from China and Italy, because the mathematics curricula in these countries are aligned: by the end of second grade, children in both countries are expected to master double-digit addition and subtraction. Moreover, the mathematics curricula of both countries provide minimal instruction in arithmetic estimation. In the current study, children completed two types of arithmetic tasks (i.e., exact arithmetic and arithmetic estimation). We expected Chinese children to outperform their Italian peers in exact arithmetic tasks, due to their education system's greater emphasis on these skills. However, considering the limited attention given to arithmetic estimation by both the Chinese and Italian educational systems, this advantage is expected to be less pronounced in arithmetic estimation tasks. We also expected to find a higher level of mathematical anxiety in Italian children and better performance in working memory and executive function tasks in Chinese children, consistent with previous research [36, 69–71]. To explain the cultural differences in arithmetic tasks, we hypothesized that working memory would be a significant predictor of the differences in exact arithmetic performance between the two countries [72, 73]. Among the considered executive functions, we hypothesized that visuospatial updating would be also a significant predictor, presumably providing children with the necessary resources to tackle mathematical tasks [74]. Finally, we hypothesized that mathematical anxiety would be a significant predictor due to its consistent, albeit negative, relation with mathematical attainment [17].

To our knowledge, this was the first study examining cultural differences in arithmetic estimation ability among primary school children, including the underlying cognitive and affective factors that may explain differences in performance. Children completed five cognitive tasks (i.e., visuospatial short-term memory, inhibition, shifting and visuospatial updating, and fluid reasoning) and one questionnaire on mathematical anxiety. A multigroup analysis was conducted to explore whether the patterns of the relation between arithmetic abilities and independent variables (i.e., cognitive and affective factors) differed between Chinese and Italian children.

Method

Participants

According to Kline's [75] recommendation for determining the required sample size[1], a minimum of 160 children per group was required. In total, 178 Chinese and 226 Italian primary school children attending the third and fourth grades were recruited for this study. The two samples were comparable in age and gender distribution (Table 1). Participants from both countries were recruited from contacting schools located in middle-class urban areas. The Chinese participants were native Chinese speakers, and the Italian participants were native Italian speakers. None of the participants had a prior history of neurological disease, psychiatric disorders, or diagnosis of neurodevelopmental disorders. The study was approved by the IRB of Zhejiang University, China and the Ethics Committee on Psychology Research at the University of Padova, Italy. After approval from each school, written informed parental consent was obtained before testing the children.

Materials

Arithmetic tasks

Exact arithmetic This task, adapted from Dehaene et al.'s study [76], included two blocks of 24 double-digit arithmetic problems, 12 problems each of addition and subtraction. The addition and subtraction problems in each block were randomly represented. The two blocks were separated by a 30-seconds break. For each trial, an addition or subtraction problem appeared on the screen, with a choice of four alternatives beneath it. Participants had to select the correct answer as quickly and accurately as possible by pressing a key on the keyboard, depending on the screen position of the given answer. The problem remained on the screen for 15 s until the participants responded. The three wrong answers were obtained by adding/subtracting ±1, ±10, and ±15 units from the right answer, respectively. The constraints of the problems were the same as those used in previous studies [77]. The proportion of correct answers was calculated. Good internal consistencies for exact arithmetic (China: Cronbach's α = 0.87; Italy: Cronbach's α = 0.82) were observed.

Arithmetic estimation This task was similar to exact arithmetic, except that the participants were asked to choose the closest answer from the provided four alternatives. The closet answer was the exact answer ± 3. The other three alternatives were obtained by adding/subtracting ± 5, ±15, and ± 20 units from the closest answer. As for the Exact Arithmetic task, the percentage of correct answers were computed. Good internal consistencies for arithmetic estimation (China: Cronbach's α = 0.90; Italy: Cronbach's α = 0.77) were observed.

Cognitive tasks

Inhibition The Flanker task, adapted from Eriksen and Eriksen's study [78], was used to measure the inhibition ability of executive function. For each trial, five arrows in a row were presented in the middle of the screen. Participants were asked to focus on the middle arrow and judge its direction as quickly as possible. If the middle arrow pointed to the left, participants were asked to press the "F" button; if it pointed to the right, participants were to press the "J" button. Two conditions were included in the study. One was the congruent condition, in which the middle arrow had the same direction as the other four. The other was the incongruent condition, in which the middle arrow had the opposite direction. 96 trials were randomly presented and divided into two blocks. The reaction time of the corrected trials and the accuracy were recorded. In order to avoid confounds of speed-accuracy trade-off, an inverse efficiency score (IES) was calculated [79]. We calculated IES for each condition with the average correct reaction time divided by the proportion of correct responses. The final score (corrected IES) was the IES of incongruent condition subtracted from the IES of congruent condition. Good internal consistencies of corrected reaction time (China: Cronbach's α = 0.96; Italy: Cronbach's α = 0.94) and corrected accuracy (China: Cronbach's α = 0.85; Italy: Cronbach's α = 0.81) were observed.

Shifting The Hearts and flowers task was adapted from Davidson et al.'s study [80] to measure the shifting ability of executive function. In the center of the screen, a heart or flower was presented on either the left or right side of a horizontal rectangle. There were three conditions (i.e., congruent, incongruent, and mixed), with congruent and incongruent conditions consisting of 30 trials each, whereas the mixed condition consisting of 60 trials. In the congruent condition, a heart appeared on the left or right side of the rectangle for 1500 ms. Participants had to press the button on the same side as the heart appeared. In the incongruent condition, a flower appeared on either side of the rectangle for 1500 ms. Participants had to press the button on the opposite side of the flower. In the mixed condition, a heart or flower was presented on one side of the rectangle. Sixty trials were presented in a pseudo-randomized order, and participants had to react according to the rules of the previous conditions. If the $n+1$ trial used a different rule from the last trial, it was defined as a shift

[1] To determine the required sample size for the main analyses (multigroup path analyses), we followed Kline's (75) recommendation that the ratio of observations to estimated parameters should be 20:1 (i.e., 20 participants per estimated parameter). In the present study, we aimed to compare the paths from eight cognitive (i.e., inhibition, shifting, updating, and short-term memory), affective (i.e., math anxiety), and control variables (i.e., gender, grade, and fluid reasoning) to the arithmetic outcomes between Chinese and Italian children; thus, a minimum of 160 children per group was required for the multigroup analyses

Table 1 Sample demographics

	Chinese ($n=178$)				Italian ($n=226$)			
	Grade 3		Grade 4		Grade 3		Grade 4	
	n	*M (SD)$_{age}$*	*n*	*M (SD)$_{age}$*	*n*	*M (SD)$_{age}$*	*n*	*M (SD)$_{age}$*
Boy	53	8.54 (0.33)	50	9.52 (0.30)	63	8.48 (0.44)	58	9.43 (0.35)
Girl	39	8.51 (0.32)	36	9.47 (0.30)	53	8.41 (0.39)	52	9.53 (0.35)
All	92	8.53(0.32)	86	9.50 (0.30)	116	8.45 (0.42)	110	9.47 (0.35)

trial. Meanwhile, using the same rule to react was defined as a non-shift trial. The reaction time of the corrected trials and the accuracy were recorded. Similar to the Flanker task, we calculated IES for each condition with the average correct reaction time divided by the proportion of correct responses. The final score (corrected IES) was derived by subtracting the IES of the only shift trials in the mixed condition from the half of the sum of IESs calculated on the congruent and incongruent conditions respectively. Good internal consistencies of corrected reaction time (China: Cronbach's α=0.93; Italy: Cronbach's α=0.90) and corrected accuracy (China: Cronbach's α=0.91; Italy: Cronbach's α=0.87) were observed.

Visuospatial updating This task was adapted from Crisci et al.'s study [81] and requires recognizing, classifying, memorizing, and updating information that changes over time. In this task, the participants were asked to memorize and recall the last positions of various shapes (i.e., circle, square, triangle, star, diamond, and pentagon) that appear in a 4×4 matrix. The visuospatial updating task consisted of eight series of six to twelve shapes, two for each span level. The target shapes appeared in the center of the screen (for the first 600ms), then remained visible at the bottom of the screen throughout the presentation of the series. Each shape appeared in randomized positions on a 4×4 matrix for 600ms, with an interval of 600 ms between them. There were four levels of increasing difficulty depending on the number of target categories to remember. At the end of the presentation, participants were asked to use the mouse to indicate the last position of the target shape. Accuracy, as the proportion of positions remembered correctly out of the total positions to remember, was considered for each item. Good internal consistencies (China: Cronbach's α=0.75; Italy: Cronbach's α=0.76) were observed.

Visuospatial short-term memory The visuospatial matrix task was used to measure short-term memory and was adapted from Giofrè and Mammarella's study [72, 82]. The participants were presented with a 4×4 matrix. They had to memorize the positions of black cells that appeared sequentially for one second in different positions on the matrix. After a series of black cells was presented: a blank matrix appeared on the screen. Subsequently, the children used the mouse to click on the locations where they had seen a black cell. The number of black cells in each series ranged from 2 to 8. Each span was tested in three trials. Two practice trials with feedback and seven formal blocks were tested. The number of corrected answers was used as the dependent variable. Good internal consistencies (China: Cronbach's α=0.86; Italy: Cronbach's α=0.82) were observed.

Fluid reasoning Cattell's Culture Fair Intelligence Test Scale [83] was used to measure participants' fluid reasoning skills. The task asked the participants to choose one of the five candidate answers according to the inherent regularity of each question. This task included four subtests (classification, series, matrices and analogies) for a total of 46 items. The number of correct answers for all subtests was summed up as the final score. Good internal consistencies (China: Cronbach's α=0.62; Italy: Cronbach's α=0.63) were observed.

Affective task

Mathematical anxiety Children's mathematical anxiety was measured by the *Abbreviated Math Anxiety Scale* (AMAS) [84, 85]. The Chinese and Italian versions of the AMAS were used in this study. It is a self-report mathematical anxiety questionnaire consisting of nine items scored on a Likert-type scale from 1 to 5. Participants were asked to report their level of anxiety in situations involving math. Higher scores on the scale indicate higher levels of mathematical anxiety. Good internal consistencies (China: Cronbach's α=0.83; Italy: Cronbach's α=0.78) were observed.

Procedure

Children were tested in a single collective session lasting about 1 h at school and monitored by three experimenters. All tasks were presented on a laptop computer with a 15-inch LCD screen and were programmed using E-prime software (version 2.0) [86], except for mathematical anxiety and fluid reasoning, which were being measured on paper. The participants were asked to complete the computerized tasks and then the pen-and-paper tasks. To prevent interference between the two arithmetic tasks, other tasks were inserted between the two arithmetic tasks. The order of the tasks was fixed: exact arithmetic, inhibition, visuospatial short-term memory, arithmetic estimation, visuospatial updating, shifting, mathematical anxiety and fluid reasoning. There was a short break at the end of each task.

Analytical plan

Using SPSS 22.0 (SPSS Inc., Chicago, IL, USA), we first conducted a series of independent *t*-tests to examine performance differences between Chinese and Italian children, applying Bonferroni correction for multiple comparisons ($p<.05/8=0.006$). Next, we conducted a repeated-measures Analysis of Variance (ANOVA) to examine the interaction between task type (exact arithmetic and arithmetic estimation) and country (China vs. Italy) on performance. Lastly, we conducted multi-group path analyses using *M*plus [87] to test for cross-cultural differences in the predicted paths from cognitive (i.e., inhibition, shifting, updating and short-term memory) and affective (i.e., mathematical anxiety) factors to exact arithmetic and arithmetic estimation between Chinese and Italian children. Additional exploratory analyses, including grade and gender, are provided in the Supplementary Material.

Results

Preliminary analyses

Extreme outliers (defined as values with |z-scores| > 3.29) [88] were found for the inhibition ($n=8$) and shifting tasks ($n=6$). Sensitivity analyses with and without these outliers showed similar patterns of results, and thus all data were included in the final analyses.

Descriptive statistics of the raw data for all variables are shown in Table 2. A series of independent *t*-test was conducted to compare the children's abilities between the Chinese and Italians. The results revealed significant differences between the two countries across most of the tasks. Specifically, Chinese children performed better in exact arithmetic ($t(402)=24.06$, $p<.001$, $d=3.16$) and arithmetic estimation ($t(402)=13.39$, $p<.001$, $d=1.00$) than Italian children. As for the cognitive and affective factors, Chinese children performed better on the shifting ($t(400) = -7.07$, $p<.001$, $d = -0.72$), and fluid reasoning tasks ($t(402)=14.91$, $p<.001$, $d=1.52$) than Italian children. In contrast, Italian children performed better on the visuospatial updating task ($t(402) = -4.80$, $p<.001$, $d = -0.50$) and showed higher levels of mathematical anxiety ($t(402) = -6.15$, $p<.001$, $d = -0.63$) than Chinese children. In addition, no significant differences were observed between countries for the visuospatial short-term memory ($t(402)=1.84$, $p=.07$, $d=0.18$), and the inhibition task ($t(401) = -0.65$, $p=.52$, $d = -0.06$).

To investigate whether the patterns of performance on the two types of arithmetic tasks were different between countries, performance was analyzed in a 2(type: exact, estimation) x 2(country: China, Italy) repeated-measure ANOVA. The results revealed a significant main effect of the tasks, $F(1, 402)=308.50$, $p<.001$, $\eta_p^2=0.43$, showing that the overall accuracy of exact arithmetic was higher than the accuracy in the arithmetic estimation (see Fig. 1). There was a significant interaction between arithmetic tasks and country, $F(1, 402)=132.28$, $p<.001$, $\eta_p^2=0.25$, which showed how the execution of the two arithmetic tasks likely reflects distinct underlying mechanisms in each country. Simple effects analyses were conducted to examine this interaction using Bonferroni adjustments. The results showed that children were more accurate on exact arithmetic than arithmetic estimation for both Chinese (0.86 vs. 0.64, $p<.001$, $\eta^2_p = .48$) and Italian children (0.44 vs. 0.39, $p<.001$, $\eta^2_p = .05$). However, as shown in Fig. 1, the difference between

Table 2 Means (Standard Deviations), Range, Skewness and Kurtosis for all variables in China and Italy

Variables	Index	China (*n* = 178)				Italy (*n* = 226)			
		M (SD)	Range	Skewness	Kurtosis	M (SD)	Range	Skewness	Kurtosis
Exact arithmetic	Proportion correct	0.86 (0.14)	0.29 ~ 1.00	-1.88	3.82	0.44 (0.20)	0.08 ~ 1.00	0.50	-0.31
Arithmetic estimation	Proportion correct	0.64 (0.21)	0.17 ~ 0.98	-0.46	-0.95	0.39 (0.16)	0.08 ~ 0.90	0.59	0.02
Inhibition	Corrected IES[a]	135.19 (400.00)	-630.58 ~ 3610.92	6.41	48.71	157.90 (302.94)	-1171.34 ~ 2550.95	3.55	24.05
Shifting	Corrected IES[a]	440.94 (375.13)	-1734.64 ~ 2109.00	-1.32	13.31	734.52 (441.98)	-633.02 ~ 3190.51	1.67	5.35
Visuospatial updating	Proportion correct	0.58 (0.18)	0.06 ~ 0.93	-0.60	-0.07	0.66 (0.16)	0.08 ~ 0.95	-0.96	1.42
Visuospatial short-term memory	Total correct	46.02 (18.63)	7 ~ 95	0.77	0.08	42.46 (19.91)	19 ~ 93	0.82	-0.13
Fluid reasoning	Total correct	31.41 (4.69)	14 ~ 41	-0.82	1.70	23.12 (6.14)	7 ~ 37	-0.10	-0.55
Mathematical anxiety	Sum score	17.63 (6.72)	9 ~ 39	0.78	0.15	21.88 (7.04)	9 ~ 43	0.37	-0.12

Note[a] IES: Inverse efficiency score, details in the Methods section

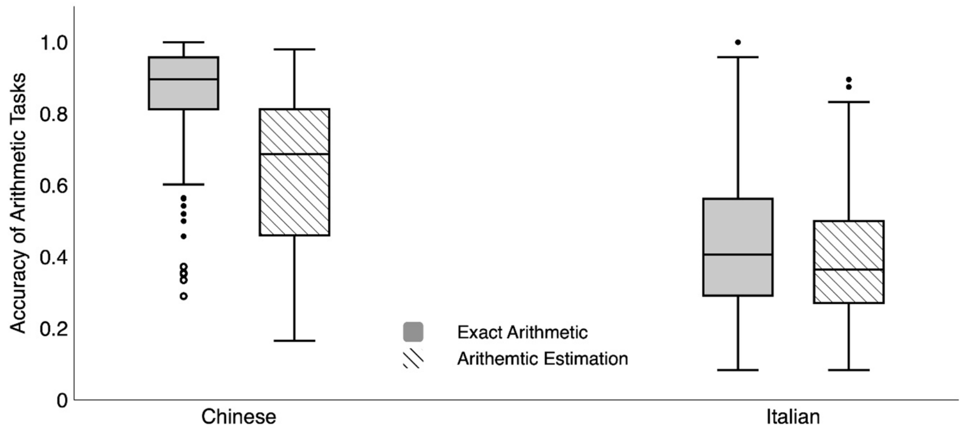

Fig. 1 Significant interaction between type of arithmetic tasks and country. *Note* The boxplots represent the quartiles of accuracy for arithmetic tasks. The upper and lower bars of the box represent the 75th and 25th percentiles, respectively. The line within the box indicates the median

Table 3 Correlations among arithmetic and other variables (Upper Triangle representing partial correlations of China and Lower Triangle representing that of Italy)

	1	2	3	4	5	6	7	8	9	10
1. Gender	-	−0.01	−0.02	0.11	**0.24****	0.08	0.11	0.07	**−0.17***	−0.03
2. Grade	0.02	-	−0.06	−0.13	0.12	−0.13	0.02	0.06	**0.20****	−0.05
3. Fluid reasoning	0.05	**0.27*****	-	**0.43*****	**0.20****	−0.09	−0.01	**0.43*****	**0.42*****	**−0.42*****
4. Exact arithmetic	−0.09	**0.23*****	**0.41*****	-	**0.57*****	−0.04	0.07	**0.39*****	**0.28*****	**−0.37*****
5. Arithmetic estimation	−0.09	**0.27*****	**0.36*****	**0.74*****	-	−0.07	0.11	**0.39*****	**0.28*****	**−0.29*****
6. Inhibition	−0.12	−0.08	**−0.20****	**−0.20****	**−0.26*****	-	−0.05	−0.07	−0.09	0.07
7. Shift	0.09	−0.06	**−0.22****	**−0.14***	**−0.21****	0.10	-	−0.02	−0.12	−0.10
8. Visuospatial updating	0.04	**0.17***	**0.37*****	**0.32*****	**0.28*****	−0.10	−0.04	-	**0.34*****	**−0.21****
9. Visuospatial short-term memory	−0.001	**0.19****	**0.45*****	**0.39*****	**0.44*****	**−0.22****	−0.09	**0.34*****	-	**−0.19***
10. Mathematical anxiety	0.09	0.06	**−0.15***	**−0.18****	**−0.21****	−0.01	**0.25*****	**−0.14***	**−0.17****	

Note $^{*}p<.05$, $^{**}p<.01$, $^{***}p<.001$. Bold values represent significant results at $p<.05$

Gender: 1=boys, 2=girls

performance on exact arithmetic and arithmetic estimation was larger for Chinese children compared to Italian children.

Correlational analyses

Correlations were conducted for the two countries separately (see Table 3). For both Chinese and Italian groups, although with variations in the strength of associations, accuracy in exact arithmetic and arithmetic estimation was positively correlated with visuospatial updating and short-term memory tasks, while negatively correlated with mathematical anxiety. Additionally, arithmetic estimation was found to be significantly correlated with inhibition and shifting among Italian children, a pattern not observed in the Chinese group.

Multi-group path analyses

Multi-group path analyses were used to test for cross-cultural differences. Given that fluid reasoning task measures general cognitive ability and was correlated with the arithmetic tasks for both groups, and gender and grade were correlated with at least one arithmetic task in one of the groups (see Table 3), these three variables were included as control variables in the models. For readability, the path coefficients associated with the control variables are shown in the figure note.

Two multi-group models were conducted, one with exact arithmetic and the other with arithmetic estimation as the outcome variable respectively. In each model, all paths were specified in Chinese and Italian groups, with the coefficients for each of the paths estimated independently for each group. The models were saturated, that is, all parameters estimated were equal to the elements in the covariance matrix, resulting in 0 degrees of freedom, thus, model fit indices were not applicable. Below, we present and interpret the results based on the estimated path coefficients for each model.

For exact arithmetic performance (see the top panel of Fig. 2), for Chinese children, updating and mathematical anxiety were unique predictors; for Italian children, updating and short-term memory were unique predictors. Post hoc comparisons of the strength of the predicted paths (i.e., reasoning, mathematics anxiety, short-term memory, updating, inhibition, and shifting)

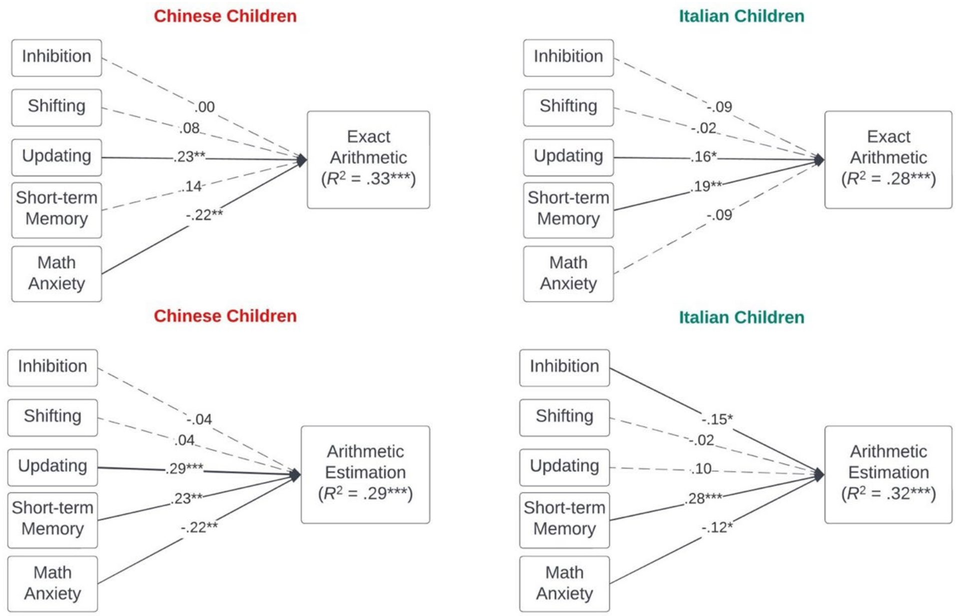

Fig. 2 *Multi-group Path Analyses showing Relations between Cognitive, Affective and Exact Arithmetic (top panel) and Arithmetic Estimation (bottom panel) for the Chinese and Italian children controlling for Gender, Grade and Fluid Reasoning. Note* Numbers on the arrows are standardized coefficients. *$p<.05$, **$p<.01$, ***$p<.001$. Dashed lines represent non-significant paths. Fluid reasoning was controlled for exact arithmetic (Chinese: $\beta=0.18$, $p=.020$; Italian: $\beta=0.21$, $p=.002$) and arithmetic estimation (Chinese: $\beta=-0.11$, $p=.161$; Italian: $\beta=0.09$, $p=.198$). Gender was controlled for exact arithmetic (Chinese:$\beta=0.10$, $p=.104$; Italian:$\beta=-0.12$, $p=.032$) and arithmetic estimation (Chinese:$\beta=23$, $p<.001$; Italian:$\beta=-0.10$, $p=.069$). Grade was also controlled for exact arithmetic (Chinese: $\beta=-0.17$, $p=.008$; Italian: $\beta=0.115$, $p=.054$) and arithmetic estimation (Chinese: $\beta=0.02$, $p=.718$; Italian: $\beta=0.16$, $p=.004$)

between Chinese and Italian children were further tested. Specifically, we used a difference test, using a model constraint command, to evaluate whether the path coefficients from each group are statistically different from each other. Post hoc comparisons revealed that all path coefficients in the model did not significantly differ between the two groups (*p*s > 0.05), suggesting that the patterns of relations among cognitive, affective factors, and exact arithmetic performance were similar across the Chinese and Italian children.

For arithmetic estimation performance (see the bottom panel of Fig. 2), for Chinese children, updating, short-term and mathematical anxiety were unique predictors; for Italian children, inhibition, short-term memory and mathematical anxiety were unique predictors. Post hoc comparisons revealed that all path coefficients in the model did not significantly differ between the two groups (*p*s > 0.05), with one exception: The path coefficient from updating to arithmetic estimation was statistically different between groups ($\beta=-0.23$, $p=.03$).

Taken together, these results suggest that for both Chinese and Italian children, cognitive and affective factors similarly predicted exact arithmetic performance, with no significant differences between the groups in the model's path coefficients. In contrast, for arithmetic estimation, while most path coefficients were similar between the groups, the path from updating to arithmetic estimation was stronger for the Chinese than for the Italian children. This finding indicated that the country moderated the relations between updating and arithmetic estimation.

Discussion

To bridge the gap identified in prior research, we examined cross-cultural differences in the performance of arithmetic estimation, a skill that is often undervalued in mathematics education globally [11]. We also examined how both cognitive (i.e., working memory and executive functions) and affective (i.e., mathematical anxiety) components contributed to performance on different arithmetic tasks (i.e., exact arithmetic and arithmetic estimation) among school-aged children in China and Italy. The results showed that both Chinese and Italian children performed better in exact arithmetic, which is more emphasized in mathematics education, compared to arithmetic estimation. Notably, Chinese children outperformed their Italian peers in both types of arithmetic tasks, with a more pronounced difference on the exact arithmetic than the arithmetic estimation. Multi-group path analyses revealed that the patterns of relations among cognitive factors, mathematical anxiety, and arithmetic performance were similar across both groups, with one exception that visuospatial updating was a unique predictor of arithmetic estimation for Chinese children but not for Italian children.

In line with previous studies [3–7, 67], Chinese children demonstrated better performance in exact arithmetic compared to their Western peers, particularly with double-digit arithmetic tasks [89, 90]. One possible explanation for this performance gap is the different arithmetic strategies used by the children. Previous research has demonstrated cultural differences in children's arithmetic problem solving strategies. For example, Chinese children prefer to rely on algebraic representations to solve arithmetic problems (i.e., fact retrieval), whereas Italian children are more inclined to use less-efficient strategies like finger counting and the right-to-left solution algorithm [91]. Similarly, American children prefer to rely on pictorial or verbal representations, which are generally less efficient [3]. Moreover, Shen et al. [90] found that 7-year-old Chinese children prefer to use retrieval strategies in simple arithmetic tasks, in contrast to their Russian and American peers who prefer counting strategies. Additionally, Chinese children are more likely to use decomposition strategies for complex arithmetic problems than their Russian and American peers.

Another possible explanation for the performance gap in exact arithmetic task between the two countries could be differences in developmental trajectories of arithmetic strategies, reflecting variances in the education systems. The early development of basic, albeit fundamental, arithmetical skills allows the faster acquisition of more advanced arithmetic strategies. Chinese children develop retrieval strategies in their preschool years, much earlier than their Western peers [92, 93]. This early advantage is further enhanced by substantial parental involvement in home numeracy activities and considerable practice with mathematical tasks by the children [94, 95]. Furthermore, Chinese parents typically have higher expectations for their children's mathematical achievement and more equipped to support their children's mathematical learning than Western parents [66]. Collectively, these cultural differences in the use of arithmetic strategies and early mathematical experiences may account for the superior exact arithmetic performance between Chinese and Western children.

In the current study, beyond the advantage in exact arithmetic, Chinese children also demonstrated a smaller yet significant advantage over their Italian peers in arithmetic estimation. This finding aligns with previous research [19, 28], which show that the children's proficiency in arithmetic estimation is generally moderate. In particular, the educational systems in both China and Italy introduce strategies for solving double-digit exact arithmetic problems starting in the second grade. In contrast, arithmetic estimation is not emphasized in mathematics education, resulting in limited instruction and practice to enhance children's estimation skills. Children seemingly begin to understand and apply various rounding-off strategies for estimation by Grade 6 [8]. Thus, it is plausible that younger Chinese and Italian children do not spontaneously use the rounding strategies when estimating [20]. An alternative explanation relates to the paradigm used in the current study for arithmetic estimation tasks, where participants had to choose the answer from four alternatives within a limited time. Some children may attempt to calculate the exact answers for estimation problems and then find it challenging to select one closest to the exact answer. Our results also show a higher correlation between exact arithmetic and arithmetic estimation performance for the Chinese sample compared to the Italian sample. Notably, educational practices prioritize exact calculation over estimation in China [96, 97] and Italy [28, 98]. This educational approach may influence individuals' efficiency in solving arithmetic estimation problems, particularly when the exact answer is within their mental calculation capability or, better yet, is readily retrievable from long-term memory as a stored arithmetic fact. Because of the greater emphasis on arithmetic fluency for Chinese children, we speculate that Chinese children might spontaneously use exact strategies to carry out the calculations involving the unit digits when solving double-digit estimation problems resulting in a higher correlation between exact arithmetic and arithmetic estimation compared to the Italian sample.

The current findings also offer insight into the specific contributions of the cognitive components of arithmetic processing. Our results reveal a cross-cultural difference in the involvement of one executive function component: visuospatial updating. Specifically, the relation between updating and arithmetic estimation was moderated by country, showing to be stronger for the Chinese than the Italian children. One possible reason is that Chinese children adapt more complex strategies to solve arithmetic estimation problems. Updating, which involves constant monitoring and rapid addition or deletion of contents in working memory, likely aids in maintaining intermediate results during arithmetic processing [99, 100]. A strategy involving multiple steps may demand greater working memory resources than a simpler one [101]. For example, the first step in solving an arithmetic estimation problem often involves rounding operands up or down to simplify the calculations. To obtain results that are closer to the exact answer, the second step may involve decomposing the problem to adjust for any rounding discrepancies. This procedure requires participants to maintain the results of the first step in their working memory [19, 21, 22]. As a result, it is possible that the reliance on a multi-step strategy leads Chinese children to rely more on updating when solving arithmetic estimation problems, thereby contributing to their better performance than Italian children in this task.

Among these cognitive factors, we found that Chinese children outperformed their Italian peers in shifting and fluid reasoning tasks, while Italian children performed better than Chinese peers in visuospatial updating task. Research on cultural differences in cognitive styles indicates that Western individuals tend to be more field-independent, focusing more on parts than on the whole. In contrast, Eastern individuals pay more attention to contextual and relational information, and thus tend to be more field-dependent [102]. Field-dependent styles require greater shifting ability [103] and enhance the ability to solve complex visuospatial tasks, such as fluid reasoning tests [104]. In our updating task, the stimuli were presented sequentially, without relational information to assist the Chinese participants in solving the task. Taken together, we speculate that the differences in cognitive styles may contribute to the different performance in various cognitive tasks between the Chinese and Italian children.

In addition to the cognitive factors, we also examined the role of an affective factor, specifically mathematical anxiety, in arithmetic processing. Unsurprisingly, Italian children were more worried about mathematics than Chinese peers. This finding is in line with previous research, which shows that Western children experience higher levels of mathematical anxiety than their East Asian peers [71] (but see [5, 6]). Mathematical anxiety has been consistently associated with poorer mathematics performance [15, 105]. Nevertheless, in the current study, the correlations between mathematical anxiety and the two types of arithmetic tasks were similar among the Chinese and Italian children. A prior study shows that, compared to Western peers, East Asian children have more positive beliefs and attitudes towards mathematics, which may lead to higher motivation for mathematical achievement [106]. Further research is needed to deepen our understanding of how affective and protective factors interact in cross-cultural contexts.

Among all the tasks, mathematical anxiety correlated not only with performance on numerical tasks, but also with the performance on cognitive tasks (i.e., updating and short-term memory tasks). Although our memory tasks do not involve numbers, memory ability may mediate the relation between mathematical anxiety and math performance. Processing efficiency theory proposes that anxiety influences task performance by taxing an individual's working memory resources [107]. Consistent with this view, previous studies have found that mathematical anxiety disrupts working memory functioning, leading to poor math performance [17, 52, 54–58].

The current study had some limitations. Firstly, our study highlights the need to address the scarcity of cross-cultural studies in this academic domain, where factors such as educational context (at the family and school levels) and the structure of the educational system (national curricula) may play significant roles. Indeed, it did not yield a pattern of results that could be anticipated based on existing literature, with the exception of mathematical proficiency. Secondly, we only tested third and fourth graders. Thus, the results cannot be generalized to other age groups because of the differences in the development of cognitive and mathematical abilities. Third, we did not account for linguistic abilities. The Chinese and Italian languages have substantial differences; for example, the Chinese pronunciation of numbers is shorter than that of Italian, which may facilitate the retrieval speed of arithmetic facts. Future studies should include linguistic tasks to investigate the effect of language in cross-cultural differences on arithmetic performance [29]. Fourth, parents' attitudes and expectations toward mathematics can greatly influence the frequency and nature of children's experience with arithmetic. We did not collect any measures in this regard, which may explain the cross-cultural differences observed in the current study. Future studies could interview participants and survey the information on parents' attitudes and expectations, which might be important to further understand the roots of cultural differences. Despite these limitations, our findings have shed light on cross-cultural differences in arithmetic skills and the underlying cognitive and affective factors between Italian and Chinese children.

Implications and conclusion

Based on the differences in mathematics education between China and Italy, we speculate that the advantage of Chinese children in arithmetic tasks may be attributed to their rigorous mathematics curriculum and home numeracy activities. Our overall results underscore the importance of enhancing arithmetic fluency in young students through comprehensive instruction and practice. Increasing the pool of arithmetic facts, safely stored and easily accessible from long-term memory, allows students to solve more complex arithmetic problems with lower cognitive cost, resulting in improved arithmetic efficiency. With practice, the arithmetic strategy will shift from procedural to retrieval-based [91, 108]. Therefore, we recommend that children receive adequate arithmetic training and practice both at school and at home.

In conclusion, we found that Chinese children outperformed their Italian peers in both types of arithmetic tasks. However, the performance advantage was smaller in the arithmetic estimation tasks compared to the exact arithmetic task. We also found that the relations between cognitive (i.e., short-term memory, inhibition and shifting), affective factors (i.e., mathematical anxiety), and arithmetic performance were similar among the Chinese and Italian children. However, there was a stronger unique link between updating and arithmetic estimation in Chinese compared to Italian children. These findings may be attributed to cultural differences in educational practices. The greater emphasis on acquiring fluency in basic arithmetic facts in China may contribute to children's efficiency in solving arithmetic estimation problems.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s40359-024-01965-6.

Supplementary Material 1

Acknowledgements

We would like to thank the children and teachers who participated in this research.

Author contributions

Wei Wei, Chang Xu and Sara Caviola analyzed the data, wrote the main manuscript. Wei Wei, Sara Caviola and Irene C. Mammarella designed the study and organized the data collection. All authors reviewed the manuscript.

Funding

This research was supported by the Science and Technology Innovation 2030-"Brain Science and Brain-like Research" Major Project (2022ZD0210800).

Data availability

All data are available at https://osf.io/yma26/.

Declarations

Ethics approval and consent to participate

This study is in line with the Declaration of Helsinki and approved by the IRB of Zhejiang University, China and the Ethics Committee on Psychology Research at the University of Padova, Italy. After approval from each school, written informed parental consent was obtained before testing the children.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

Received: 25 May 2024 / Accepted: 22 August 2024
Published online: 31 August 2024

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