Complex-Arithmetic Problem Solving: Differences among Belgian, Canadian, and Chinese participants

Ineke Imbo (Ineke.Imbo@UGent.be)
Department of Experimental Psychology, Ghent University, Ghent, Belgium
Jo-Anne LeFevre (jo-anne_lefevre@carleton.ca)
Centre for Applied Cognitive Research, Carleton University, Ottawa, Canada

Abstract

The complex-arithmetic performance of three different populations was tested: Flemish-speaking Belgians; English-speaking Canadians; and Chinese-speaking Chinese participants currently living in Canada. All participants solved complex addition problems (e.g., 58 + 73) under no-load and load conditions, in which one component of working memory (either the central executive or the phonological loop) was loaded. The results showed (a) cultural differences in strategy selection, strategy efficiency, and strategy adaptivity, and (b) cultural differences in the involvement of phonological and executive working-memory resources. Limitations and implications of the present results are discussed.

Keywords: mental arithmetic; strategies; working memory; phonological loop; central executive; carry; cultural differences.

Introduction

The aim of the present study was to investigate cultural differences in people's complex-arithmetic performance. More specifically, two main issues were addressed. First, do people of various cultures use their *working memory* differently when solving complex addition problems? And second, is there any cultural variation in these people's *strategic* performance? Obviously, both research questions do interact: other strategy choices and/or other strategy efficiency levels may need other working-memory resources.

Cultural Differences

Among the different ways in which people may vary (e.g., gender, personality, etc.), culture is probably one of the most intriguing. Cultural differences may exert powerful influences on people's cognitive performance. In the present study, we examined the effects of culture on one aspect of people's cognition, namely mental arithmetic. Until now, most studies on this topic compared the performance of North Americans with that of Asians on single-digit arithmetic (e.g., Campbell & Xue, 2001; Geary, 1996; Geary et al., 1993, 1996a, 1996b, 1997; LeFevre & Liu, 1997). In these studies, Asians were more likely to retrieve arithmetic facts from memory and used more efficient strategies than did North Americans.

In the present study, we tested Asians, North Americans, and Europeans. Indeed, although there are many studies that investigated Europeans' arithmetic performance, until now, no study *compared* the arithmetic performance of Europeans with that of other nationalities or cultures or tested cultural differences in *complex* mental arithmetic.

Arithmetic Strategy Use

Researchers studying people's strategic competence have distinguished four dimensions (cf. Lemaire & Siegler, 1995). The first dimension is the *repertoire* of strategies that people use. In complex arithmetic, strategy categorization usually includes the right-to-left order of problem solving and the left-to-right order of problem solving (e.g., Green, Lemaire, & Dufau, 2007; Hitch, 1978).

The second dimension of people's strategic competence is the relative *frequency* with which the different strategies are applied. In complex arithmetic, the relative frequency of the different strategies depends greatly on the presence of carry operations, with more frequent use of the right-to-left strategy when carry operations have to be performed (e.g., Green et al., 2007; Hitch, 1978). 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.

The third dimension of people's strategic competence is the *efficiency* with which each strategy is executed, which also depends on the presence of carry operations. Green et al. (2007) observed more efficient right-to-left strategy use for carry problems, but more efficient left-to-right strategy use for no-carry problems. Strategy efficiency has further been shown to decrease with the number of carry operations as well as with the value that has to be carried (Imbo, Vandierendonck, & De Rammelaere, 2007; Imbo, Vandierendonck, & Vergauwe, 2007).

The last dimension of people's strategic competence is the *adaptivity* with which the different strategies are chosen and applied on a given set of problems. This often overlooked dimension examines which information people take into account when choosing among several available strategies.

In the present study, we examined the cultural effects on these various dimensions of strategic performance. First, do the different cultures vary in the strategies they use to solve complex-arithmetic problems (i.e., strategy selection)? Second, are there cultural differences in the speed and the accuracy with which the strategies are executed (i.e., strategy efficiency)? Third, are all cultures equally proficient in choosing the 'best' strategy when solving complex-arithmetic problems (i.e., strategy adaptivity)? And finally, is the carry effect on people's strategic performance equally large across the different populations?

Moreover, as will be outlined below, we also investigated the role of working memory in these various aspects of strategic performance. Indeed, cultural differences in (for example) strategy efficiency may go together with different working-memory requirements (e.g., less/more executive needs). Specifically, we hypothesized that the greater cognitive efficiency shown by Asians in solving single-digit arithmetic may result in reduced working memory demands, other strategy choices, greater levels of strategy efficiency, and greater levels of strategy adaptivity as compared to individuals from North America or Europe.

Working Memory

Most researchers agree that the function of working memory is to store and manipulate temporary information. Research into the role of working memory in mental arithmetic is mostly based on the specific predictions of the multi-componential model (Baddeley, 2000), which includes a central executive, a phonological loop, a visuo-spatial sketchpad, and an 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 binds information from the slave systems and from long-term memory into a unitary representation.

Research has shown that the central executive is always needed in complex-arithmetic problem solving, whereas the phonological loop is involved only under certain conditions (DeStefano & LeFevre, 2004). Because the possible roles of the visuo-spatial sketchpad and the episodic buffer are equivocal and theoretically less established, they were not investigated in the current study.

In the present study we examined whether or not the roles of the central executive and the phonological loop are similar across the three cultures. Different predictions were made for the central executive and the phonological loop. Because the arithmetic performance of Asians is much faster and more automatic than that of North Americans, we expected smaller executive load effects in the former than in the latter. Indeed, more automated strategy execution implies lower executive involvement (e.g., Hecht, 2002; Imbo & Vandierendonck, 2007a,b,c). The predictions concerning the role of the phonological loop are less straightforward. Because the frequency of direct retrieval strategies, that are said to be phonologically based (Dehaene & Cohen, 1997), is higher in Asians than in North Americans, one prediction is that Asians would experience greater phonological load effects than North Americans. However, recent imaging studies (e.g., Tang et al., 2006) observed greater perisylvian activity in English speakers than in Chinese speakers, which was interpreted as lower working-memory efficiency for processing number symbols in the former than in the latter. According to this reasoning, we predicted higher phonological load effects in North Americans than in Asians. As noted before, no studies compared Europeans' arithmetic performance with that of other cultures, so no predictions were made.

Method

To test the role of the different working-memory components in the various strategy dimensions, the choice/no-choice method and the selective interference paradigm were combined. The choice/no-choice method was used to investigate strategy selection and strategy efficiency independently (Siegler & Lemaire, 1997). The selective interference paradigm was used to investigate the role of working memory. Both methods have been combined in simple-arithmetic studies (Imbo & Vandierendonck, 2007a,b,c) but not yet in complex-arithmetic studies.

Participants

One hundred twenty-five adults participated. Forty participants (20 women; mean age 21.3 years old) were native Flemish-speaking students at Ghent University who had received their education in Flanders, Belgium. Forty-five participants (25 women; mean age 21.3 years old) were native English-speaking students at Carleton University who had received their education in Canada. Forty participants (23 women; mean age 25.1 years old) were native Chinese-speaking students at Carleton University who had received their education in China.

Procedure

All participants solved the complex-arithmetic problems in three conditions: first the choice condition, and then two no-choice conditions, the order of which was randomized across participants. 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. Instructions were provided in Flemish for the Belgians and in English for the Chinese and the Canadians.

Complex-arithmetic task

Six sets of 24 addition problems were constructed. Each set was presented only once. All problems consisted of two 2-digit numbers. 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. Half of the problems were no-carry problems (e.g., 34+21), the other half were one-carry problems (e.g., 16+38). The mean size of the correct sum was equally large for no-carry and one-carry problems and equally large in all six sets. The even/uneven status of the correct sum and the position of the largest operand were also controlled for.

A trial started with a fixation point for 500ms. Then the addition problem was presented horizontally in the center of the screen, with the "+" sign at the fixation point. The problem remained on screen until the participant responded. Timing began when the stimulus appeared and ended when the response triggered the sound-activated relay. Feedback (correct/incorrect) was presented on each trial.

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. If participants did not choose the UT or the TU strategy, they had the option to report 'Other'.

In the no-choice conditions, participants were asked to use one particular strategy to solve *all* problems. In no-choice/UT, participants were required to use the UT strategy; in no-choice/TU, they were required to use the TU strategy. After having solved the problem, participants had to answer with 'yes' or 'no' whether they had succeeded in using the required strategy. Non-compliant trials were excluded from analyses. Invalid trials (e.g., failures of the voice-activated relay) were discarded as well, and returned at the end of the block, which minimized data-loss due to unwanted failures.

Executive Secondary Task

In this continuous choice reaction time task (Szmalec, Vandierendonck, & Kemps, 2005), low tones (262 Hz) and high tones (524 Hz) were sequentially presented with an interval of 900 or 1500 ms. Participants had to press the 4 when they heard a high tone and the 1 when a low tone was presented. The duration of each tone was 200ms.

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 arithmetic problems. Following the response of the participant, the experimenter presented a new 4-letter string.

Results

All trials that were spoiled due to failures of the sound-activated relay (0.7%), all choice trials on which participants reported having used an 'Other' strategy (0.7%), and all no-choice trials on which participants failed to use the required strategy (2.4%) were deleted from all further analyses. Further, five participants (two Belgians, two Canadians, and one Chinese) had to be removed due to voice-key problems. All data were analyzed on the basis of the multivariate general linear model; and all reported results were significant at $p < .05$, unless mentioned otherwise.

Strategy Selection

The TU strategy was used on 55% of all trials. A 2 x 3 x 2 x 2 ANOVA was conducted on the percentages of TU strategy use (of correctly solved problems only) observed in choice conditions, with Working-memory component (phonological vs. executive) and Population (Belgian vs. Canadian vs. Chinese) as between-subjects factors and Carry (0 vs. 1) and Load (no load vs. load) as within-subjects factors.

The main effects of Carry and Population were significant, $F(1,114) = 4.57$ and $F(2,114) = 4.89$, respectively. Participants used the TU strategy more frequently on no-carry problems (57%) than on one-carry problems (54%). TU strategy use was higher in Belgians (69%) than in Canadians (52%) and Chinese (44%). Carry and Population also interacted, $F(2,114) = 5.07$ (see Figure 1). Whereas Chinese and Belgian participants did not change their strategy choices according to the presence of a carry operation, Canadian participants used TU less frequently when a carry operation had to be completed (47 % vs. 57%).

The main effect of Load was not significant ($p = .10$), but there were interactions between Load and Working-memory component, $F(1,114) = 4.16$, between Load and Population, $F(2,113) = 5.03$, and between Load, Working-memory component, and Population, $F(2,114) = 3.53$. The amount of TU strategy use did not change under a phonological load in any group. Similarly, the executive load did not affect the strategy choices of either Belgians or Canadians. However, Chinese participants used the TU strategy less often under executive load than in the control condition (37% vs. 58%), $F(1,114) = 16.96$. No other effects were significant.

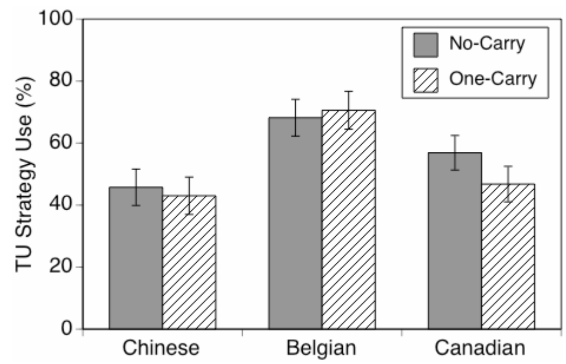

Figure 1: TU strategy use (%) as a function of Carry and Population.

Strategy Efficiency: Speed

A 2 x 3 x 2 x 2 x 2 ANOVA was conducted on no-choice RTs (of correctly solved problems), with Working-memory component (phonological vs. executive) and Population (Belgian vs. Canadian vs. Chinese) as between-subjects factors and Strategy (UT vs. TU), Carry (0 vs. 1), and Load (no load vs. load) as within-subjects factors.

The main effects of Population, Strategy, Carry, and Load were significant, $F(2,114) = 18.50$, $F(1,114) = 6.75$, $F(1,114) = 117.97$, and $F(1,114) = 27.11$, respectively. Chinese (2.6s) were faster than Belgians (3.5s), who were faster than Canadians (4.8s). Further, participants were faster when using the TU strategy (3.4s) than when using the UT strategy (3.8s), faster on no-carry problems (2.8s) than on one-carry problems (4.4s), and faster in no-load conditions (3.4s) than in load conditions (3.8s). Carry and Population interacted, $F(2,114) = 10.35$ (see Figure 2). The carry effect was larger in Canadians (2.3s) than in Belgians (1.5s), and larger in Belgians than in Chinese (0.8s).

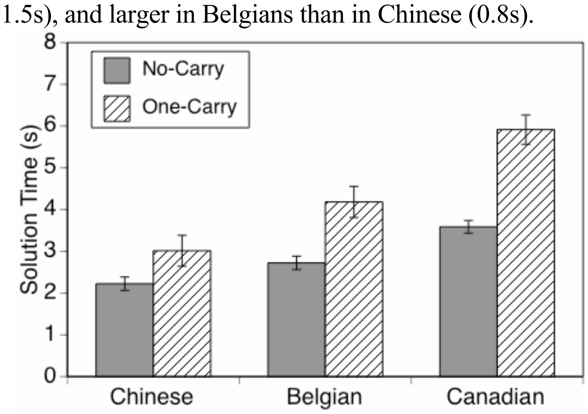

Figure 2: RT (seconds) as a function of Carry and Population.

Further, Load interacted with Working-memory component, $F(1,114) = 5.07$. Executive load effects (0.7s) were significantly greater than phonological load effects (0.3s). Planned comparisons (see Figure 3) showed that a phonological load affected Belgians' speed, $F(1,114) = 4.85$ but did not affect Canadians' or Chinese's speed. An executive load affected Canadians' and Belgians' speed, $F(1,114) = 19.18$ and $F(1,114) = 8.80$, respectively, and tended to affect Chinese's speed, $F(1,114) = 3.54$ ($p = .06$).

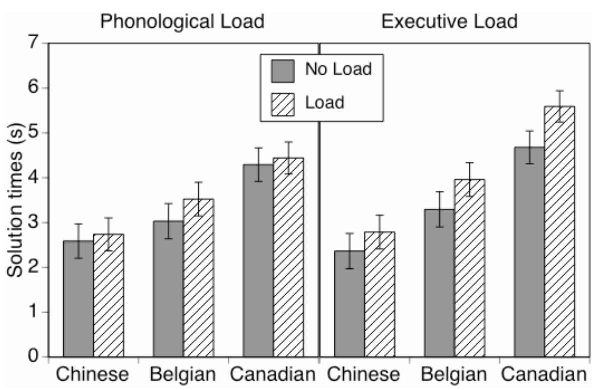

Figure 3: RT (in seconds) as a function of Load, Working-memory component, and Population.

Strategy Efficiency: Accuracy

A 2 x 3 x 2 x 2 x 2 ANOVA was conducted on no-choice accuracies, with Working-memory component (phonological vs. executive) and Population (Belgian vs. Canadian vs. Chinese) as between-subjects factors and Strategy (UT vs. TU), Carry (0 vs. 1), and Load (no load vs. load) as within-subjects factors.

The main effects of Carry, Load, and Population were significant, $F(1,114) = 160.93$, $F(1,114) = 22.43$, and $F(2,114) = 9.75$, respectively. Participants made fewer errors on no-carry problems (5%) than on one-carry problems (12%) and fewer in no-load conditions (7%) than in load conditions (10%). Error rates were also lower for Chinese (7%) and Belgians (8%) than for Canadians (11%). Although the Carry x Population interaction did not reach significance ($p = .11$), planned comparisons showed significantly larger carry effects in Canadians than in Chinese, $F(1,114) = 2.28$.

The Load x Population interaction was significant as well, $F(2,114) = 6.88$. Load effects were significantly larger in Canadians than in Belgians and Chinese, $F(1,114) = 7.64$ and $F(1,114) = 11.73$, respectively, but equally large in Belgians and Chinese ($F<1$). Planned comparisons (see Figure 4) showed that Canadians made more errors under phonological load, $F(1,114) = 7.03$ and under executive load, $F(1,114) = 31.97$. Belgians' error rate was not affected by any load but Chinese tended to make more errors under phonological load, $F(1,114) = 3.59$ ($p = .06$).

Strategy Adaptivity

Regression analyses were performed in order to test which information participants take into account when making strategy choices. The dependent variable was the amount of TU strategy use under no-load and load choice conditions.

There were three predictor variables: (1) the presence of a carry operation, (2) the relative strategy's speed, and (3) the relative strategy's accuracy. The relative strategy accuracy (speed) is the difference between UT accuracy (speed) and TU accuracy (speed) and was calculated for each participant separately. The regression analyses were run for Chinese, Belgian, and Canadian participants separately.

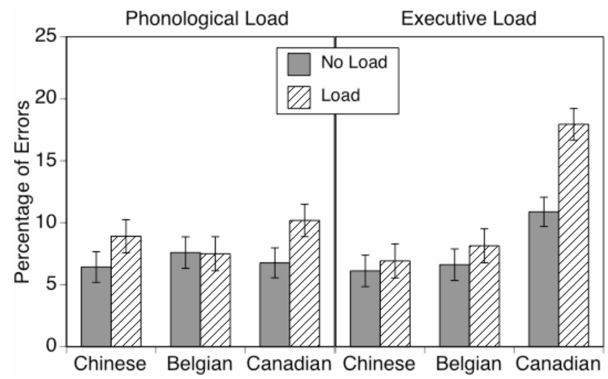

Figure 4: Accuracy (percentage of errors) as a function of Load, Working-memory component, and Population.

Under no-load conditions, the R^2 values were .146, .204, and .190 for Canadians, Chinese, and Belgians, respectively. The relative strategy's speed was a significant predictor in all three populations, $\beta = .341$, $\beta = .415$, and $\beta = .439$, respectively. A faster TU speed predicted more frequent TU strategy use. The relative strategy's accuracy was a significant predictor for Chinese only, $\beta = .209$, indicating that Chinese used the TU strategy more frequently when this strategy was less erroneous.

Under load conditions, the R^2 values were .155, .194, and .146 for Canadians, Chinese, and Belgians, respectively. The relative strategy's speed was a significant predictor in all three populations, $\beta = .394$, $\beta = .432$, and $\beta = .370$, respectively. Again, a faster TU speed predicted more frequent TU strategy use. The other predictors did not reach significance; so, under load conditions, Chinese did not take the relative strategy's accuracy into account. This pattern of results indicates working-memory load effects on Chinese's strategy adaptivity.

Discussion

The present study investigated cultural differences in people's complex-arithmetic strategy performance. Cultural differences were observed in strategy selection, strategy efficiency, and strategy adaptivity, on the one hand, and in the involvement of working-memory resources, on the other.

Strategy Selection

Overall, the TU strategy was used more often than the UT strategy. Selection of the TU strategy was highest among Belgians (on about 70% of trials) whereas Canadians chose TU just over half the time. The Chinese, in contrast, chose TU just less than half the time. Thus, we observed cultural differences in the use of the two strategies. Because participants in all three groups claimed that they were taught to use the UT strategy in school, it seems that education is not the main cause of the cultural differences in strategy selection. It might be adherence to what is taught, though, with higher levels of adherence in Chinese participants than in Belgian and Canadian participants.

Canadians changed their strategies according to the presence of a carry, whereas Belgians and Chinese did not. When confronted with the difficult carry problems, Canadians may have switched to the UT strategy because they feel more confident in implementing this 'default' strategy. Furthermore, Chinese (but not Belgians or Canadians) switched to more frequent use of the UT strategy under executive working-memory loads. Chinese were already frequent UT users in general – even under no-load conditions. The switch to even *more frequent* use of the UT strategy under load conditions suggests that some aspect of the UT strategy (perhaps greater familiarity) influenced strategy choices for the Chinese participants. An executive load thus caused Chinese participants to switch to this 'default' strategy that has been taught in elementary school.

It is interesting to note that working-memory load effects have never been shown on people's strategy choices in the domain of *simple* arithmetic (e.g., Hecht, 2002; Imbo & Vandierendonck, 2007a,b,c); that is, frequencies of chosen strategies were always equal in load and no-load conditions. Comparable results were obtained in the present study for the Belgians and the Canadians, who did not switch their strategy choices under working-memory loads. The absence of working-memory load effects on strategy choices can easily be accounted for by the Adaptive Strategy Choice Model (ASCM, Siegler & Shipley, 1995). According to this model, strategy choices are not necessarily deliberate and conscious but rather 'automatic' (i.e., the most highly activated strategy is selected). Hence, no working-memory resources are needed in the strategy selection process. The fact that Chinese participants *did* choose other strategies under an executive load may be related to the fact that – in no-load conditions – Chinese had spare working-memory resources that could be used to overcome the automatic activation of certain strategies. However, when the Chinese's central executive was loaded, they also switched to a more automatic and less controlled strategy selection process – hence a greater reliance on the default UT strategy.

Although working-memory load effects have been shown on people's strategy choices in the domain of *complex* arithmetic (e.g., Imbo, Duverne, & Lemaire, 2007), people in that study were explicitly asked to select the 'best' strategy for each problem, which might have caused a greater level of awareness about the strategy choice process. The strategy's efficiencies were also further apart than in the present study, in which we observed no large efficiency advantages for one strategy over the other (i.e., the TU strategy was slightly faster than the UT strategy but both strategies were equally accurate). Further research is thus needed in order to investigate (a) the exact role of working memory in the strategy selection process, and (b) the factors determining 'automatic' strategy choices (e.g., age of acquisition, feeling of confidence, history of practice, etc.).

Strategy Efficiency

Large cultural differences were observed in both speed and accuracy. Chinese were faster than (but as accurate as) Belgians, who were in their turn faster and more accurate than Canadians. Interestingly, Chinese were not only more efficient in general; they were also more efficient in performing carry operations. This finding shows that Chinese participants have both better access to declarative knowledge and more efficient procedural skills.

The working-memory load effects also differed across populations. Chinese participants' speed and accuracy were only slightly affected by working-memory loads. This result is remarkable; researchers generally hypothesize that working memory plays a significant role in complex-arithmetic problem solving - independent of culture. The results of the present study suggest that the Chinese participants have achieved a level of skill at two-digit addition problems that approaches that of other groups for single-digit addition.

Belgians' strategy speed was affected by both phonological and executive working-memory loads. However, neither phonological nor executive working-memory loads affected Belgians' strategy accuracy. Thus Belgians may require working memory resources to execute these arithmetic processes, but the demands of the working memory tasks do not drastically limit their performance.

In contrast, Canadians' speed *and* accuracy were affected by working-memory loads. 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.

In conclusion, the involvement of working-memory resources was not equivalent across the different cultures. More specifically, Canadians used considerable working-memory resources when solving complex-arithmetic problems, whereas Belgians required fewer resources and Chinese required even fewer resources. Thus, as a cultural group's problem solving was less efficient (i.e., slower and more erroneous), more executive resources were needed to maintain a reasonable level of performance (Hecht, 2002; Imbo & Vandierendonck, 2007a,b,c).

The results further showed that the phonological loop is mainly used to maintain accuracy. Both Canadians and Chinese made more errors when their phonological resources were loaded. However, it is also possible that these phonological load effects were an overestimate of the extent to which phonological resources are typically used by the Chinese because they were asked to respond in English and not in Chinese. The phonological load effects on the Canadians' accuracy and the Belgian's speed are probably caused by the inefficiency of their number language – which is less straightforward and more resource-demanding than the Chinese number language.

Although it is difficult to determine the causes of the cultural differences in strategy efficiency, it is very plausible that early educational experiences (in elementary school) play a significant role. Drill and automaticity are highly favored in Asian education, less so in European and North American education. In the latter two cultures, exploration and true understanding are more highly favored. Frequent calculator use is also less accepted in Asian than in European and North American cultures. Other factors that may have contributed are (a) the structure and efficiency of the number language, which is more straightforward and less resource-demanding in Chinese than in Flemish and English, (b) cultural standards (e.g., competitiveness, motivation, etc.), and (c) emotional variables such as feelings of anxiety vs. enthusiasm when confronted with math problems.

Strategy Adaptivity

The strategy adaptivity analyses showed that participants generally took only one source of information into account when choosing strategies, namely strategy speed. Belgian, Canadian, and Chinese participants used the TU strategy more frequently when this strategy was faster. Interestingly, Chinese were also affected by strategy accuracy, but only when their working memory was not loaded, indicating that their strategy adaptivity was affected by working-memory load. Whether or not working-memory resources are needed in strategy adaptivity is still a highly debated topic.

Limitations and Implications

One limitation of the present study is that the Chinese participants were asked to respond in English, their second language. Although all Chinese participants understood and spoke English fluently, we acknowledge that the Chinese participants' performance might have suffered accordingly. Consequently, the true performance differences between Chinese participants, compared to Belgian and Canadian participants, might even be larger.

One implication of the current study is that theories and models concerning people's cognitive performance should include variables that explain cultural differences such as: skill level, educational history, emotions (e.g., anxiety vs. motivation), number language efficiency, or working-memory capacity. The current results also question the merits and limits of the various teaching methods currently used in elementary school (i.e., drill and automaticity vs. insight and discovery). Further research might examine the costs and benefits of both education types.

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