Running head: CULTURAL DIFFERENCES IN COMPLEX ADDITION

Cultural differences in complex addition:
Efficient Chinese versus adaptive Belgians and Canadians

Journal of Experimental Psychology: Learning, Memory, and Cognition (in press)

Ineke Imbo[1] and Jo-Anne LeFevre[2]

[1] Ghent University; [2] Carleton University

Correspondence Address: Ineke Imbo

Department of Experimental Psychology

Ghent University

Henri Dunantlaan 2

B – 9000 Ghent, Belgium

Tel: +32 (0)9 2646409

Fax: + 32 (0)9 2646496

E-mail: Ineke.Imbo@UGent.be

Abstract

The present study tested the effects of working-memory load on math problem solving in three different cultures: Flemish-speaking Belgians, English-speaking Canadians, and Chinese-speaking Chinese currently living in Canada. They solved complex addition problems (e.g., 58 + 76) in no-load and working-memory load conditions, in which either the central executive or the phonological loop was loaded. The choice/no-choice method was used to obtain unbiased measures of strategy selection and strategy efficiency. The Chinese participants were faster than the Belgians, who were faster and more accurate than the Canadians. The Chinese also required fewer working-memory resources than the Belgians and Canadians. However, the Chinese chose less adaptively from the available strategies than the Belgians and Canadians. These cultural differences in math problem solving are likely the result of different instructional approaches during elementary school (practice and training in Asian countries versus exploration and flexibility in non-Asian countries), differences in the number language, and informal cultural norms and standards. The relevance of being adaptive is discussed, as well as the implications of the results in regards to the SCADS model of strategy selection (Shrager & Siegler, 1998).

Keywords: mental arithmetic, strategies, working memory, cultural differences

Cultural differences in complex addition: Efficient Chinese versus adaptive Belgians and Canadians

Increased globalization in the 21st century has made the world seem smaller and more homogeneous. However, large differences among cultures persist, despite extensive travel opportunities and cross-cultural interactions. Cultural differences occur not only in habits, norms and language but may also be expressed as differences in individuals' basic cognitive processes. In the present study, we examined the effects of culture on one aspect of cognition, namely mental arithmetic. More specifically, we tested whether cultural differences in early instructional approaches have an influence on adults' math performance. Our participants were from three different nationalities, cultures, and continents. Asian, European, and North American participants solved complex arithmetic problems and reported their solution strategy after each problem. The Asians had been educated in China (through high school); the Europeans had been educated in Belgium; and the North Americans had been educated in Canada. Educational approaches to mathematics differ greatly among these three cultures. In Asia, the focus is on training and automaticity: pupils are expected to be fast and accurate – whatever strategy they use. In North America and Europe, the focus is on exploration and flexibility, and less so on speed. The question is now whether these early educational approaches have a persistent influence on people's math performance in adulthood.

The goal of the present study was to address two important empirical questions about cognitive arithmetic. First, is there any cultural variation in adults' *strategic* performance? And second, do people of various cultures use their *working memory* differently when solving math problems? Obviously, these research questions interact: variations in strategy choices and in levels of strategy efficiency may implicate a differential use of available working-memory resources. We also address a more theoretical question, that is, are current models of strategy selection such as the Strategy Choice And Discovery Simulation model (SCADS; Shrager & Siegler, 1998) able to account for cultural differences in strategic math performance?

Strategic Performance

According to Lemaire and Siegler (1995), there are at least four dimensions of people's strategic performance. The first dimension is the *repertoire* or collection of strategies that people use. In complex addition, the strategy repertoire usually consists of left-to-right strategies and right-to-left strategies (e.g., Hitch, 1978; Green, Lemaire, & Dufau, 2007). The right-to-left order of problem solving implies that participants start by adding the units, then the tens, and so on. For addition, the right-to-left algorithm is typically taught for written, paper-and-pencil solutions (Fuson, 1990). The left-to-right order of problem solving implies that participants start by adding the leftmost digits and move rightwards until they reach the units. The left-to-right order is often taught as a strategy for solving arithmetic problems mentally (Beishuizen, 1993).

The second dimension of strategic performance is the relative *frequency* with which the different strategies are applied. In complex arithmetic, this relative frequency depends greatly on the presence of carries. Carry operations are needed when the sum of a category (e.g., the units or the tens) exceeds 10. For example, in the problem 25 + 37, the sum of the units is 12, and hence the value 10 has to be carried from the units to the tens. In a seminal study, Hitch (1978) observed that some participants used the right-to-left strategy when they had to perform a carry operation and the left-to-right strategy when no carry operation was required.

These first two dimensions (strategy repertoire and strategy frequency) constitute the dimension "strategy *selection*", which refers to the strategies people choose in order to solve the presented problems. For at least the last 15 years, children in Belgium, Italy, and the Netherlands have been taught mental procedures for solving two-digit + two-digit addition problems that involve processing tens first and units second (Beishuizen, 1993; Beishuizen, Van Putten, & Van

Mulken, 1997; Blöte, Klein, & Beishuizen, 2000; Lucangeli, Tressoldi, Bendotti, Bonanomi, & Siegel, 2003; Torbeyns, Verschaffel, & Ghesquière, 2006; reviewed by Varol & Farran, 2007). For example, to solve the problem 45 + 33, a tens-units strategy could be implemented as 45 + 30 = 75 + 3 = 78 or as 40 + 30 = 70; 5 + 3 = 8; 70 + 8 = 78. In North America, however, the focus was on teaching children the paper-and-pencil algorithm in which they first add the units and then the tens (see Cooper, Heirdsfield, & Irons, 1996; Fuson, 1990). So for the problem 45 + 33, they would first add 5 + 3 = 8, then 4 + 3 = 7, to produce the answer 78. In the present study we thus predicted that the Belgians would use a tens-units strategy whereas the Canadians would use the units-tens strategy. In China, it does not matter what type of strategy is used, as long as the result is fast and accurate. Therefore, we predict an equal amount of units-tens and tens-units strategy use in the Chinese participants.

The third dimension of strategic performance is the *efficiency* with which each strategy is executed (i.e., speed and accuracy). As for the relative frequency of strategy use, the efficiency of complex arithmetic strategies depends greatly on the presence of carry operations. Efficiency decreases when carry operations have to be performed (Hitch, 1978; Fürst & Hitch, 2000; Imbo, Vandierendonck, & De Rammelaere, 2007; Imbo, Vandierendonck, & Vergauwe, 2007; Logie, Gilhooly, & Wynn, 1994; Noël, Désert, Aubrun, & Seron, 2001). Interestingly, cultural differences in strategy efficiency have been shown in the domain of simple arithmetic. Asians solve simple arithmetic problems (e.g., 7 + 5) more quickly and accurately than North Americans (Campbell & Xue, 2001; Geary, 1996b; Geary, Bow-Thomas, Fan, & Siegler, 1993; Geary, Bow-Thomas, Liu, & Siegler, 1996; Geary, Salthouse, Chen, & Fan, 1996; Geary et al., 1997; LeFevre & Liu, 1997; Penner-Wilger, Leth-Steensen, & LeFevre, 2002). This effect was, in part, a result of cultural differences in strategy selection: Asians retrieved the answers from long-term memory more frequently than North Americans, who were more inclined to use non-retrieval strategies such as transformation (e.g., 7 + 5 = 7 + 3 + 2 = 10 + 2 = 12) or counting (e.g., 7 + 2 = 7, 8, 9). The present study will be one of the first to investigate cultural differences in the domain of complex arithmetic. Because training and automaticity are highly favored in Asian education, we predict higher efficiency levels in the Chinese than in the Belgians and the Canadians.

The last – and least investigated – dimension of people's strategic competence is the *adaptivity* with which the different strategies are chosen and applied on a given set of problems. As discussed in detail by Schunn and Reder (2001), strategy adaptivity refers to the extent to which people change their selection of strategies in response to task-relevant factors that influence performance. Thus, people are adaptive when they adjust their strategy choices according to problem characteristics (e.g., the presence of a carry) and/or to strategy characteristics (e.g., the strategy's speed relative to other possible strategies). In the domain of mental arithmetic, strategy adaptivity has mainly been investigated in developmental studies with children, adults, and elderly people (e.g., Green et al., 2007; Lemaire, Arnaud, & Lecacheur, 2004; Lemaire & Lecacheur, 2002; Torbeyns, Verschaffel, & Ghesquière, 2002, 2004, 2005). There are no studies in which strategy adaptivity was explored across culture. Given the expected differences in strategy efficiency, we predicted higher adaptivity levels in the Chinese than in the Belgians and the Canadians. Being able to calculate efficiently may free mental resources that then can be used in order to make adaptive strategy choices.

In the present study, we thus examined whether the culturally different educational approaches influenced the various dimensions of adults' strategic performance (selection, efficiency, and adaptivity). According to current strategy selection models (e.g., the SCADS model by Shrager and Siegler, 1998), people store data about each strategy's past speed and accuracy. This information constitutes a strategy association strength, on which strategy choices are based. During problem solving, as soon as a strategy's association strength exceeds a predefined confidence criterion, that strategy is executed. Because the strategy strengths are continually adjusted based on speed and accuracy data, this associative learning process produces increases in strategy efficiency and in strategy adaptivity. Hence, our predictions are that the culture with most math experience (i.e., Chinese) will show greater levels of strategy efficiency and strategy adaptivity.

We used the choice/no-choice method, designed by Siegler and Lemaire (1997), to independently assess strategy selection and strategy efficiency (see Luwel, Onghena, Torbeys, Schillemans, & Verschaffel, in press, for review). In this method, participants are first tested in a choice condition, in which they choose a strategy to solve each problem. Participants are also tested in two or more no-choice conditions, in which they have to solve *all* problems with the same specified strategy. Data obtained in no-choice conditions are unbiased because they are not susceptible to selection effects (e.g., if a certain strategy is only used on easier problems, this strategy may look more efficient than it actually is). The comparison of the efficiency scores obtained in the no-choice conditions with the actual performance in the choice condition gives an indication of people's strategy adaptivity.

Working memory

Working memory is generally used to store and manipulate temporary information. Research into the role of working memory in mental arithmetic is mostly based on the multi-componential model of Baddeley and Hitch (1974; Baddeley, 2000). According to this model, four components constitute working memory: the central executive, the phonological loop, the visuo-spatial sketchpad, and the episodic buffer. The central executive is a modality-free, limited-capacity system that includes control processes, monitoring, response selection, planning and sequencing. The phonological loop and the visuo-spatial sketchpad store phonological and visuo-spatial information, respectively. The episodic buffer combines temporary working-memory information with long-term memory information.

Research has shown that the central executive is needed when people solve both simple and complex arithmetic problems (see DeStefano & LeFevre, 2004, for review). The phonological loop, in contrast, is needed for complex arithmetic but is only applied to simple arithmetic when non-retrieval strategies, such as counting are used (e.g., Hecht, 2002; Imbo & Vandierendonck, 2007a,b,c; Seyler, Kirk, & Ashcraft, 2003). The possible roles of the visuo-spatial sketchpad and the episodic buffer in mental arithmetic are theoretically less established and will not be considered in the current research.

In the present study we examined the degree to which the central executive and the phonological loop are involved across the three cultures. In the domain of simple arithmetic fewer executive resources are needed as the strategy execution gets more automated (Hecht, 2002; Imbo & Vandierendonck, 2007a,b,c; Seyler et al., 2003). On the assumption that the educational focus in Asia on speed and accuracy results in more automated math problem solving, we predicted smaller executive load effects in the Asians than in the North Americans and the Europeans. We also predicted smaller phonological load effects in the Asians than in the North Americans and the Europeans. This prediction is based the assumption that non-Asians process digits less efficiently and use a phonological code to maintain intermediate solutions. For example, in the problem 45 + 18, the phonological loop may be used to retain the unit answer '3' (5 + 8 = 13) during addition of the tens portion of the problem. The observation of greater perisylvian activity in English speakers than in Chinese speakers during number processing (Tang et al., 2006) confirms that the former employ more language-related working-memory processes than the latter.

The involvement of working memory in complex arithmetic is also closely associated with the presence of carry operations. More specifically, the recruitment of executive and phonological working memory increases as a function of the number of carry operations (Fürst & Hitch, 2000; Imbo, Vandierendonck, & De Rammelaere, 2007; Imbo, Vandierendonck, & Vergauwe, 2007; Noël et al., 2001). In the present experiment, we investigated whether the carry effect (i.e., the relative inefficiency on carry problems as compared to no-carry problems) differed across cultures. Smaller carry effects were expected in Asians than in Europeans and North Americans because of the expected superiority of strategy efficiency by the former group.

Method

Participants

One hundred twenty-five participants were recruited for the present experiment. Forty participants (20 men and 20 women; mean age 21.3 years old) were Flemish-speaking students at Ghent University who had received their education in Belgium. Forty-five participants (20 men and 25 women; mean age 21.3 years old) were English-speaking students at Carleton University who had received their education in Canada. Forty participants (17 men and 23 women; mean age 25.1 years old) were Chinese-speaking students at Carleton University who had received their education in China but were currently living and studying in Canada. Their first language was Chinese and their second language was English. One hundred and twelve people participated for extra course credit and thirteen people were paid $12.

Although the Chinese participants in the current research were tested in Canada, Campbell and Xue (2001) showed that cultural background (Chinese vs. Canadian) rather than current place of residence (China or Canada) is the main cause of cultural differences in mental arithmetic performance. Furthermore, researchers have shown differences in arithmetic performance between Chinese and North Americans even before children begin elementary school (e.g., Siegler & Mu, 2008). Although the Chinese responded in English, rather than their native language, Campbell and Epp (2004) found that Chinese-English bilinguals are only slightly slower when they respond to arithmetic problems in English versus Chinese. If anything, having to respond in a second language might have been a small disadvantage for the Chinese, but as shown in the Results, they nevertheless performed best of the three cultural groups. Thus, although issues related to language of testing and issues of participant selection cannot be discounted in the current research, these issues seem unlikely to have compromised the main conclusions.

Materials

Six sets of 24 additions problems were constructed, resulting in a total of 144 different problems. As there were six blocks, defined by the three strategy conditions (i.e., choice, no-choice/units-tens, and no-choice/tens-units) and two load conditions (i.e., no-load vs. load), one set was presented per block. All problems consisted of two two-digit numbers (e.g., 13 + 52). Because tie problems (e.g., 4 + 4) and problems that can be solved by a rule (e.g., $n + 0 = 0$; $n + 9 = n + 10 - 1$) are easier, three types of problems were excluded: (a) problems involving a 0 in the first operand, in the second operand, or in the sum, (b) problems involving a 9 in the first operand or in the second operand, and (c) problems with a tie in the units or in the tens. In order to exclude problem-size effects, the correct sums of each set were equally distributed among the decades from the 40s to the 150s (i.e., two problems per decade). Half of the problems did not have a carry from the units to the tens (e.g., 34 + 21) and the other half did involve a carry (e.g., 16 + 38). The size of the correct sum was equal for no-carry problems and one-carry problems. We also controlled for the even/odd status of the correct sum and for the position of the largest operand.

Procedure

The same experimenter tested each participant individually. The experiment took place in a quiet room and lasted for approximately 1 hour.

Experimental trials. All participants solved the complex-arithmetic problems in three conditions: first the choice condition (in order to exclude influence of no-choice conditions on the choice condition), and then two no-choice conditions, the order of which was randomized across participants. In the choice condition, 6 practice problems and 24 experimental problems were presented. Each condition was further divided in two blocks: one in which no working-memory component was loaded, and one in which one working-memory component was loaded. The working-memory load differed across participants: for half of them the central executive was loaded, and for the other half the phonological loop was loaded. For half of the participants, each condition started with the no-load block and was followed by the working-memory load block; the order was reversed for the other half of the participants.

A trial started with a fixation point for 500 ms. Then the addition problem was presented horizontally in the center of the screen, with the “+” sign at the fixation point. Participants were asked to work out the problem mentally (i.e., without use of pen-and-paper) and to state their answer aloud as quickly and as accurately as possible. The problem remained on the screen until the participant responded. Timing began when the stimulus appeared and ended when the participant’s response triggered the sound-activated relay. On each trial, feedback about the answer (“Correct” or “Incorrect”) was presented on the computer screen.

Immediately after solving each problem, participants in choice conditions were asked to report verbally whether they had used the units-tens (UT) strategy or the tens-units (TU) strategy. The experimenter clearly explained both strategies before the experiment. In particular, participants were informed they could use a mix of the strategies or use an alternative strategy to solve the problems and that the presented strategies were not meant to encourage the use of a particular strategy. In the two no-choice conditions, participants were asked to use the UT or TU strategy to solve all problems. After they solved the problem, participants had to indicate (with 'yes' or 'no') whether they had succeeded in using the required strategy. Trials on which participants did not comply with the instructions were deleted. In choice and no-choice conditions, the answer of the participant, the strategy information, and the validity of the trial were recorded on-line by the experimenter. All invalid trials (e.g., failures of the voice-activated relay) were re-presented at the end of the block, which minimized loss of data.

Executive secondary task. A continuous choice reaction time task (CRT task) was used to load the executive component of working memory. Stimuli for this task consisted of low tones (262 Hz) and high tones (524 Hz) that were sequentially presented with a randomly-determined interval of 900 or 1500 ms. Participants had to press the 4 on the numerical keyboard when they heard a high tone and the 1 when a low tone was presented. The tones were presented continuously during the complex arithmetic task. Szmalec, Vandierendonck, and Kemps (2005) have shown that this task interferes with the central executive, while the load on the slave systems is negligible. The CRT task was also performed alone (i.e., without the concurrent solving of arithmetic problems) for 2 minutes.

Phonological secondary task. In this task, letter strings of 4 consonants (e.g., T K X L) were read aloud by the experimenter. The participant had to retain these letters and repeat them aloud after three consecutive complex arithmetic problems. Following the response of the participant, the experimenter presented a new 4-letter string. This task was also tested individually (i.e., without the concurrent solving of arithmetic problems) for 2 minutes. In this secondary-task-only condition, an interval of 15 seconds was used between the presentation of the 4-letter string and the question to repeat the letters.

Results

In total, 5.4% of trials were spoiled due to failures of the sound-activated relay. Because all these invalid trials returned at the end of the block, the loss was reduced to 0.7%. Further, all choice trials on which participants reported having used an alternative strategy (0.7%) and all no-choice trials on which participants failed to use the required strategy (2.4%) were deleted. All data were analyzed on the basis of the general linear model, and all reported results were significant at $p < .05$, unless mentioned otherwise. Initial analyses indicated that there were no order effects in the no-choice conditions. Therefore, the data were collapsed over order in all analyses on no-choice data. Due to voice-key problems, five participants were excluded from all further analyses (two Belgians, two Canadians, and one Chinese). Thus, the final sample included 38 Belgians, 43 Canadians, and 39 Chinese.

Secondary Task Performance

Mean percentage correct on both secondary tasks and response times on the CRT-task (i.e., executive load) are shown in Table 1. Each dependent variable was analyzed in a 3 (Culture: Chinese, Belgian, Canadian) x 4 (Condition: single, choice, no-choice/UT, no-choice TU) mixed ANOVA, with repeated measures on the second factor. Performance varied with Condition for all three analyses, $F(3,55) = 70.71$, $MSe = 0.029$, $\eta_p^2 = 0.56$, $F(3,55) = 298.40$, $MSe = 0.008$, $\eta_p^2 = 0.84$, and $F(3,55) = 64.98$, $MSe = 5228.06$, $\eta_p^2 = 0.54$, respectively. Performance was better in the single- than in the dual-task conditions for all three measures: Letter-recall accuracy (94% vs. 54%), $F(1,57) = 218.47$; CRT-task accuracy (94% vs. 36%), $F(1,57) = 761.25$; and CRT-task latencies (540 vs. 680 ms), $F(1,57) = 194.88$. The main effects of Culture and the Culture x Condition interactions did not reach significance (each $F < 1.8$).

Participants were slower and more erroneous on the secondary tasks when these tasks had to be solved simultaneously with the arithmetic problems than when the secondary tasks were done alone. Thus, when people were solving complex arithmetic problems, they had fewer working-memory resources available. Consequently, performance was also impaired on the arithmetic task (as will be shown below). Importantly, there were no cultural differences in secondary task performance suggesting that cultural differences on the complex arithmetic task could be interpreted without concern for differential tradeoffs between primary task and secondary task. Hence, cultural differences in arithmetic-task performance cannot be explained by cultural differences in adherence to the secondary tasks.

Strategy Selection in the Choice Condition

As noted above, participants rarely claimed to use alternative strategies, indicating that almost all strategies used to solve complex addition problems could be categorized as UT or TU strategies. The TU strategy was the most frequently used strategy and was reported for 55% of all trials. Percentage use of the TU strategy (of correctly solved problems only) in the choice conditions was analyzed with two between-participants factors and two within-participants factors, thus a 2 (Working-memory component: phonological vs. executive) x 3 (Culture: Belgian, Canadian, Chinese) x 2 (Carry: 0 vs. 1) x 2 (Load: no load vs. load) mixed design. To reduce the positive skew of the distribution, the data were arcsine transformed for the analyses. However, for ease of comprehension, raw means are reported. Because each participant completed either the phonological or executive load condition, type of load and single vs. dual-task conditions were fully crossed.

Selection of strategies varied with Culture, $F(2,114) = 5.50$, $MSe = 1.309$, $\eta_p^2 = 0.05$. As predicted, Belgians (69%) reported the TU strategy more frequently than did Canadians (52%) or Chinese (44%), $F(1,114) = 4.12$ and $F(1,114) = 7.97$, respectively. There was no difference in frequency of TU strategy use between the Canadian and Chinese participants, $F<1$. Culture and Carry interacted, $F(2,114) = 5.84$, $\eta_p^2 = 0.05$. Canadians chose the TU strategy less frequently on one-carry problems (47%) than on no-carry problems (57%), $F(1,114) = 12.81$. In contrast, the strategy choices of Belgians and Chinese were similar on no-carry and one-carry problems (each $p > .20$). Thus, only Canadians chose the UT strategy more frequently when confronted with carry problems.

We tested whether the phonological and executive load effects differed across Chinese, Belgians, and Canadians (see Figure 1)[1]. For participants under phonological load, none of the Chinese, Belgian, or Canadian participants varied their strategy choices across single versus dual-task conditions (each $p > .25$). Similarly, Belgian and Canadian participants did not vary their strategy choices under an executive load (each $p > .30$). In contrast, Chinese participants used the TU strategy less frequently under an executive load (37%) than under no-load conditions (58%), $F(1,114) = 14.98$. The analyses on strategy adaptivity (see below) will shed further light on this strategy switch of the Chinese.

Strategy Efficiency in the No-Choice Conditions

Response latencies. A 2 x 3 x 2 x 2 x 2 ANOVA was conducted on correct latencies with Working-memory component (phonological vs. executive) and Culture (Belgian, Canadian, Chinese) as between-participants factors and Strategy (UT vs. TU), Carry (0 vs. 1), and Load (no load vs. load) as within-participants factors (see Table 2). The main effects of Strategy, Carry, and Load were significant. Participants were slower when they were using the UT strategy (3.8 s) than the TU strategy (3.4 s), $F(1,114) = 6.75$, $MSe = 4025039$, $\eta_p^2 = 0.06$; slower on one-carry problems (4.4 s) than on no-carry problems (2.8 s), $F(1,114) = 117.97$, $MSe = 4721639$, $\eta_p^2 = 0.51$; and slower under load conditions (3.8 s) than under no-load conditions (3.4 s), $F(1,114) = 27.11$, $MSe = 1913639$, $\eta_p^2 = 0.19$. Latencies also varied with Culture, $F(2,114) = 18.50$, $MSe = 20536498$, $\eta_p^2 = 0.14$. As predicted, the Chinese (2.6 s) were faster than the Belgians (3.5 s), $F(1,114) = 5.20$, and the Belgians were faster than the Canadians (4.8 s), $F(1,114) = 13.25$. Culture interacted with Carry, $F(2,114) = 10.35$, $\eta_p^2 = 0.08$. As predicted, the effect of carrying was smaller for Chinese (0.8 s) than for Belgians (1.5 s), $F(1,114) = 3.66$, and smaller for Belgians than for Canadians (2.3 s), $F(1,114) = 6.44$.

We tested whether the phonological and executive load effects differed across Chinese, Belgians, and Canadians (see Figure 2). These analyses showed that Chinese and Canadians were not affected by a phonological load (each $F<1$), whereas Belgians performed significantly slower under phonological load, $F(1,114) = 4.85$. Under an executive load the performance of both Belgians and Canadians was significantly slower, $F(1,114) = 8.80$ and $F(1,114) = 19.18$, respectively. The effect of an executive load on Chinese participants' latencies just failed to reach significance, $F(1,114) = 3.54$, $p = .06$. These results show that all cultures needed executive working-memory resources to maintain a reasonable speed when solving complex addition problems – although the amount of executive resources needed was smaller in the highly efficient Chinese than in the – less efficient – Belgians and Canadians.

Percentage of errors. A 2 x 3 x 2 x 2 x 2 ANOVA was conducted on error percentages with Working-memory component (phonological vs. executive) and Culture (Belgian, Canadian, Chinese) as between-participants factors and Strategy (UT vs. TU), Carry (0 vs. 1), and Load (no load vs. load) as within-participants factors. To reduce the positive skew of the distribution, the data were arcsine transformed for the analyses. However, for ease of comprehension, raw means are reported (see Table 3). The main effects of Carry and Load were significant. Participants made more errors on one-carry problems (12.4%) than on no-carry problems (4.9%), $F(1,114) = 156.74$, $MSe = 0.009$, $\eta_p^2 = 0.58$; and more errors in load conditions (9.9%) than in no-load conditions (7.4%), $F(1,114) = 22.44$, $MSe = 0.007$, $\eta_p^2 = 0.16$. Errors also varied with Culture, $F(2,114) = 9.84$, $MSe = 0.021$, $\eta_p^2 = 0.08$. The percentage of errors did not differ between Chinese (7.1%) and Belgians (7.5%), $F<1$, but was significantly higher in Canadians (11.4%),

$F(1,114) = 15.67$ and $F(1,114) = 13.09$, respectively. The main effect of Strategy did not reach significance, nor did the interaction between Culture and Strategy (each $F<1$).

We tested whether the phonological and executive load effects differed across Chinese, Belgians, and Canadians (see Figure 3). These analyses showed that Canadians were affected by a phonological load, $F(1,114) = 7.05$ whereas Belgians were not ($F<1$). Chinese participants tended to make more errors under a phonological load as compared to no-load but this effect just failed to reach significance, $F(1,114) = 3.53$, $p = .06$. Neither Belgians nor Chinese were affected by an executive load ($F = 1.41$ and $F<1$, respectively), but Canadians did make significantly more errors under an executive load, $F(1,114) = 32.23$. The significant phonological and executive load effects indicate that the least efficient group (i.e., the Canadians) required working-memory resources in order to maintain a reasonable level of accuracy, whereas the more efficient Belgians and Chinese did not.

The Culture x Carry x Load interaction, $F(2,114) = 3.46$, $\eta_p^2 = 0.03$, finally, indicated that the Carry x Load interaction was significant in Canadians, $F(1,114) = 10.69$, but not in Belgians or Chinese (each $F<1$). As shown in Figure 3, Canadians made more errors on one-carry problems than on no-carry problems under both phonological and executive working-memory loads, $F(1,114) = 3.69$ ($p = .06$) and $F(1,114) = 7.36$, respectively. Neither Chinese nor Belgians made more errors on one-carry than on no-carry problems under phonological or executive working-memory loads (each $p > .10$). Presumably, the Belgians and Chinese were able to manage the working-memory demands of carry problems to preserve both accuracy and latency.

Strategy Adaptivity

Did participants in the choice condition choose strategies that yielded the best performance, as evidenced by the information obtained in the no-choice conditions? To answer this question, a measure of strategy adaptivity was calculated for each participant in each Load by

Carry condition. The adaptivity measure was the percentage of trials on which participants chose their *best* strategy as determined by their performance in no-choice conditions. For example, if a participant was faster in correctly implementing the UT strategy than the TU strategy on carry problems under no-load conditions, then UT was defined as that individual's "best" strategy in that condition[2]. Because there were no differences in accuracy between UT and TU strategies in the no-choice conditions (cf. strategy efficiency analyses), the adaptivity analyses were not repeated on error rates. Adaptivity was the percentage of trials on which that participant used his or her "best" strategy on the same problem type in the choice condition.

A 2 x 3 x 2 x 2 ANOVA was conducted on the percentage of adaptive strategy choices, with Working-memory component (phonological vs. executive) and Culture (Belgian, Canadian, Chinese) as between-participants factors and Carry (0 vs. 1) and Load (no load vs. load) as within-participants factors. On average, participants selected their best strategy on 63% of problems in the choice condition.

Adaptivity varied with Culture[3], $F(2,114) = 2.95$, $MSe = 2885.14$, $\eta_p^2 = 0.03$, $p = .06$. In contrast to our hypothesis, Chinese (55%) were significantly *less* adaptive than Belgians (69%) and Canadians (67%), $F(1,114) = 4.98$ and $F(1,114) = 3.87$, respectively. Belgians and Canadians were equally adaptive ($F<1$). Although there were no main effects of Load or Working-memory component (each $F<1$), planned comparisons were run to test the adaptivity levels of Belgians, Canadians, and Chinese under working-memory loads. We expected to observe changed adaptivity levels under an executive load for Chinese participants only, because they showed changes in strategy choices in that situation. This prediction was confirmed (see Figure 4) as Chinese participants were significantly less adaptive under an executive load (49%) than in no-load conditions (65%), $F(1,114) = 5.42$. As expected, an executive load did not affect the adaptivity of Belgians or Canadians (each $F<1$). A phonological load had no effect on adaptivity level, $F(1,114) = 1.30$ ($p = .26$), and this was true for every culture. To conclude, an executive working-memory load only affected the least adaptive group (i.e., the Chinese).

Discussion

In the present study we observed large cultural differences in strategy selection, strategy efficiency, and strategy adaptivity. As expected, Asians showed higher levels of strategy efficiency and reduced working-memory demands. However, and contrary to our expectations, Asians were significantly less adaptive than Europeans and North Americans – an effect that was exacerbated under executive working-memory loads. In the following, the results are summarized and interpreted in relation to our original hypotheses.

Cultural differences in Strategic Performance

What is the origin of the cultural differences in strategy selection, strategy efficiency, and strategy adaptivity? Previous studies excluded potential causes such as cognitive ability or intelligence (e.g., Geary, 1996a; Geary, Salthouse, et al., 1996). However, there is a variety of other explanations. One possibility is that formal educational experiences may play a significant role in explaining cultural differences in adults' math performance. Mathematics instruction is a focus in Asian countries, relative to other cultures (e.g., Stigler, Lee, & Stevenson, 1987). Practice and training are also highly favored in Asia, both at school and at home (e.g., Zhang & Zhou, 2003), resulting in greater efficiency of arithmetic performance. These differences across culture in levels of training and automaticity may also explain the unexpected adaptivity results. Because the Chinese are so highly practiced, they may have automated both the *execution* of strategies (resulting in high efficiency scores), and the strategy *selection* process (resulting in low adaptivity levels). The high level of automaticity may thus reduce adaptively choosing among strategies. In contrast, in European and North American education, exploration and flexibility are more highly favored, explaining the higher adaptivity levels in Belgians and Canadians – and probably also their lower efficiency levels.

A second important factor in understanding cultural differences is the role of language in mathematics. The structure of the Chinese number language is more straightforward than the structure of Indo-European number languages. Chinese languages use a consistent system for constructing number names (e.g., 12 is *ten two* and 53 is *five ten three*), whereas English and Flemish are irregular (e.g., the teens words are rather idiosyncratic, and the formation of decade words is not completely regular). There are also cultural differences in the speed with which basic number names (e.g., *one, two, three*) can be pronounced. The speed of number pronunciation influences digit span (i.e., the number of digits than can be retained in short-term memory) and may, in turn, influence people's arithmetic efficiency. Stigler, Lee, and Stevenson (1986) showed that Chinese participants have about a two-digit span advantage over North Americans; and Geary, Bow-Thomas et al. (1996) showed that individual differences in digit span influence individual differences in simple arithmetic performance. The ability to retain more digits in short-term memory during calculations may be a factor in the Chinese advantage, especially on these multi-digit problems that require retention of intermediate sums in working memory.

A third factor in understanding cultural differences is the level of bilingualism. All Chinese and Belgian participants were bilingual (i.e., Chinese and English vs. Flemish and French/English) whereas only half of the Canadian participants were bilingual (i.e., English and French). It has been shown that bilinguals have an advantage over monolinguals in nonlinguistic tasks involving executive control (e.g., Bialystok, Craik, & Ryan, 2006; Bialystok, Craik, Klein & Viswanathan, 2004; Bialystok, Craik, & Luk, 2008). Because complex arithmetic problem solving relies on executive control (see DeStefano & LeFevre, 2004, for review), bilinguals' higher level of executive control might have contributed to their strategy efficiency.

Finally, cultural-specific informal factors may also explain cultural differences in math performance (Stevenson, Chen, & Lee, 1993; Stevenson, Lee, et al., 1990). Examples of such informal factors are "having parents and peers who hold high standards, believing that the road to success is through effort, having positive attitudes about achievement, studying diligently, and facing less interference with their schoolwork from jobs and informal peer interactions" (Chen & Stevenson, 1995). The PISA survey of 2003 focused on attitudes towards mathematics (tested by questions such as "I look forward to my mathematics lessons"), and showed that Chinese students were more interested in math than were Belgians and Canadians.

Cultural Differences in Working-memory Involvement

The Chinese participants' arithmetic performance was only slightly affected by working-memory loads, suggesting that they have achieved a level of skill at two-digit addition problems that approaches that of other cultures for single-digit addition. In contrast, the Belgians' strategy speed was affected by both phonological and executive working-memory loads. The finding that a phonological load caused Belgians to answer more slowly might be related to the counter-intuitive pronunciation of number words in Flemish. For two-digit numbers, Flemish-speaking people say the units before the tens (e.g., *thirty five* is pronounced as *vijfendertig*, of which the literal translation would be *five and thirty*). However, the question of whether this pronunciation issue requires more phonological working-memory resources than other languages still needs to be tested empirically. Neither phonological nor executive working-memory loads affected Belgians' strategy accuracy, however. The Belgians thus required working-memory resources to execute the arithmetic processes quickly, but the demands of the working-memory tasks did not drastically limit the accuracy of their performance. Finally, Canadians' speed *and* accuracy were affected by working-memory loads. Trbovich and LeFevre (2003) also found that Canadians relied on phonological working-memory resources when solving complex addition problems – and especially so for horizontally presented problems, the format used in the present research. The large effect of executive load on Canadians' accuracy suggests that they have not automated the solution of these problems and thus required a considerable investment of central executive resources to successfully implement their procedures.

To summarize, the lower a cultural group's arithmetic skill level and efficiency, the more working-memory resources were needed to maintain a reasonable level of performance. This correspondence between efficiency and working-memory demands is consistent with the view that working-memory resources are important in mental arithmetic (DeStefano & LeFevre, 2004). Because of the greater degree of practice during elementary school, Chinese participants had achieved a level of efficiency that is almost 'automatic', and in which minimal working-memory resources were necessary to solve these multi-digit addition problems. Consistent with the compensatory-encoding theory proposed by Walczyk and Griffith-Ross (2006), a high level of efficiency frees up working-memory resources for other processes. Individuals with inefficient processing, in contrast, are disadvantaged as the demands of the situation increase, for example in dual-task situations. The cumulative effect of the lower automaticity and the dramatically higher load effects for Canadians is likely to have a variety of consequences in real world situations. For example, they may experience great difficulties when they are required to perform complex mental addition in the context of other cognitive tasks such as reading, reasoning, or estimating.

Importantly, working-memory load effects were not only observed on strategy efficiency, but also on strategy selection and strategy adaptivity. More specifically, Chinese participants changed their strategy choices under working-memory load, such that they showed reduced strategy adaptivity. This is a surprising result, because intuitively we might expect that more efficient problem solvers (who experience lower working memory loads) would be more adaptive in stressful situations than less efficient problem solvers. A phonological load did not affect strategy adaptivity in any culture, indicating that choosing among strategies loads on controlling, monitoring, planning and sequencing processes (cf. the central executive) rather than on the storage device of the phonological loop.

The observation that the highly efficient Chinese were less adaptive than the less efficient Belgians and Canadians, and especially so in high-pressure situations (i.e., in executive load conditions), is in agreement with recent results obtained by Beilock and DeCaro (2007) and DeCaro, Thomas, and Beilock (2008). In these studies, participants with high working-memory capacity were less apt to switch to the optimal strategy than participants with low working-memory capacity. According to Beilock and DeCaro (2007), high-capacity participants are especially good at focusing their attention on specific task properties and at ignoring other task properties. Consequentially, they have no resources left to decide among alternative strategies and are worse at selecting the most adaptive strategy for the situation. Low-capacity participants, in contrast, are not able to allocate attentional resources solely to one task approach. Hence, they are more likely to select the most adaptive strategy. Similarly, Ricks, Turley-Ames, and Wiley (2007) suggested that high-capacity individuals are less likely to abandon a wrong strategy to find the correct one. In conclusion, the possibility that high-capacity individuals may have difficulty identifying the most adaptive strategies may explain why the Chinese in our study failed to use strategies adaptively.

The relevance of being adaptive

The fact that the Chinese were, despite their lower adaptivity levels, nevertheless the most successful group in terms of strategy efficiency challenges the importance of adaptivity. Even though the Chinese did not choose the most adaptive strategy, they were very fast and accurate and required relatively little working-memory resources. It is possible that the Chinese were not adaptive because they did not *need* to be: whatever strategy they used, it led to a fast and accurate response. Both strategies also loaded equally heavily on working memory, so there was no need to switch to less demanding strategies – and especially not for the Chinese, who were good at performing complex addition strategies in line with the greater working-memory requirements. However, although the level of adaptivity did not really matter in the present study, it may be extremely important under other circumstances. For example, when one strategy is more efficient than another one, choosing the 'best' strategy on a trial-by-trial basis is highly relevant. Being adaptive is also important in real life situations (e.g., traffic control, health industry, politics, et cetera). People often have to weigh costs and benefits of the available strategies, and wrong strategy choices can have severe consequences. The present study is especially important because we show significant lower adaptivity levels under stressful situations (i.e. working-memory load conditions; see also Imbo, Duverne, & Lemaire, 2007), albeit for one culture only.

In future studies, researchers should investigate what would happen if the participants were explicitly asked to choose the "best" strategy on each problem. In the present study, they were only asked to calculate "as fast and as accurately as possible". It is possible that this small difference in instructions would engage the Chinese participants, who are eager to obey the rules, to higher adaptivity levels. It would also be interesting to test what would happen in situations where the adaptivity level would influence the overall performance. In the present study, both strategy types led to the correct answer; but this is not always the case (cf. reasoning, algebra, et cetera). Further research is needed to test if Chinese participants are also less adaptive on these types of cognitive tasks and if, or under what conditions, this lack of adaptivity has negative consequences for their overall performance.

Implications for strategy selection models.

One implication of the present research is that theories and models concerning people's cognitive performance (e.g., the SCADS model; Shrager & Siegler, 1998; Siegler & Araya, 2005) should include variables that predict and explain cultural differences. In the current version of these models, people store data about each strategy's speed and accuracy over all problems (global data), its speed and accuracy on problems with a particular feature (featural data, such as the presence of a carry), and its speed and accuracy on each specific problem. These three pieces of information then constitute the associative strength of each strategy, on which strategy choices are based.

The results for the Belgians and the Canadians can be accommodated within the existing assumptions of the SCADS model. The Belgians' global strategy associative strengths seem to be stronger for the TU strategy than for the UT strategy, irrespective of problem characteristics such as carrying. The Canadians, in contrast, used the UT strategy more frequently on one-carry problems than on no-carry problems, suggesting that they not only used global strategy association strengths, but also featural strategy association strengths such as between carry problems and the UT strategy. When confronted with the difficult carry problems, Canadians switched to the strategy they were taught at elementary school (i.e., the UT strategy). We further observed that Belgians and Canadians did not change their strategy choices under working-memory load. According to the SCADS model, strategy selection is based on activation weighting and association strengthening and not on conscious, deliberate, or metacognitive processes requiring working-memory resources. Hence, no working-memory resources are needed in the strategy selection process. Both Belgians and Canadians showed adaptive strategy use, such that they were more likely to use the strategy in those situations for which it was more efficient. These patterns support the view that strategy strength is a consequence of long term experience with particular strategies and particular problems that accumulates in a data base and is then activated in response to cues such as problem type.

In contrast, the results for the Chinese participants do not fit as neatly into the existing assumptions of the SCADS model. Chinese participants changed their strategy selection in response to the situation (i.e., working-memory load), suggesting that their strategy selection was not predominately linked to past experiences or stored strategy strengths, but was instead responsive to other cues. Stated differently, the Chinese participants' database not only includes information about strategy speed and strategy accuracy, but may also include implicit knowledge regarding their socio-cultural values, standards and norms. As noted by Ellis (1997), such socio-cultural influences can play a role in the strategy selection process because people get increasingly skilled at making strategy choices in line with their implicit knowledge of cultural values. The finding that strategy choices may be responsive to task demands that are external to the problems cannot be accounted for by current models of strategy selection. Hence, these models fail in explaining cultural differences in the strategy selection process.

Conclusion

The current research demonstrates that differences in instructional approaches, number language, and cultural standards affect how adults approach complex arithmetic problems and that these approaches can differ depending on situational demands (such as working-memory load) and problem difficulty (such as carrying). Under stressful situations, people performed worse on that one aspect that was already challenging: Chinese participants were less adaptive; Belgian and Canadian participants were less efficient. It is clear that these results have implications for strategic behavior in various situations that may reach beyond experimental settings, such as high-stakes exams (in which stress factors may load working-memory resources and consequentially affect performance), intercultural negotiations (in which selecting and executing a good strategy is critical), and educational decisions (e.g., when stakeholders have to choose between a focus on practice and training versus a focus on exploration and flexibility).

References

Baddeley, A.D. (2000). The episodic buffer: A new component of working memory? *Trends in Cognitive Sciences, 4*, 417-423.

Baddeley, A.D., & Hitch, G.J. (1974). Working Memory. In G. Bower (Ed.). *The Psychology of Learning and Motivation* (pp. 47-90). New York: Academic Press.

Beilock, S.L., & De Caro, M.S. (2007). From poor performance to success under stress: Working memory, strategy selection, and mathematical problem solving under pressure. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 33*, 983-998.

Beishuizen, M. (1993). Mental strategies and materials or models for addition and subtraction up to 100 in Dutch 2nd grades. *Journal for Research in Mathematics Education, 24*, 294-323.

Beishuizen, M., Van Putten, C.M., & Van Mulken, F. (1997). Mental arithmetic and strategy use with indirect number problems up to one hundred. *Learning and Instruction, 7*, 87-106.

Bialystok, E., Craik, F.I.M, Klein, R., & Viswanathan, M. (2004). Bilingualism, aging, and cognitive control: Evidence from the Simon task. Psychology and Aging, 19, 290-303.

Bialystok, E., Craik, F., & Luk, G. (2008). Cognitive control and lexical access in younger and older bilinguals. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 34*, 859-873.

Bialystok, E., Craik, F.I.M., & Ryan, J. (2006). Executive control in a modified anti-saccade task: Effects of aging and bilingualsm. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 32*, 1341-1354.

Blöte, A.W., Klein, A.S., & Beishuizen, M. (2000). Mental computation and conceptual understanding. *Learning and Instruction, 10*, 221-247.

Campbell, J.I.D., & Xue, Q. (2001). Cognitive arithmetic across cultures. *Journal of Experimental Psychology: General, 130*, 299-315.

Chen, C., & Stevenson, H.W. (1995). Motivation and mathematics achievement: A comparative study of Asian-American, Caucasian-American, and East-Asian high school students. *Child Development, 66*, 1215-1234.

Cooper, T. J., Heirdsfield, A. M., & Irons, C. J. (1996). Children's mental strategies for addition and subtraction word problems. In J. Mulligan & M. Mitchelmore (Eds.), *Children's number learning* (pp. 147–162). Adelaide: Australian Association of Mathematics Teachers, Inc.

DeCaro, M.Q., Thomas, R.D., & Beilock, S.L. (2008). Individual differences in category learning: Sometimes less working memory capacity is better than more. *Cognition, 107,* 284-294.

DeStefano, D., & LeFevre, J.-A. (2004). The role of working memory in mental arithmetic. *European Journal of Cognitive Psychology, 16*, 353-386.

Ellis, S. (1997). Strategy choice in sociocultural context. *Developmental Review, 17*, 490-524.

Fürst, A.J., Hitch, G.J. (2000). Separate roles for executive and phonological components of working memory in mental arithmetic. *Memory & Cognition, 28*, 774-782.

Fuson, K.C. (1990). Conceptual structures for multiunit numbers : Implications for learning and teaching multidigit addition, subtraction, and place value. *Cognition and Instruction, 7*, 343-403.

Geary, D.C. (1996a). International differences in mathematical achievement : Their nature, causes, and consequences. *Current Directions in Psychological Science*, *5*, 133-137.

Geary, D.C. (1996b). The problem-size effect in mental addition: Developmental and cross-national trends. *Mathematical Cognition, 2*, 63-93.

Geary, D.C., Bow-Thomas, C.C., Fan, L., & Siegler, R.S. (1993). Even before formal instruction, Chinese children outperform American children in mental addition. *Cognitive Development, 8*, 517-529.

Geary, D.C., Bow-Thomas, C.C., Liu, F., & Siegler, R. (1996). Development of arithmetical competencies in Chinese and American children: Influence of age, language, and schooling. *Child Development, 67*, 2022-2044.

Geary, D.C., Hamson, C.O., Chen, G.-P., Fan, L., Hoard, M.K., & Salthouse, T.A. (1997). Computational and reasoning in arithmetic: Cross-generational change in China and the United States. *Psychonomic Bulletin & Review, 4*, 254-263.

Geary, D.C., Salthouse, T.A., Chen, G.-P., & Fan, L. (1996). Are East Asian versus American differences in arithmetic ability a recent phenomenon? *Developmental Psychology, 32*, 254-262.

Green, H.J., Lemaire, P., & Dufau, S. (2007). Eye movement correlates of younger and older adults' strategies for complex addition. *Acta Psychologica, 125*, 257-278.

Hale, G.A. (1977). On use of ANOVA in developmental research. *Child Development, 48*, 1101-1106.

Hecht, S.A. (2002). Counting on working memory in simple arithmetic when counting is used for problem solving. *Memory & Cognition, 30*, 447-455.

Hitch, G.J. (1978). Role of short-term memory in mental arithmetic. *Cognitive Psychology, 10*, 302-323.

Imbo, I., Duverne, S., & Lemaire, P. (2007). Working memory, strategy execution, and strategy selection in mental arithmetic. *Quarterly Journal of Experimental Psychology, 60*, 1246-1264.

Imbo, I., & Vandierendonck, A. (2007a). The role of phonological and executive working-memory resources in simple-arithmetic strategies. *European Journal of Cognitive Psychology, 19,* 910-933.

Imbo, I., & Vandierendonck, A. (2007b). Do multiplication and division strategies rely on executive and phonological working-memory resources? *Memory & Cognition, 35,* 1759-1771.

Imbo, I., & Vandierendonck, A. (2007c). Strategy use in elementary-school children: Working memory and individual differences. *Journal of Experimental Child Psychology, 96*, 284-309.

Imbo, I., Vandierendonck, A., & De Rammelaere, S. (2007). The role of working memory in the carry operation of mental arithmetic: Number and value of the carry. *Quarterly Journal of Experimental Psychology, 60,* 708-731.

Imbo, I., Vandierendonck, A., & Vergauwe, E. (2007). The role of working memory in carrying and borrowing. *Psychological Research, 71,* 467-483.

LeFevre, J.-A., & Liu, J. (1997). The role of experience in numerical skill : Multiplication performance in adults from China and Canada. *Mathematical Cognition, 3*, 31-62.

LeFevre, J.-A., Bisanz, J., Daley, K.E., Buffone, L., Greenham, S.L., & Sadesky, G.S. (1996a). Multiple routes to solution of single-digit multiplication problems. *Journal of Experimental Psychology: General, 125*, 284-306.

LeFevre, J.-A., Sadesky, G.S., & Bisanz, J. (1996b). Selection of procedures in mental addition: Reassessing the problem size effect in adults. *Journal of Experimental Psychology: Learning, Memory, & Cognition, 22*, 216-230.

Lemaire, P., Arnaud, L., Lecacheur, M. (2004). Adults' age-related differences in adaptivity of strategy choices: Evidence from computational estimation. *Psychology and Aging,* 19, 467-481.

Lemaire, P., & Lecacheur, M. (2002). Children's strategies in computational estimation. *Journal of Experimental Child Psychology, 82*, 281-304.

Lemaire, P., & Siegler, R.S. (1995). Four aspects of strategic change: Contributions to children's learning of multiplication. *Journal of Experimental Psychology: General, 124*, 83-97.

Logie, R. H., Gilhooly, K. J., Wynn, V. (1994). Counting on working memory in arithmetic problem solving. *Memory & Cognition, 22*, 395-410.

Lucangeli, D., Tressoldi, P.E., Bendotti, M., Bonanomi, M., & Siegel, L.S. (2003). Effective strategies for mental and written arithemtic calculation from the third to the fifth grade. *Educational Psychology, 23*, 507-520.

Luwel, K., Onghena, P., Torbeyns, J., Schillemans, V., & Verschaffel, L. (in press). Strengths and weaknesses of the choice/no-choice method on strategy choice and strategy change. *European Psychologist*.

Noël, M.-P., Désert, M., Aubrun, A., & Seron, X. (2001). Involvement of short-term memory in complex mental calculation. *Memory & Cognition, 29*, 34-42.

Penner-Wilger, M., Leth-Steensen, C., & LeFevre J.-A. (2002). Decomposing the problem-size effect : A comparison of response time distributions across cultures. *Memory & Cognition, 30*, 1160-1167.

PISA (2003). *Learning for tomorrow's world*. http://pisa.oecd.org

Ricks, T.R., Turley-Ames, K.J., & Wiley, J. (2007). Effects of working memory capacity on mental set due to domain knowledge. *Memory & Cognition, 35*, 1456-1462.

Schunn, C.D., & Reder, L.M. (2001). Another source of individual differences: Strategy adaptivity to changing rates of success. *Journal of Experimental Psychology: General, 130*, 59-76.

Seyler, D.J., Kirk, E.P, & Ashcraft, M.H. (2003). Elementary subtraction. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 29*, 1339-1352.

Shrager, J., & Siegler, R.S. (1998). SCADS: A model of children's strategy choices and strategy discoveries. *Psychological Science, 9*, 405-410.

Siegler, R.S., & Araya, R. (2005). A computational model of conscious and unconscious strategy discovery. *Advances in Child Development and Behavior, 33*, 1-42..

Siegler, R.S., & Lemaire, P. (1997). Older and younger adults' strategy choices in multiplication: Testing predictions of ASCM using the choice/no-choice method. *Journal of Experimental Psychology: General, 126*, 71-92.

Siegler, R.S., & Mu, Y. (2008). Chinese children excel on novel mathematics problems even before eleementary school. *Psychological Science, 19*, 759-763.

Stevenson, H.W., & Lee, S.Y. (1990). Context of achievement. *Monographs of the Society for Research in Child Development, 55* (Serial No 221).

Stevenson, H.W., Lee, S., Chen, C., Lummis, M., Stigler, J., Fan, L., & Ge, F. (1990). Mathematics achievement of children in China and the United States. *Child Development, 61*, 1053-1066.

Stevenson, H.W., Chen, C., & Lee, S.Y. (1993). Mathematics achievement of Chinese, Japanese, and American children: Ten years later. *Science, 259*, 53-58.

Stigler, J.W., Lee, S.Y., & Stevenson, H.W. (1986). Digit memory in Chinese and English: Evidence for a temporally limited store. *Cognition, 23*, 1-20.

Stigler, J.W., Lee, S., & Stevenson, H.W. (1987). Mathematics classrooms in Japan, Taiwan, and the United States. *Child Development, 58*, 1272-1285.

Szmalec, A., Vandierendonck, A., & Kemps, E. (2005). Response selection involves executive control: Evidence from the selective interference paradigm. *Memory & Cognition, 33*, 531-541.

Tang, Y., Zhang, W., Chen, K, Feng, S., Ji, Y., Shen, J., Reimand, E.M., & Liu, Y. (2006). Arithmetic processing in the brain shaped by cultures. *Proceedings of the National Academy of Sciences of the United States of America, 103*, 10775-10780.

Torbeyns, J., Verschaffel, L., & Ghesquière, P. (2002). Strategic competence: Applying Siegler's theoretical and methodological framework to the domain of simple addition. *European Journal of Psychology of Education, 17*, 275-291.

Torbeyns, J., Verschaffel, L., & Ghesquière, P. (2004). Strategic aspects of simple addition and subtraction: the influence of mathematical ability. *Learning and Instruction, 14*, 177-195.

Torbeyns, J., Verschaffel, L., & Ghesquière, P. (2005). Simple addition strategies in a first-grade class with multiple strategy instruction. *Cognition and Instruction, 23*, 1-21.

Torbeyns, J., Verschaffel, L., & Ghesquière, P. (2006). The development of children's adaptive expertise in the number domain 20 to 100. *Cognition and Instruction, 24*, 439-465.

Trbovich, P.L., & LeFevre, J.-A. (2003). Phonological and visual working memory in mental addition. *Memory & Cognition, 31*, 738-745.

Varol, F., & Farran, D. (2007). Elementary school students' mental computation proficiencies. *Early Childhood Education Journal, 35*, 89-94.

Walczyk, J.J., & Griffith-Ross, D.A. (2006). Time restriction and the linkage between subcomponent efficiency and algebraic inequality success. *Journal of Educational Psychology, 98*, 617-627.

Zhang, H., & Zhou, Y. (2003). The teaching of mathematics in Chinese elementary schools. *International Journal of Psychology, 38*, 286-298.

Foot Notes

1. Although some within-culture differences (i.e., between participants in the "phonological load" group and participants in the "executive load" group) may look significant in the Figures, they were not. For each dependent variable, we explicitly tested (with planned comparisons) whether, under no-load conditions, there were within-culture differences between participants in the "phonological load" group and participants in the "executive load" group. For percentages TU strategy use, no significant differences were observed for Belgians, Canadians, or Chinese (each $p > .25$). This was confirmed by an extra analysis in which we used a generalized linear mixed effects model with logistic link function. In this analysis, the difference between participants in the "phonological load" group and participants in the "executive load" group was not significant for Belgians ($p = .44$), Canadians ($p = .85$), or Chinese ($p = .53$). For the analysis on response times, no significant differences between participants in the phonological load" group and participants in the "executive load" group were observed for Belgians, Canadians, or Chinese (each $F<1$). And finally, for the analysis on error rates, no significant differences between participants in the "phonological load" group and participants in the "executive load" group were observed for Belgians or Chinese (each $F<1$). However, under no-load conditions, the Canadians in the "phonological load" group made fewer errors than the Canadians in the "executive load" group, $F(1,114) = 6.06$. These results were confirmed by the extra analysis in which we used a generalized linear mixed effects model with logistic link function. In this analysis, the difference between participants in the "phonological load" group and participants in the "executive load" group was not significant for Belgians ($p = .54$) or Chinese ($p = .80$), but it was significant for Canadians ($p = .02$). However, thanks to the dual-task design, this

significant difference does not compromise the conclusions about the single-to-dual task comparisons. The dual-task methodology, where no-load and load conditions are measured as a within-groups variable, controls for any such pre-existing differences. The crucial comparison is the *decrement* in performance (dual-task vs. single-task) for the primary task.

2. We tested whether the difference between UT speed and TU speed in no-choice conditions was sufficiently meaningful. If the difference between both strategy types would be very small (e.g., the UT strategy is only slightly faster or slower than the TU strategy), adaptivity analyses are pointless. *T*-tests confirmed that the difference between UT and TU speed was different from zero for Chinese, $t(38) = 3.11$ ($p < .01$), Belgians, $t(37) = 4.21$ ($p < .001$), and Canadians, $t(41) = 4.15$ ($p < .001$). To test whether the differences between strategies were similar across cultures, a 2 x 3 x 2 x 2 ANOVA was conducted on the difference between no-choice UT and TU speed (of correctly solved problems only), with Working-memory component (phonological vs. executive) and Culture (Belgian, Canadian, Chinese) as between-participants factors and Carry (0 vs. 1) and Load (no load vs. load) as within-participants factors. There were no significant main effects (highest $F = 1.19$) and no significant interaction effects (highest $F = 2.11$). Thus, the difference between UT speed and TU speed was similar in Belgians (408 ms; range -1467ms – 3615ms), Canadians (340 ms; range -3801ms – 5337ms), and Chinese (263 ms; range -1852ms – 3784ms). An additional analysis also showed that using a minimum difference of 200 ms to define the 'best' strategy did not change the adaptivity analysis. Therefore, the adaptivity analyses (which are based on the difference in efficiency between strategy types) are meaningful.
3. Although the effect of Culture did not reach statistical significance ($p = .056$), we do report the overall 2 degree of freedom test because we are explicitly testing for cultural differences in strategy adaptivity. The differences between the Chinese, on the one hand, and the

Belgians and the Canadians on the other hand (i.e., the 1 degree of freedom tests), did reach statistical significance. The lack of significance of the overall 2 degree of freedom contrast is a function of power and does not undermine the importance of the 1 degree of freedom tests (Hale, 1977).

Author note

Ineke Imbo, Department of Psychology, Ghent University; Jo-Anne LeFevre, Department of Psychology and Institute of Cognitive Science, Carleton University.

Support for this research was provided by the Research Foundation Flanders (FWO Flanders) with a postdoctoral fellowship to I. Imbo, and by the Natural Sciences and Engineering Research Council of Canada through a Discovery Grant to J. LeFevre. We thank Caitlyn Varenne and Michael Henighan for their assistance in setting up the experiment; Kevin Diependaele for his help with statistics; and Guy Lacroix and Nicole Robert for their helpful comments on previous versions of this paper. Correspondence concerning this article should be addressed to Ineke Imbo. Email: Ineke.Imbo@UGent.be

Figure captions

Figure 1. Percentage use of the TU strategy in the choice condition as a function of Culture, Load, and Working-memory component. Error bars denote standard errors.

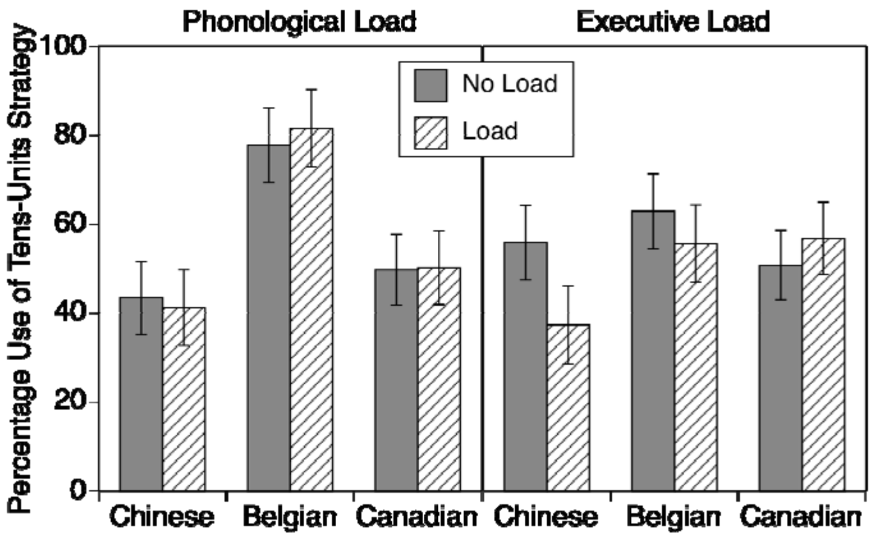
Figure 2. Response latencies (in seconds) in no-choice conditions as a function of Culture, Load, and Working-memory component. Error bars denote standard errors.

Figure 3. Error rates (%) in no-choice conditions as a function of Culture, Carry, Load, and Working-memory component. Error bars denote standard errors.

Figure 4. Percentage of adaptive strategy choices in the choice condition as a function of Culture, Carry, Load, and Working-memory component. Error bars denote standard errors.

Figure 1

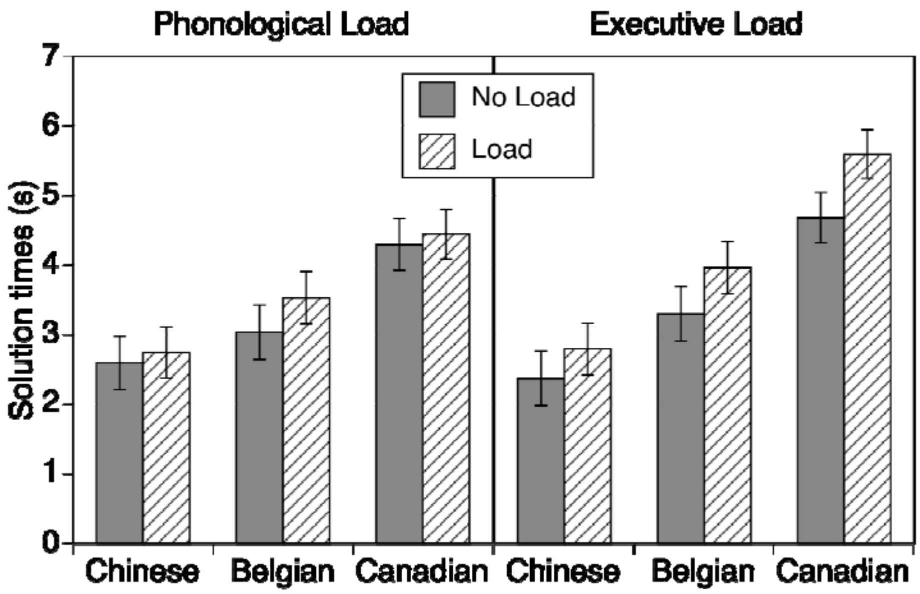
Percentage use of the TU strategy in the choice condition as a function of Culture, Load, and Working-memory component. Error bars denote standard errors.



Note. Data in this figure are collapsed over Carry because Carry did not interact with any other variable than Culture (each $p > .15$)

Figure 2

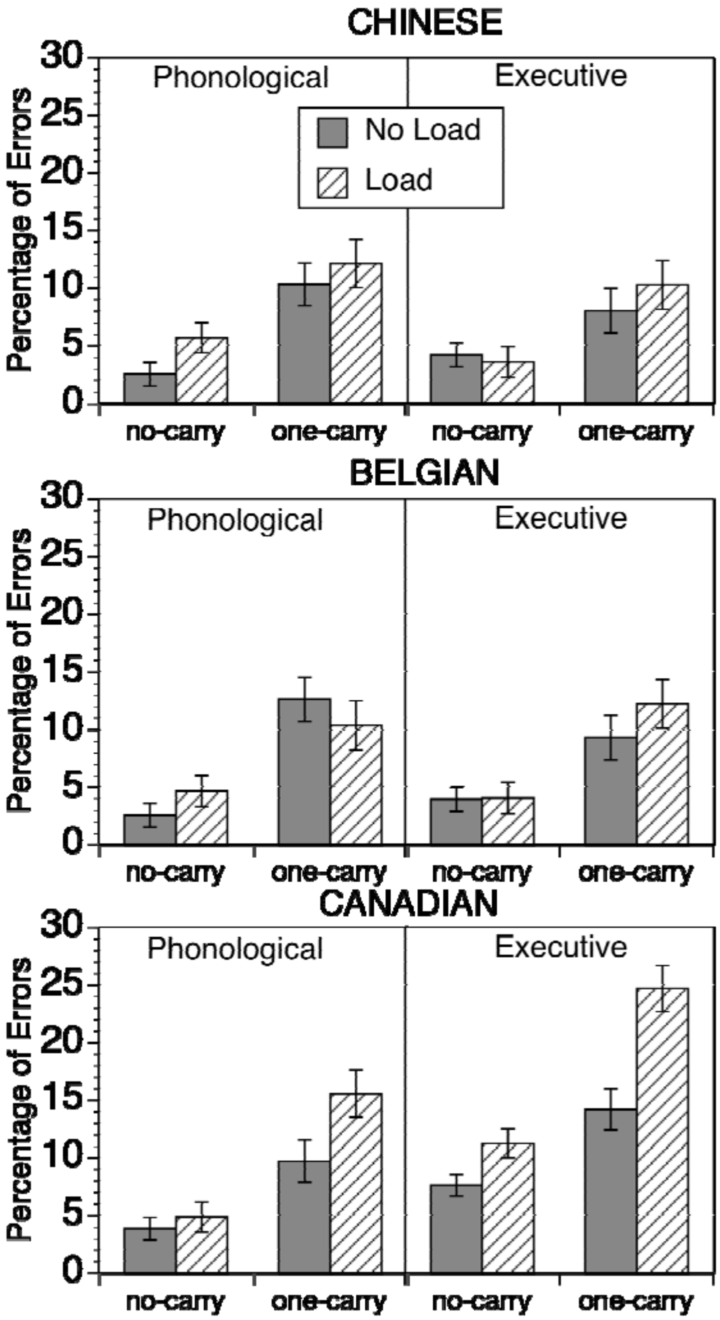
Response latencies (in seconds) in no-choice conditions as a function of Culture, Load, and Working-memory component. Error bars denote standard errors.



Note. Data in this figure are collapsed over Carry and Strategy. Carry did not interact with any other variable than Culture (each $p > .20$) and Strategy did not interact with any other variable at all (each $p > .15$).

Figure 3

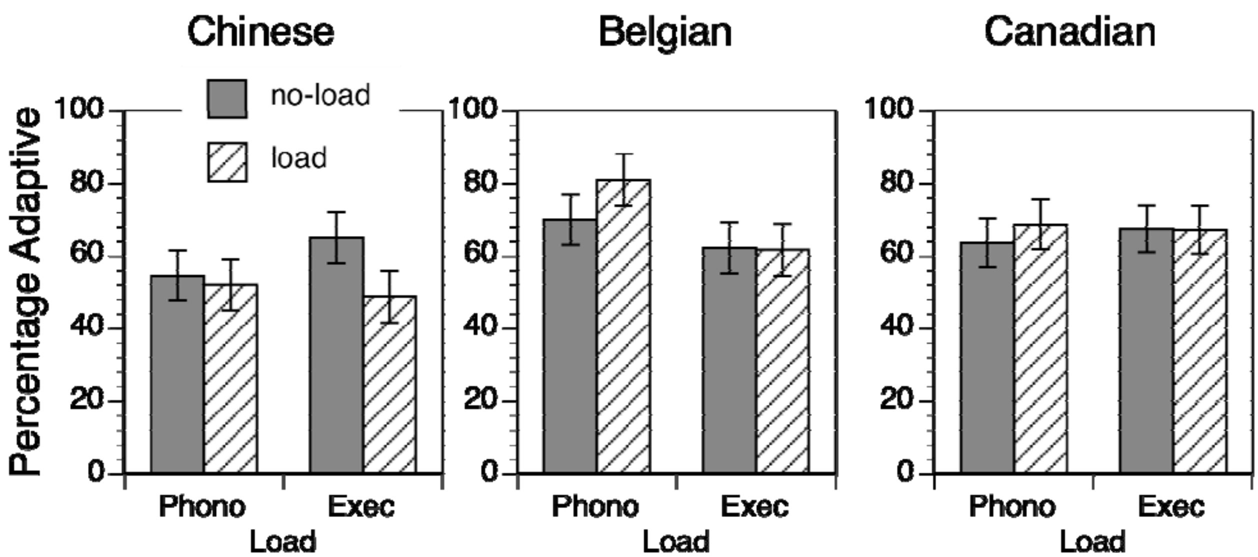
Error rates (%) in no-choice conditions as a function of Culture, Carry, Load, and Working-memory component. Error bars denote standard errors.



Note. Data in this figure are collapsed over Strategy because Strategy did not interact with any other variable (each $p > .25$).

Figure 4

Percentage of adaptive strategy choices in the choice condition as a function of Culture, Load, and Working-memory component. Error bars denote standard errors.



Note. Because Carry did not affect strategy adaptivity ($p > .70$), data in this figure are collapsed over Carry.

Table 1

Percentages of errors on the phonological secondary task and latencies (in ms) and percentages of errors on the executive secondary task as a function of Culture and Condition (standard errors in parentheses)

		Phonological Task	Executive Task	
		% Errors	% Errors	Latency
Chinese	Single	3.8 (2.1)	5.5 (2.7)	527.0 (15.0)
	Choice	57.3 (5.1)	65.1 (2.9)	650.9 (18.5)
	No-choice/UT	49.2 (4.8)	64.1 (2.9)	701.5 (18.2)
	No-choice/TU	44.1 (4.7)	60.2 (3.4)	656.5 (21.3)
Belgian	Single	7.3 (2.2)	5.3 (2.7)	542.7 (15.0)
	Choice	50.5 (5.3)	63.5 (2.9)	696.9 (18.5)
	No-choice/UT	41.4 (4.9)	61.1 (2.9)	698.6 (18.2)
	No-choice/TU	41.7 (4.8)	58.4 (3.4)	692.3 (21.3)
Canadian	Single	6.0 (2.1)	7.0 (2.5)	550.1 (14.0)
	Choice	46.3 (5.0)	66.3 (2.7)	688.4 (17.2)
	No-choice/UT	36.8 (4.7)	65.7 (2.7)	668.3 (16.9)
	No-choice/TU	35.1 (4.6)	63.3 (3.1)	669.4 (19.8)

Table 2

Response latencies (in seconds) of both strategies in no-choice conditions, as a function of Culture, Carry, Load, and Working-memory component (standard errors in parentheses).

		No carry		One carry	
Strategy		No load	Load	No load	Load
Units-Tens (UT)					
Chinese	Phonological	2.2 (0.2)	2.5 (0.3)	3.1 (0.4)	3.5 (0.5)
	Executive	2.2 (0.2)	2.4 (0.3)	2.7 (0.4)	3.4 (0.5)
Belgian	Phonological	2.6 (0.2)	2.9 (0.3)	3.7 (0.4)	4.6 (0.5)
	Executive	2.8 (0.2)	3.3 (0.3)	4.3 (0.4)	5.1 (0.5)
Canadian	Phonological	3.3 (0.2)	3.6 (0.3)	5.0 (0.4)	5.4 (0.5)
	Executive	3.9 (0.2)	4.7 (0.3)	6.3 (0.4)	7.2 (0.5)
Tens-Units (TU)					
Chinese	Phonological	2.2 (0.2)	2.1 (0.3)	2.8 (0.9)	2.8 (0.5)
	Executive	2.0 (0.2)	2.3 (0.3)	2.6 (0.9)	3.1 (0.6)
Belgian	Phonological	2.3 (0.2)	2.7 (0.3)	3.5 (0.9)	3.9 (0.6)
	Executive	2.3 (0.2)	2.9 (0.3)	3.7 (0.9)	4.6 (0.6)
Canadian	Phonological	2.8 (0.2)	3.3 (0.3)	6.1 (0.9)	5.5 (0.5)
	Executive	3.2 (0.2)	4.1 (0.3)	5.4 (0.9)	6.4 (0.5)

Table 3

Percentage of errors of both strategies in no-choice conditions, as a function of Culture, Carry, Load, and Working-memory component (standard errors in parentheses).

		No carry		One carry	
Strategy		No load	Load	No load	Load
Units-Tens (UT)					
Chinese	Phonological	2.1 (1.3)	5.7 (1.5)	11.2 (2.3)	13.0 (2.5)
	Executive	4.0 (1.3)	4.1 (1.5)	7.7 (2.4)	11.4 (2.6)
Belgian	Phonological	2.7 (1.3)	4.6 (1.5)	12.3 (2.4)	10.3 (2.6)
	Executive	5.2 (1.3)	3.3 (1.5)	9.3 (2.4)	14.5 (2.6)
Canadian	Phonological	2.5 (1.3)	2.9 (1.4)	9.2 (2.3)	14.2 (2.4)
	Executive	7.8 (1.3)	10.6 (1.4)	14.8 (2.2)	25.8 (2.4)
Tens-Units (TU)					
Chinese	Phonological	3.0 (1.4)	5.7 (1.5)	9.5 (2.3)	11.2 (2.8)
	Executive	4.4 (1.4)	3.1 (0.2)	8.4 (2.4)	9.2 (2.9)
Belgian	Phonological	2.4 (1.4)	4.6 (2.0)	13.0 (2.4)	10.4 (2.9)
	Executive	2.7 (1.4)	4.8 (2.0)	9.3 (2.4)	9.9 (2.9)
Canadian	Phonological	5.2 (1.3)	6.8 (1.9)	10.2 (2.3)	16.9 (2.7)
	Executive	7.3 (1.3)	11.8 (1.8)	13.5 (2.2)	23.5 (2.6)