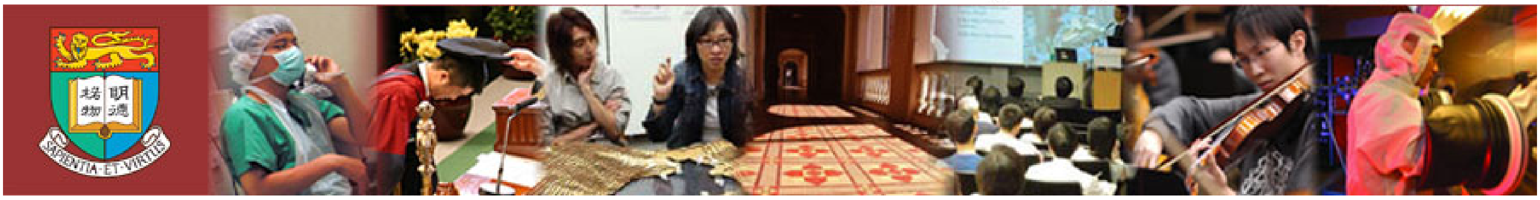

Title	The cognitive profile of Chinese children with mathematics difficulties
Author(s)	Chan, BMY; Ho, CSH
Citation	Journal Of Experimental Child Psychology, 2010, v. 107 n. 3, p. 260-279
Issued Date	2010
URL	http://hdl.handle.net/10722/124298
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The Cognitive Profile of Chinese Children with Mathematics Difficulties

Abstract

The present study examined how four domain-specific skills (i.e., arithmetic procedural skills, number-fact retrieval, place-value concept, and number sense) and two domain-general processing skills (i.e., working memory and processing speed) may account for Chinese children's mathematics learning difficulties. Children with mathematics difficulties (MD) of two age groups (aged 7 to 8 and 9 to 11) were compared with age-matched typically-achieving children. For both age groups, children with MD performed significantly worse than their age-matched controls in all the domain-specific and domain-general measures. Further analyses revealed that the MD children with literacy difficulties (MD/RD group) performed the worst in all the measures while the MD-only group was significantly outperformed by the controls in the four domain-specific measures and verbal working memory. Stepwise discriminant analyses showed that both number-fact retrieval and place-value concept were significant factors differentiating the MD and non-MD children. To conclude, deficits in domain-specific skills, especially those of number-fact retrieval and place-value understanding, characterize the profile of Chinese children with mathematics difficulties.

Keywords:

Mathematics difficulties; domain-specific skills; number skills; domain-general skills; Chinese

The Cognitive Profile of Chinese Children with Mathematics Difficulties

Children with mathematic disabilities (MD) appear to constitute a heterogeneous group, with different children showing different profiles of knowledge, learning strengths and deficits (Geary, 2002). This may be the reason why different terminologies have been used. In this study, we set out to explore the cognitive profile of Chinese children with marked difficulties in mathematics. We adopted relatively lenient criteria in order to obtain a reasonably large sample in an exploratory study with little known findings about MD in Chinese. We use the term “mathematic difficulties” instead of “mathematics disorder” or “mathematics disabilities” to include children having a broader range of difficulties.

Previous research studies have suggested that mathematic disabilities or difficulties tend to be associated with deficits in four domain-specific numerical skills (i.e., arithmetic procedural skills, number-fact retrieval, place-value concept, and number sense) and two domain-general processing skills (i.e., working memory and processing speed).

Deficits in Domain-Specific Numerical Skills

Arithmetic procedural skills. A deficit in arithmetic procedural skills typically means difficulties in executing arithmetic procedures (e.g., carrying or trading in complex addition problems), or in executing counting procedures to solve simple addition problems (Geary, 1996). For multi-step arithmetic problems, the procedural errors may include misalignment of numbers while writing down partial answers, or errors in carrying or borrowing from one column to the next (Russell & Ginsburg, 1984). Children with mathematics disabilities or difficulties, in comparison with typically-achieving children, tend to use less sophisticated strategies and commit more errors in solving addition problems (Geary, Hamson, & Hoard, 2000; Geary, Hoard, Byrd-Craven, & DeSoto, 2004; Ostad, 1997). However, many of these children improve by the middle of elementary school years (Geary, 2000; Torbeyns, Verschaffel, & Ghesquiere, 2004). Thus, their error-prone use of immature procedures seems to represent a developmental delay instead of a long-term cognitive deficit. Such delay seems to be domain-specific and does not characterize children with other academic-related learning deficits. For example, children with reading disability (RD) only do not seem to differ from typically-achieving children in their strategies for solving simple addition problems in the accuracy of strategy use (Geary & Hoard, 2002), or in multi-step calculation (Reikeras, 2006).

Number-fact retrieval. A deficit in number-fact retrieval means difficulties in accessing arithmetic facts from long-term memory (Geary, 2004). According to Geary's conceptual framework, the difficulties of storing arithmetic facts was related to the limitations of MD children in retaining information in working memory while performing other operations. For example, in doing a simple addition task of 5 + 2, children with MD may favor the "counting-all" strategy which refers to counting from 1, 2, 3…instead of counting up or on from the higher number: 5, 6, 7. The counting procedure may influence formation of long-term memory representations of basic facts if activation of numerical representations in working memory decays more quickly for children with MD. In this situation, the representation of the problem addends may decay before the count is completed and thus an association between the problem stem (e.g., 5+2) and the answer generated by means of counting may not be formed in long-term memory. A second form of retrieval deficit may have to do with difficulties in inhibiting the retrieval of irrelevant associations. For example, children with learning disorders more often incorrectly answer the question "6 + 2 = ?" with "7" or "3," which are numbers following the addends in the counting string, than their typically-achieving peers (Geary et al. 2000). Indeed, deficits of number-fact mastery among MD children seem to be rather persistent and are quite independent of reading and language abilities (Jordan, Hanich, & Kaplan, 2003a). Number-fact retrieval deficits increasingly emerge as a central characteristic of mathematics disabilities, at least with respect to addition and subtraction operations (Geary, 2004; Gersten, Jordan, & Flojo, 2005; Jordan, Hanich, & Kaplan, 2003b; Ostad, 1998; Robinson, Menchetti, & Torgesen, 2002).

While arithmetic procedural deficit in children with MD may prove to be a developmental delay, number-fact retrieval deficit seems to persist. In the present study, we compared younger and older children with MD to examine the persistence of these and other cognitive deficits.

Conceptual understanding of place value. A key insight about numbers is that the value of a digit depends on its place in a group of digits (Chinn & Ashcroft, 1999). For example, while most second-grade children have some trouble with positional knowledge and digit correspondence, the typically-achieving children outperform children with reading and/or mathematical difficulties on this (Hanich, Jordan, Kaplan, & Dick, 2001). A reliable connection between place-value understanding and addition and subtraction skills among Chinese children has also been documented. Training in place-value concept also effectively improves Chinese children's place-value understanding as well as addition skills (Ho & Cheng, 1997).

*Number sense. N*umber sense was referred to "a child's fluidity and flexibility with numbers, the sense of what numbers mean and an ability to perform mental mathematics and to look at the world and make comparisons" (Gersten & Chard, 1999, p.19). It has also been considered as important to mathematics learning as phonemic awareness is to reading. According to Berch (2005), it has generally been agreed that number sense involves abilities related to counting, number patterns, magnitude comparisons, estimation, and number transformation. Often acquired informally, it is basic and important for early formal arithmetic learning. It was found that kindergarteners' number sense performance and growth together accounted for 66% of the variance in first grade mathematics achievement in a study by Jordan, Kaplan, Locuniak, and Ramineni (2007). Similarly, results of longitudinal studies suggested that screening early weakness in number sense could help identify children who might develop mathematics difficulties or disabilities later (Gersten et al., 2005; Jordan et al., 2007; Jordan, Kaplan, Olah, & Locuniak, 2006). For instance, Locuniak and Jordan (2008) found that number sense screening in kindergarten successfully ruled out 84% of children who were not at risk for fluency difficulties and positively identified 52 % of those who later showed fluency difficulties. Because number sense is related to the meaning of numbers stored in long-term memory, Robinson et al. (2002) speculated that weak number sense might contribute to number-fact retrieval deficits in children with MD. Baroody (2008) later suggested that the best way to help students master efficient number fact retrieval was to develop their general number sense by facilitating them to discover patterns and relations among numbers. The proposed close connection between number sense and mathematics achievement in young children is supported in the recent findings by Jordan, Kaplan, Ramineni, and Locuniak (2009).

They reported that kindergarten number competence (which is similar to the concept of number sense) predicted rate of growth in mathematics achievement between first and third grades and achievement level through third grade. Poor number sense may therefore underlie children's weaknesses in fact retrieval which contribute to mathematics difficulties.

Deficits in Domain-General Cognitive Skills

Working memory. The mental capacity for temporary processing and storage of information (i.e., working memory) has been a focus in research on mathematical performance (Rosselli, Matute, Pinto, Ardila, 2006). While many would agree that children with mathematics difficulties seem to have some working memory deficit (e.g., Bull, Johnston, & Roy, 1999; Geary et al., 2004; McLean & Hitch, 1999; Rossell et al., 2006; Wilson & Swanson, 2001), contribution of specific working memory components to mathematics difficulties remains unclear.

DeStefano and LeFevre (2004) have suggested that all three components proposed by Baddeley (Baddley & Logie, 1999)—i.e. the phonological loop, the visuo-spatial sketchpad, and the central executive of the working memory system—could play a role in mental arithmetic. Yet, some studies suggested that the relation between working memory and mathematics performance varied as a function of age and ability (Andersson & Lyxell, 2007), with a stronger role for the visuo-spatial sketchpad in younger children's mathematics performance (Holmes & Adams, 2006). Other studies found that mainly the central executive was impaired in children with MD (Andersson & Lyxell, 2007; Bull et al., 1999; McLean & Hitch, 1999; Passolunghi & Siegel, 2004; Wilson & Swanson, 2001). Central executive seems to be a core deficit for children with mathematics disability, whereas phonological loop and visuo-spatial sketch pad may contribute to more specific math-related cognitive deficits (Geary, Hoard, Byrd-Craven, Nugent, & Numtee, 2007). Still other studies concluded that children with MD had problems with working memory tasks involving numerical information and not those involving non-numerical verbal information (Geary, Brown, & Samaranayake, 1991; McLean & Hitch, 1999; Passoulunghi & Siegel, 2001; Siegel & Ryan, 1989). In other words, no conclusive findings regarding the relations between mathematics difficulties and various working-memory components have so far been reported.

In the present study, Chinese children with mathematics difficulties were compared with typically-achieving children on both verbal and visual memory.

Processing speed. Children with mathematics difficulties (MD) are generally slow in solving arithmetic problems (e.g., Ostad, 2000). For instance, Jordan and Montani (1997) found that children with MD performed worse than the control group in both story and number-fact problems in timed conditions but not in untimed conditions. Perhaps children with MD simply take more time than typically-achieving peers to execute all basic numerical processes, or perhaps they favor slower counting strategies (e.g., counting-all) rather than the faster number-fact retrieval strategies (Geary, 1996). With little increase in fact retrieval speed with age, many MD children lag further and further behind their peers. Because arithmetic performance seems strongly predicted by processing speed (e.g., Bull & Johnston, 1997; Fuchs et al., 2006), arithmetic difficulties persist perhaps due to persistent processing-speed deficit, hampering automatic basic arithmetic fact retrieval (e.g., Geary et al., 2007). Slow processing speed as a general obstacle for efficient numerical operation and slowing the fact retrieval process are both plausible but not mutually exclusive. The close connection between processing speed and storage capacity of the working memory may help to explain its contribution to arithmetic difficulties (Case, Kurland, & Goldberg, 1982). The present study examined processing speed as part of the cognitive profile of Chinese children with or without mathematics difficulties and tested whether processing speed contributed to fact retrieval efficiency.

Mathematics Abilities of Chinese Children

The superiority of Chinese students' mathematics performance in comparison with their Western counterparts in cross-cultural studies has been well documented (Aunio, Ee, Lim, Hautamäki, & Luit, 2004; Geary, Bow-Thomas, Liu, & Siegler, 1996; Ho & Fuson, 1998; Miller, Kelly, & Zhou, 2005; Miura & Okamoto, 2003; Yang & Cobb, 1995). Contributing factors identified for the cross-cultural discrepancy in mathematics performance include numerical language characteristics like short pronunciation duration of Chinese numbers that would increase efficiency of mathematical operations and the regularity of Chinese number-naming system that enhances cognitive representation of numbers and understanding of place-value concepts (e.g., Ho & Cheng, 1997; Miura & Okamoto, 2003). In addition, the cross-cultural differences may be related to school curriculum, teaching practices, Chinese valuation of mathematics, parental expectations of children's mathematics performance, and the amount of time parents spent on home teaching (Stevenson & Stigler, 1992; Miller, Kelly, & Zhou, 2005). There are very few research studies on Chinese children's mathematics abilities and learning, and those on mathematics difficulties of Chinese children are even scarce. Findings of the present study would give us insights about the manifestations of mathematics difficulties among Chinese children.

Research Aims and Hypotheses

Understanding the cognitive profile of MD children is an essential first step for developing appropriate identification tools and intervention methods. Given the different numerical language characteristics of Chinese, Chinese children with MD may exhibit different numerical and cognitive difficulties that could not be informed by research studies with American or European students. The aim of the present study was to examine the cognitive profile of Chinese children with mathematics difficulties (MD). Specifically, we examined if and how children with MD would be different from their typically-achieving peers in four domain-specific numerical skills (i.e., arithmetic procedural skills, number-fact retrieval, place-value concept, and number sense) and two domain-general processing skills (i.e., working memory and processing speed). We focused on two age groups in primary school: children aged 7 to 8 because MD typically becomes quite noticeable by this age; children aged 9 to 10 because MD not outgrown by then is probably rather persistent. The main hypotheses were as follows:

1. Both younger and older MD groups would perform significantly worse than the typically-achieving controls in all the domain-specific and domain-general measures. As the domain-specific numerical skills may contribute more directly to children's arithmetic performance, it is expected that performance differences between the MD and control groups on the domain-specific measures would be greater than those on the domain-general measures.
2. Previous research findings have suggested that arithmetic procedural deficit in children with MD may prove to be a developmental delay, whereas number-fact retrieval deficit seems to persist.

Based on such previous findings and our preliminary findings (Chan, 2008), we expected that all four basic number skills (i.e., arithmetic procedural skills, number-fact retrieval, place-value concept, and number sense) would be useful for differentiating the younger MD and non-MD groups, whereas number-fact retrieval and place-value concept would be especially useful for differentiating the older MD and non-MD groups as children with MD are likely to have outgrown their earlier deficits in arithmetic procedural skills and basic number sense by fourth grade.

3. Since children with both mathematics and literacy difficulties (MD/RD) might suffer from a more severe general impairment than those with mathematics difficulties only (MD-only), we expected that the MD/RD group would perform worse than both MD-only and Control groups in all the measures.

For testing hypotheses 1 and 2, four groups of children (younger MD, older MD and their corresponding Control groups) were formed for comparison and analyses. Another three groups of children (MD-only, MD/RD and Control groups) were formed to test hypothesis 3.

Method

Participants

The younger and older MD groups and their controls. Children with mathematics difficulties (MD) were recruited through two channels: local Child Assessment Service and ordinary primary schools. For those recruited from child assessment service, they had been diagnosed to have mathematics disorder or mathematics difficulties by paediatricians or clinical psychologists. For those recruited from schools, their parents had indicated in the questionnaire that their mathematics performance were very unsatisfactory. Selection criteria for both sources were those: (1) studying in mainstream school at Grade 2 to Grade 4 with IQ scores $\geqq$ 85; (2) with both the total score of the Hong Kong Attainment Test on Mathematics (Education Department, Hong Kong SAR Government, 2000) and the Arithmetic subtest score below the bottom 25^{th} or 20^{th} percentile for Grade 2 and Grades 3 and 4 respectively; and (3) no known sensory disorders (e.g., hearing or vision impairment, seizures, and cerebral palsy) or reported poor learning motivation. A lower cut-off point for Grade 3 and Grade 4 was adopted because recent curriculum change had rendered the attainment test (being normed 4 to 5 years prior to our data collection) rather difficult for children in these two grades. Using a lower cut-off point helped to exclude some false alarm cases (i.e., children who probably did not have MD). With these selection criteria, a total of 84 children with MD (38 from the Child Assessment Service and 46 from three local schools) were recruited. For comparison of developmental change, these children were further divided into two age groups: 40 in the younger MD group (aged 7 to 8) and 44 in the older MD group (aged 9 to 11).

Children of the corresponding Control groups were selected from three ordinary primary schools. Selection criteria were those with IQ scores ≧ 85, and both the standardized mathematics attainment test and its arithmetic subtest scores higher than the 25th percentile for Grade 2 and 20th percentile for Grade 3 and Grade 4 respectively. The mean scaled scores of the arithmetic performance were 105.50 and 100.07 for the younger and older Control groups respectively. Similar cut-off criteria were used in past studies (e.g., Jordan & Montani, 1997). We also matched the age, IQ scores, and socioeconomic background (in terms of parent education and family income) of children in the Control groups with those in the MD groups. Altogether, 40 and 44 children were recruited for the younger and older Control groups respectively. Table 1 shows the details of the children's characteristics of the four groups. It was noteworthy that the two MD groups also performed less well in literacy than their corresponding Control groups.

The MD-only, MD/RD, and the Control group. To further examine whether literacy difficulties in addition to MD represents a qualitatively distinct group or a simple combination of number and language weaknesses, a MD/RD group was identified. With the two MD age groups combined, those children whose Literacy composite score on the standardized Hong Kong Test of Specific Learning Difficulties in Reading and Writing (HKT-SpLD) (Ho, Chan, Tsang, & Lee, 2000) was 7 or below (i.e., 1 or more SD below the age mean) were identified as having literacy difficulties in addition to mathematics difficulties. Out of the total 84 MD children across the two age levels, there were 28 having both literacy and mathematics difficulties (MD/RD) and 49 with mathematics difficulties only (MD-only). Meanwhile, we did not have information about the literacy performance of 7 children in the MD groups.

For the Control group of this three-group comparison, with the two original Control age groups combined, 76 of them had literacy composite score on the HKT-SpLD above 7. They were treated as controls for the MD-only and MD/RD groups. Table 2 presents the characteristics of these three groups of children.

Materials and Procedures

All the participants were given a battery of tests on mathematics attainment, intellectual functioning, and tasks on basic numerical skills, working memory and processing speed. For those recruited from schools, the tasks on number sense, working memory, and processing speed were individually administered, while others were administered in group. For the children with MD recruited from Child Assessment Service, all tests were individually administered.

Intellectual functioning. The Raven's Standard Progressive Matrices was used for assessing non-verbal intelligence. There were 60 items presented in five sets. Each item contained a target visual matrix with one missing part, and the child was asked to find the missing piece from six to eight alternatives. Scoring was based on the local norms established by the Hong Kong Education Department in 1986. The reported test-retest reliability of different age levels ranged from .72 to .82. The test was given to all of the children recruited from schools. For children recruited from the CAS, this test was administered if no IQ scores within the normal range (i.e., ≧ 85) had been documented in their clinical records at Child Assessment Service.

Mathematics attainment. The Hong Kong Attainment Test on Mathematics is a standardized test for Hong Kong children of Grades 1 to 9, with local norm for each grade level. With 35 to 38 items for Grades 2 to 4 children, the Test covered items on arithmetic, measure, shape and space, and data handling. Arithmetic items constituted around 55% of the Test. The children were required to complete the Test in 45 minutes. Raw scores were converted to percentile scores according to the graded local norms.

Arithmetic procedural skills. Basic arithmetic computation skills were assessed with criterion-referenced test items developed by Chinn (2004, p.164-168) on the four operations with positive integers. The test consisted of 16 items which included addition, subtraction, and two simple multiplication questions. Complexity of the problems varied from simple operation like 7 + 6 to multiple operations such as 8000 – 1056 + 1963. The Cronbach's alpha reliability coefficient of the test was .76.

The participants' types of errors on the Arithmetic computation test were coded independently by one of the authors and a research assistant. The children's computation errors were categorized into 3 error types: no attempt, basic number-fact error, and procedural error. Basic number-fact errors referred to errors in recalling basic number facts, for example. 6 + 7 = 14. Procedural errors refer to errors that involved procedural steps in computation. For example, procedural errors might result from a child's forgetting to do carrying in addition or borrowing in subtraction; or when the child reversed the subtrahend and minuend in the ones place, thus omitting the borrowing step like 84 – 47 = 43. Inter-rater reliability between the two independent coders was high (intraclass *R*s ranged from 0.76 to 0.98). One procedural error represented a mistake in a procedural step and so in computing an item, a child might commit from no errors to several errors. There was no maximum score for this task. The number of procedural errors was used in later analyses for us to understand children's arithmetic procedural skills.

Number-fact retrieval. The Addition and Subtraction sections of the One Minute Tests of Basic Number Facts (Westwood, 2000) were used to assess children's number-fact retrieval skills. In the original version, there were 33 items of single-digit addition, 20 items of single-digit subtraction, and 13 items of single-digit from two-digit substraction. The reported test-retest reliability of different age levels ranged from .88 to .94. For the present study, 17 items modelled on the original items were added to the addition and the subtraction section (i.e., 50 items in total for each section) because most fourth graders in our pilot testing took considerably less than one minute to complete the original 33-item test.

A child's number of correct responses for the addition and subtraction parts combined was used to assess the child's number-fact retrieval skills and the maximum score of this task was 100.

Place-value concept. With reference to standardized achievement tests and local textbooks, Hong Kong second grade children were expected to understand place value in positive integers up to the hundreds, while children in the fourth grade should understand place value up to thousands. A place-value concept task was constructed which asked the children to mark the digit representing a certain place value in a 2- or 3-digit number, trans-code numbers written in Chinese characters and Arabic numerals, combine digits to form the largest or smallest possible numbers, and to transform diagrams representing place values (e.g., squares arranged in stacks of 10's) into numerals, etc. An English translation of the test items were listed in Appendix I. Basically, one score was given to one correct response and the maximum score of this task was 35. The test reliability (Cronbach's alpha) was .91. To establish face validity of the task, we consulted two experts on dyslexia, dyscalculia, and mathematics education, and both agreed that the task measured place-value concept.

Number sense. As in previous studies (e.g., Berch, 2005), our number sense task included items on comparison of number magnitudes, number sequencing, estimation, and number-sense application in practical situations (for easy reference, translated items were listed in Appendix II). One score was given to one correct response and the maximum score of this task was 30. The test reliability (Cronbach's alpha) was .82. Again, both of our expert consultants agreed that this task measured basic number concept.

Working memory. The backward digit span items of the Digit Span subtest of the Hong Kong Wechsler Intelligence Scale for Children (Backward DS) was used as a measure of verbal working memory. Children were asked to repeat single-digit numbers backward with increasing length of 2 to 8 numbers per each of the total 14 items. One score was given to each correct item and the maximum score was 14. The reported reliability of different age levels of the subtest ranged from .45 to .77. Visual working memory was assessed with the Visual Memory subtest of Gardner's Test of Visual-Perceptual Skills (non-motor) Revised (TVPS-NM: Gardner, 1996). For each test item, a child saw a target visual figure for 4 seconds and was then asked to identify from memory the target among 5 figures. There were a total of 16 items with one score for each correct response. The reported reliability of different age levels ranged from .36 to .64. The verbal and visual memory tasks were used to assess domain-general working memory capacity. Correlation between these two measures was .22 ($p < .01$).

Processing speed. Two tests were used to assess domain-general processing speed: Visual Matching (a subtest of the Woodcock Johnson III Cognitive Tests) and Digit Rapid Naming (a subtest of the HKT-SpLD; Ho et al. 2000). In each of the 60 items of the Visual Matching test, a child had to identify and circle two identical numbers in a row of six numbers. The task increased in difficulty by going from single-digit numbers to triple-digit numbers and the child was asked to complete the task as quickly as possible within 3 minutes. The total score for this task was 60. The reported reliability of the test of different age levels ranged from .73 to .83. In the Digit Rapid Naming test, 40 digits were printed in black on an A4 paper, with five digits (2, 4, 6, 7 and 9) arranged in eight rows, with each digit repeated eight times in random order. The child was asked to name the 40 digits as fast and as accurately as possible from left to right and row by row. The child was asked to name the list twice, and the average time was taken as the score. The reported test-retest reliability of the Digit Rapid Naming test of different age levels ranged from .68 to .93. Correlation between the visual and verbal processing speed measures was -.48 ($p < .01$). Although these two tests may not be pure measures of processing speed, we considered the efficiency of processing numbers visually and verbally relevant for general mathematics performance.

Literacy skills. Three literacy subtests of the Hong Kong Test of Specific Learning Difficulties in Reading and Writing (HKT- SpLD) (Ho et al., 2000) were administered to the children individually. The Test is a locally-normed standardized test, with sub-scores in Chinese Word Reading, One-minute Word Reading, and Chinese Word Dictation, which may be combined to yield a composite literacy score. In the Chinese Word Reading subtest, the children were asked to read aloud 150 Chinese two-character words in the order of graded difficulty. There were 90 simple Chinese two-character words in the One-minute Reading subtest. The children were asked to read aloud each word as quickly and as accurately as possible within one minute. In the Chinese Word Dictation subtest, the children were asked to write for dictation 48 Chinese two-character words. The subtest was discontinued when the child failed to write correctly 8 consecutive words. The reported reliability of these subtests of different age levels ranged from .89 to .99. Scaled score of each subtest has a mean of 10 and a standard deviation of 3. Literacy difficulties were operationally defined as having a literacy composite score 7 or below.

Results

Comparing the Younger and Older MD Groups and their Controls

Table 3 shows the means and SDs of the four groups on various measures. A 2 (MD vs Control) x 2 (younger vs older) MANOVA was conducted to examine the Math ability effect and Age effect on all the measures. The overall main effects of Math ability and Age (all *Fs* > 12.65, all *ps* < .001, all partial η^2 > .39) were significant and the effect size was large while their interaction effect [$F(8, 157) = 3.09$, $p < .01$, partial $\eta^2 = .14$] was also significant. Results of separate ANOVAs showed that the MD groups performed significantly less well than their Control groups in all the measures (all *Fs* > 9.34, all *ps* < .01, all partial $\eta^2 > .05$) and the effect sizes of the group differences on the domain-specific measures (with partial η^2 ranged from .15 to .24) were generally larger than those on the domain-general measures (with partial η^2 ranged from .05 to .13). The younger children also performed significantly less well than the older ones in all the measures (all *Fs* > 8.01, all *ps* < .01, all partial $\eta^2 > .04$). For the individual interaction effects, only those on Number sense and Digit rapid naming were significant (all *Fs* > 4.48, all *ps* < .05, all partial $\eta^2 > .02$). Further analyses showed that the MD children named digits significantly more slowly than controls in younger children ($F = 12.05$, $p = .001$, partial $\eta^2 = .13$) but not in older children. For Number sense, MD children performed significantly less well than controls for both age groups (all *Fs* > 18.08, all *ps* < .001, all partial $\eta^2 > .16$) but the effect size was greater in the younger group than in the older group (partial η^2: .25 vs. .17 respectively). These findings generally support Hypothesis 1 that children with MD lag behind their typically-achieving peers in all the domain-specific and domain-general skills. However, among various skills, the MD children tended to catch up with their peers on processing speed and narrow the gap on number sense when they were two years older around age 10. Meanwhile, it is noteworthy that there was ceiling effect for the older group on the Number sense task and the numbers of procedural errors of older children and typically-achieving children were also low. Hence, interpretation of these results requires caution.

Discriminant Analyses for Differentiating between MD and Typically- Achieving Children

Partial correlation analyses among the various measures with control of age and IQ were conducted. The pattern of associations of the MD group was largely similar to that of the typically-achieving group except that slightly more significant correlations among the various measures were found in the MD group. Results of partial correlation analyses for the two groups combined were shown in Table 4. It was found that the four domain-specific skills were significantly correlated with the arithmetic performance and among themselves in the predicted direction (all $|r|$s >.35, all ps < .001). Significant correlations were also found between arithmetic performance and the domain-general processing skills (all $|r|$s > .23, all ps < .01). It is noted that verbal working memory (i.e., backward digit span), correlated more strongly with mathematics performance and number skills than visual memory did, and processing speed also particularly associated with fact retrieval better than with other number skills. In general, the extent of associations among the domain-specific skills and with arithmetic performance was stronger than that of domain-general skills.

Hierarchical regression analyses were carried out to examine the relative contributions of the four domain-specific skills and the two domain-general processing skills to arithmetic performance. As shown in Table 5, after entering age and IQ as the first step and the domain-general measures as the second step, the domain-specific skills still made significant unique contribution and accounted for 18 % additional unique variance of arithmetic performance. Meanwhile, if the domain-specific measures were entered as the second step, they, together with age and IQ, accounted for 40 % of the variance. In both occasions, individual measures of place value, fact retrieval, and procedural errors made significant contributions to arithmetic performance. However, significant unique contribution of the domain-general measures was found only when they were entered as the second step.

Stepwise discriminant analyses were run to identify the combination of variables that most accurately differentiated children with MD and children without the difficulties. The four domain-specific and the two domain-general skills were entered as predictors. Table 6 shows results of the classification. For the younger age group, the stepwise discriminant analysis selected three variables, namely, place value ($F = 26.88$, $p < .001$), number-fact retrieval ($F = 22.32$, $p < .001$), and arithmetic procedural errors ($F = 16.96$, $p < .001$) that could effectively differentiate the MD and Control groups. This discriminant function was statistically significant (Wilks' $\Lambda = .60$, $p < .001$), and the three predictors together correctly classified 77.5% of the children into the MD and Control groups. For the older group, the stepwise discriminant analysis selected only two predictors: number-fact retrieval ($F = 25.94$, $p < .001$) and place value ($F = 20.96$, $p < .001$). The discriminant function was again statistically significant (Wilks' $\Lambda = .67$, $p < .001$), and the correct classification rate using these two predictors was 77.3%. The classification results in both younger and older age groups were considered to be good.

These results generally support Hypothesis 2 that (1) place-value concept, number-fact retrieval, and procedural skills are important factors which differentiate the MD and the Control groups in younger children; and (2) only place-value concept and number fact skills are important predictors in older children. Contrary to our prediction, number sense could not differentiate between children with or without MD in the younger age group.

Comparing the MD/RD, MD-Only, and Control Groups

Table 7 shows the results of MANOVA comparing the MD/RD, MD-only, and the Control group on the various measures. The main effect of Group was significant (F =3.91, $p < 0.001$ partial $\eta^2 = .18$) and the effect size was medium to small. Follow-up ANOVAs and post-hoc test of Scheffe showed that the MD/RD group performed significantly less well than the Control group in all the domain-specific and domain-general measures, whereas the MD-only group performed significantly less well than the Control group in all the domain-specific measures and only one domain-general measure (i.e., Backward digit span, a measure of verbal working memory). The MD/RD group also performed worse than the MD-only group in two domain-specific measures (i.e., number-fact retrieval and number sense) and one domain-general measure (i.e., digit rapid naming, a measure of verbal processing speed). The present results generally support Hypothesis 3 that the MD/RD group performed the worst among the three groups in most measures.

Discussion

With reference to research findings on mathematics learning disabilities in Western populations, the present study set out to chart the cognitive profile of Chinese children with mathematics difficulties. Specifically, children's performance on the four domain-specific numerical skills (arithmetic procedural skills, number-fact retrieval, place-value concept, and number sense) and the two domain-general processing skills (working memory and processing speed) were examined.

Profile of Chinese Children with Mathematics Difficulties

For both age groups (i.e., aged 7 to 8 and 9 to 11), children with mathematics difficulties generally performed less well than typically-achieving children in the four domain-specific and two domain-general measures. As suggested by the results of the correlation and regression analyses, the associations of the domain-specific skills with and the contributions of these skills to arithmetic performance are stronger and more significant in comparison with the domain general skills. The sizes of MD-control group differences were bigger on the domain-specific numerical measures than those on the domain-general processing measures. This may not be surprising as the domain specific skills involve basic number skills which have more direct relations with arithmetic operations than the general processing skills.

Difficulties in number-fact retrieval (Geary, 2004; Geary & Hoard, 2002; Gersten et al., 2005; Jordan et al., 2003a; Ostad,1998; Robinson et al., 2002; Shalev & Gross-Tsur, 2001) and in executing calculation procedures, use of immature problem-solving strategies, long solution time, and high error rates (Geary, 1993; Geary et al., 2000; Geary et al., 2004; Ostad, 1997) had generally been considered core features of children with mathematics disabilities. These features may partly be a result of poor working memory and slow processing speed (e.g., Adams & Hitch, 1997; Ashcraft, 1995; Bull & Johnston, 1997; DeStefano & LeFevre, 2004; Fuchs et al. 2006). Similarly, deficits in place-value understanding (Jordan & Hanich, 2000; Hanich et al., 2001) and in early number sense development (Gersten et al., 2005; Jordan et al., 2007; Jordan et al., 2006) were also documented to predict mathematics disabilities. Findings of the present study confirm that similar to those in western studies, these number-related deficits are also found among Chinese children with mathematics difficulties. Despite the fact that the regularity of Chinese number-naming system has facilitated children's understanding of place-value concepts, the present study has found that Chinese children with mathematics difficulties have also shown deficits in place-value understanding as found in western studies (Jordan & Hanich, 2000; Hanich et al., 2001).

Another important finding was that mathematics performance appears to relate more to verbal memory than to visual memory. In other words, processing numbers verbally is essential for solving most mathematic problems. Deficit in verbal working memory is also a predictor of MD. This supports domain specific memory requirement for mathematics achievement.

Overall speaking, the domain-specific and domain-general deficits seem to be rather universal among children with mathematics difficulties in different language communities.

Number-Fact Retrieval and Place-Value Understanding as Significant Factors for Differentiating Chinese Children with or without MD

For children aged 7 to 8, the present findings show that place-value understanding, number-fact retrieval, and arithmetic procedural skills are significant factors for classifying children with or without MD. Although not statistically significant in the stepwise discriminant analysis, children with MD did have weaker number sense than their peers as revealed by the ANOVA results. Future studies may explore whether number sense is a sensitive discriminator of MD for younger children like preschoolers as it develops rather early. In any case, our findings are consistent with the view of Landerl's group (2004) that MD involves domain-specific disabilities in basic numerical processing.

For older children aged 9 to 11, number-fact retrieval and place-value understanding were found to be significant in the discriminant analysis as predicted. As children's procedural skills improved during primary-school years, number-fact retrieval and place-value understanding remain the most important factors for differentiating children with or without MD. Our findings echo the general consensus that deficits in number-fact retrieval being a core and persistent characteristic of mathematics disabilities. Importantly, our findings add to the relatively sparse evidence of the importance of deficits in place-value understanding for mathematics difficulties. On the other hand, Chinese children with MD tend to be delayed in the development of verbal processing speed and they catch up with their peers around age 10. In other words, even though MD children may be slow in processing at the beginning, these are not the causes for their persistent difficulties in the long run.

In the study by Landerl et al. (2004), some 8 to 9 years old children with both reading and mathematics disabilities had problem with place-value concept. They seemed to have trouble understanding the syntax of the written number system in English. As it turns out, many of the Chinese children in our study with mathematics difficulties showed syntax confusion (e.g., they transcoded "one thousand three hundred and eighty" (一千三百八十 meaning 1380) as "13810" or "130080". Reasons for the persistence of place-value difficulties in Chinese MD children require further investigation in future research.

Similar Number-Related Deficits in Chinese MD Children with or without Literacy Difficulties

Jordan, Hanich, and Uberti (2003) have advocated examining two MD subgroups, namely, children with no reading difficulties versus those with reading difficulties. This was what we had done in the present study. In comparison with children with MD-only and typically-achieving peers, children with both mathematics and literacy difficulties (MD/RD) in general performed the worst. They were significantly outperformed by their same-age peers in all the measures. The MD-only children were also significantly outperformed by their age counterparts in all the domain-specific measures and one domain-general measure (i.e., backward digit span). The present findings are somehow consistent with those by Geary et al. (2000) that both achievement subgroups (MD/RD and MD-only) performed alike in basic number tasks, although the MD/RD subgroup appeared to be more deficient. Similarly, in the review by Jordan (2007), he concluded that "…children with MD only and MD/RD have core deficits in numerical cognition or number sense, including number processing and basic arithmetic" (p. 113). The present findings lend support to this conclusion that the character of MD-only and MD/RD number weaknesses as shown in their performance on the domain-specific tasks are similar. In other words, they are not qualitatively distinct in terms of number competence.

Children with both mathematics and literacy difficulties have been postulated to suffer from a more severe general impairment than those with mathematics difficulties only (Gifford, 2005; Jordan & Montani, 1997; Landerl, Bevan, & Butterworth, 2004). With working memory and processing speed being essential for both mathematics learning and reading (e.g., Oakhill & Cain, 2004; Oakhill, Cain, & Bryant, 2003; Perfetti, 1999; Perfetti & Hart, 2001), it is understandable why children with both mathematics and literacy difficulties tend to have more severe impairment in these domain-general processing skills than those with MD only.

In particular, the MD/RD group was significantly outperformed by the MD-only group in one domain-general measure, i.e., rapid naming. Rapid naming deficit has been identified as one of the dominant cognitive deficits in Chinese dyslexic children (Ho, Chan, Lee, Tsang, & Luan, 2004). This special cognitive deficit in Chinese dyslexic children explains why those having literacy difficulties in addition to mathematics difficulties are especially weak in rapid naming. Apart from slow processing speed, deficit in rapid naming may also reflect disruption or poor orthographic representation that is more to do with reading than with mathematics learning.

Limitations and Suggestions for Future Research

One limitation of the present study involves the inclusion criteria for children with mathematics difficulties. To achieve a good sample size, we adopted somewhat lenient inclusion criteria in this exploratory study. As Geary et al. (2007) noted, "…use of a restrictive cutoff criterion identifies children with pervasive and often severe math cognition deficits and underlying deficits in working memory and speed of processing, whereas use of a lenient criterion identifies children that may have more subtle deficits in a few math domains." (p. 1357). Our somewhat lenient criteria might have resulted in some false positive cases (i.e., children whose inferior performance in mathematics was primarily due to sub-optimal environmental factors such as lack of appropriate instructions instead of due to pervasive cognitive deficits). In future studies, it would be helpful to consider teacher's nomination and persistently below standard achievement scores across two successive academic years.

A second limitation has to do with the measures. We had ceiling effects for the Arithmetic computation and Number sense tasks for the older children. More challenging items or tasks with time limits are needed in future studies. In the present study, only addition and subtraction items were covered in the number-fact retrieval task. Inclusion of multiplication and division items may be considered in future research, especially for children of Grade 3 or above.

Furthermore, we used cross-sectional data of children in two age groups to infer about developmental changes. Longitudinal studies would be more informative for examining children in the low achievement group who has persistent difficulties versus those who have only temporary difficulties (Reikeras, 2006), and the issue of developmental delay versus persistent deficit may be addressed more adequately.

To conclude, the present study has demonstrated that the four domain-specific numerical skills (i.e., arithmetic procedural skills, number-fact retrieval, place-value concept, and number sense) and the two domain-general processing skills (i.e., working memory and processing speed) are significant contributors of arithmetic performance among Chinese school-aged children. Weaknesses in the domain-specific skills, especially number-fact retrieval and place-value understanding, characterize the profile of Chinese children with mathematics difficulties.

Table 1

Characteristics of the Younger and Older MD Groups and Their Control Groups

Characteristics	Younger Groups			Older Groups		
	MD (n = 40)	Control (n = 40)	F (1, 78)	MD (n = 44)	Control (n = 44)	F (1, 78)
Age (in years; months)	8; 3 (0; 5)	8; 2 (0; 4)	0.78	10; 1 (0; 6)	10; 1 (0; 4)	0.03
IQ[a]	98.70 (9.27)	98.68 (9.02)	0.00	98.81 (8.50)	99.60 (8.06)	0.19
Arithmetic performance[a]	77.56 (6.97)	105.50 (8.06)	274.73***	76.56 (7.15)	100.07 (8.39)	200.26***
Literacy Composite[a]	8.01 (3.04)	11.20 (2.24)	28.35***	7.71 (2.98)	10.47 (1.78)	24.99***
Father education[b]	38.40	38.61	717.50[c]	43.16	42.85	895.50[c]
Mother education[b]	38.41	42.59	716.50[c]	41.53	45.47	840.00[c]
Family income[b]	37.55	43.45	682.00[c]	39.50	48.40	752.50[c]

Note. ***$p < .001$.
[a]in scaled score. [b] mean rank. [c]Mann-Whitney U.

Table 2

Characteristics of the MD-Only, MD/RD, and the Control Group

Characteristics	MD/RD (*n* =28)	MD-only (*n* = 49)	Control (*n* =76)	*F* (2, 150)	Post hoc comparison by Scheffe
Age (years; months)	9; 2 (1; 0)	9; 0 (1; 0)	9; 0 (1; 0)	.24	MD/RD = MD-only = Control
IQ	101.32 (10.56)	96.73 (7.18)	99.11 (8.39)	2.74	MD/RD = MD-only = Control
Arithmetic Performance[a]	75.72 (7.18)	77.40 (6.75)	102.57 (8.67)	207.30***	MD/RD < Control*** MD-only < Control*** MD/RD = MD-only
Literacy Composite[a]	4.62 (1.81)	9.71 (1.63)	11.07 (1.78)	141.15***	MD/RD < Control*** MD-only = Control MD/RD < MD-only***

Note. MD/RD: Mathematics & Literacy difficulties.
MD only: Mathematics difficulties only.
[a] in scaled score. ***$p < .001$.

Table 3

Comparison of the Younger and Older MD Groups with Their Control Groups on Various Measures of the Study

Measures (max. score)	Younger Groups		Older Groups	
	MD (*n* = 40)	Control (*n* = 40)	MD (*n* = 44)	Control (*n* = 44)
Procedural Errors	6.25 (4.12)	3.15 (2.68)	2.93 (2.90)	1.30 (1.25)
Fact Retrieval (100[b])	33.60 (10.95)	44.40 (7.70)	51.43 (11.94)	66.86 (16.16)
Place Value (35)	18.23 (6.51)	24.78 (4.64)	26.30 (5.85)	31.34 (3.85)
Number Sense (30)	17.73 (5.29)	23.05 (4.12)	25.20 (3.81)	27.95 (1.96)
Working Memory				
Backward DS (14)	4.05 (1.38)	4.73 (1.62)	4.43 (1.95)	5.95 (2.25)
Visual Memory (16)	11.28 (1.92)	12.00 (1.68)	12.84 (1.40)	13.61 (1.32)
Processing Speed				
Visual Matching (60)	29.85 (6.54)	34.03 (5.36)	39.11 (6.27)	44.00 (5.84)

Digit Rapid Naming[a]	25.35 (10.47)	18.93 (5.21)	17.98 (5.62)	16.06 (3.78)

Note. [a] in seconds. [b]the score can be prorated to be more than 100 if the child finishes the task before the time limit.

Table 4

A Matrix of Partial Correlation Coefficients among Various Measures for All the Participants in the Study

	1	2	3	4	5	6.1	6.2	7.1
1. Arithmetic Performance								
2. Procedural errors	-0.41**							
3. Fact Retrieval	0.49**	-0.36**						
4. Place Value	0.51**	-0.35**	0.38**					
5. Number Sense	0.50**	-0.47**	0.51**	0.53**				
6. Working Memory								
6.1 Backward DS	0.31**	-0.28**	0.47**	0.40**	0.34**			
6.2 Visual memory	0.23**	-0.14	0.14	0.22**	0.21**	0.18*		
7. Processing speed								
7.1 Visual matching	0.37**	-0.36**	0.58**	0.34**	0.41**	0.26**	0.12	
7.2 Digit rapid naming[a]	-0.35**	0.07	-0.51**	-0.31**	-0.40**	-0.33**	-0.15	-0.39**

Note. $^{*}p < .05$. $^{**}p < .01$.
[a] in seconds.

Table 5

Hierarchical Regression Analyses predicting Arithmetic Performance by Various Measures for All the Participants in the Study

Step	Variables	*B*	*SE B*	*ß*	R^2 Change	Total R^2
1	General Control Variables				0.00	0.00
	Age	-0.02	.08	-.02		
	IQ	0.02	.12	.01		
2	Domain General Measures				0.23***	0.23
	Backward DS	1.11	.50	.17*		
	Visual memory	1.20	.58	.17*		
	Visual matching	0.45	.15	.28**		
	Digit rapid naming	-0.33	.14	-.19*		
3	Domain Specific Measures				0.18***	0.42
	Procedural errors	-0.72	.30	-.19*		
	Fact retrieval	0.20	.08	.26*		

	Place value	0.57	.17	.31**		
	Number sense	0.35	.24	.15		
2	Domain Specific Measures				0.40***	0.40
3	Domain General Measures				0.01	0.42

Note. *p < .05. **p < .01. ***p < .001.

Table 6

Classification Results of Discriminant Ananlyses for Children with or without MD

	Predicted for Younger group		Predicted for Older group	
Actual	MD	Control	MD	Control
MD	28	12	32	12
Control	6	34	9	35

Note. For Younger group, 77.5 % of original cases correctly classified.
77.5 % of cross-validated grouped cases correctly classified.
For Older group, 77.3 % of original cases correctly classified.
76.1% of cross-validated grouped cases correctly classified.

Table 7

Comparison among the MD/RD, MD-Only, and Their Control Group on Various Measures in the Study

Measure	MD/RD (*n* = 28)		MD-only (*n* = 49)		Control (*n* =76)		*F* Value	Effect Size	Post hoc comparison by Scheffe
	M	*SD*	*M*	*SD*	*M*	*SD*	*F* (2, 150)		
Procedural Errors	5.18	4.46	4.02	3.49	2.11	2.08	12.07***	.14	MD/RD > Control*** MD-only > Control** MD/RD = MD-only
Fact Retrieval	34.82	11.57	46.55	14.41	56.18	17.37	20.38***	.21	MD/RD < Control*** MD-only < Control** MD/RD < MD-only**
Place Value	20.57	7.31	23.12	7.59	28.16	5.10	17.96***	.19	MD/RD < Control*** MD-only < Control*** MD/RD = MD-only
Number Sense	19.60	5.80	22.57	5.98	25.66	3.71	17.31***	.19	MD/RD < Control*** MD-only < Control** MD/RD < MD-only*
Working Memory									
Backward DS	3.82	1.44	4.61	1.75	5.54	2.04	9.85***	.12	MD/RD < Control*** MD-only < Control** MD/RD = MD-only

Visual memory	11.79	1.81	12.16	1.90	12.82	1.73	4.07*	.05	MD/RD < Control* MD-only = Control MD/RD = MD-only
Processing Speed									
Visual matching	32.04	9.16	35.82	6.74	39.17	7.56	14.38***	.16	MD/RD < Control*** MD-only = Control MD/RD = MD-only
Digit rapid naming (in seconds)	25.65	12.18	19.81	6.17	17.31	4.61	9.54***	.11	MD/RD > Control*** MD-only = Control MD/RD > MD-only**

Note. *$p < .05$. **$p < .01$. ***$p < .001$.

Acknowledgement

We would like to thank the kind support of the three participating schools, their teachers and students. Special thanks also go to Prof. Terry Au of the University of Hong Kong for her valuable inputs to improve the draft of this paper.

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