Cultural differences in strategic behavior: A study in computational estimation

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Abstract

Imbo and LeFevre (2009) observed that Asians (responding in their second language) selected strategies less adaptively than did non-Asians (responding in their first language). In the present research, we tested whether adaptive strategy selection is (a) really more resource demanding for Asians than for non-Asians or (b) more resource demanding for participants answering in a non-preferred language. Three groups of participants were tested on a computational estimation task (e.g., 42 x 57 ≈ ?) in no-load and load conditions: 40 Belgian-educated adults who answered in their first language (Dutch), 40 Chinese-educated adults who answered in their first language (Chinese), and 40 Chinese-educated adults who answered in their second language (English). Although the Chinese were faster and more accurate than the Belgians, they selected strategies less adaptively. That is, the Chinese were less likely to choose the strategy that produced the best estimate, and especially so when their working memory was loaded. Further, we also observed that the Chinese who answered in English were slower than the Chinese who answered in Chinese; and this difference was larger for difficult strategies and under working memory load. These results are interpreted in terms of the encoding complex model, whereas the explanation for the adaptivity results is based on cultural differences in educational history.

Keywords: computational estimation; strategy efficiency; strategy selection; strategy adaptivity; working memory; executive functions; education; language; bilingualism; cultural differences

Cultural differences in strategic behavior: A study in computational estimation

Asians generally have better computational skills than non-Asians, responding faster and more accurately on both simple arithmetic problems such as 3 + 5 and 4 x 6 (Campbell & Xue, 2001; LeFevre & Liu, 1997) and on multi-digit problems such as 45 + 28 and 45 – 19 (Imbo & LeFevre, 2009, 2010). Further, Asians also require less executive working memory resources when solving complex additions than do non-Asians (i.e., Belgians and Canadians; Imbo & LeFevre, 2009). However, Imbo and LeFevre (2009) found a possible drawback of this high strategy efficiency in Asians; namely, low strategy adaptivity. Indeed, Chinese participants, who responded in their second language (English), chose their strategies less adaptively than Belgians and Canadians, who responded in their first language (Dutch and English, respectively). Specifically, Chinese were less likely to select the strategy that was optimally efficient (based on their own performance) as compared to the other groups, and this was especially so under executive working memory load. There are two competing interpretations of these results: first, adaptive strategy selection is more resource demanding for Asians than for non-Asians; or second, adaptive strategy selection is more resource demanding for participants answering in a second language.

In order to evaluate these interpretations, we compared the strategic performance of three groups on a computational estimation task: (a) Belgian-educated adults (*N*=40) responding in Dutch, their first language; (b) Chinese-educated adults responding in Chinese, their first language (Chinese/L1, *N*=40); and (c) Chinese-educated adults responding in English, their second language (Chinese/L2, *N*=40). Imbo and LeFevre (2009) defined adaptivity as the percentage of trials on which participants chose the fastest strategy as determined by their personal efficiency performance. This type of adaptivity is *person based* because it is relative to an individual's performance. In contrast, in the present study, the most appropriate strategy was determined on the basis of problem characteristics, such that there was a predefined 'best' strategy for every problem. This type of adaptivity is *problem based*. That is, participants had to choose the estimation strategy that provided the answer that was closest to the actual answer. If adaptive strategy selection is more resource demanding for Chinese participants, we expect fewer adaptive strategy choices in the Chinese/L1 and Chinese/L2 groups than in the Belgian group. However, if responding in a non-preferred language affects strategy adaptivity, we expect fewer adaptive strategy choices in the Chinese/L2 group than in the Chinese/L1 group.

The inclusion of two possible response languages in the Chinese groups also allowed us to test whether number processing is language-dependent. Observing a main effect of response language (i.e., slower responding in L2 than in L1) does not answer this question, because a main effect of language may indicate that peripheral processes (such as encoding the problem or producing the answer) are more difficult in L2 than in L1. We can only conclude that response language affects the calculation process itself when there is a significant interaction between response language and strategy difficulty. This issue of whether response language should interact with strategy difficulty differentiates the various theoretical models of numerical cognition. According to the Abstract Code model of McCloskey and colleagues (McCloskey, 1992, McCloskey & Macaruso, 1994, 1995), all input is converted into a common abstract code. Because all calculation and estimation processes are executed on this abstract code, they should operate independently of response language. Hence, the Abstract Code model predicts a main effect of response language but no interaction between strategy difficulty and response language. Similarly, according to the Triple Code model of Dehaene (1992; Dehaene & Cohen, 1995, 1997), all input is converted into one of three appropriate codes (the analog magnitude code, the visual-Arabic code, or the auditory-verbal code), depending on the task. Approximate calculation and estimation processes, for example, are supported by the analog-magnitude code, which operates independent of language. Hence, the Triple Code model also predicts that there will not be an interaction between strategy difficulty and response language.

In contrast, according to the Encoding Complex model (Campbell, 1992; 1994; Campbell & Epp, 2004), input activates a rich network of associations that includes both relevant and irrelevant information. Successful performance thus requires extraction of the relevant information from the encoding complex. Applied to the present study, the Chinese would activate four numerical codes in the estimation task: an analog magnitude code, a visual-Arabic code, a Chinese verbal code, and an English verbal code – the latter two representing language-dependent processes for verbal number production. The communication between the codes is interactive (and not additive, as in the other models), and its efficiency varies with the amount of task-specific practice. As a result of such task-specific practice, the Chinese participants' link between the magnitude code and the Chinese verbal code is stronger than their link between the magnitude code and the English verbal code. Hence, it will be harder for Chinese participants to minimize the activation of irrelevant associations when responding in L2 than when responding in L1. Because resisting the interference of irrelevant associations is even harder when solvers use more difficult strategies, the Encoding Complex model predicts an interaction between strategy difficulty and response language.

Method

Participants

One hundred and twenty participants were recruited for the present experiment. Forty participants (20 women and 20 men, mean age 22.7 years old) were Dutch-speaking students at

Ghent University who had received all their education in Belgium. All Belgian participants answered in their first language (Dutch). Eighty participants were Chinese-speaking students at Ghent University who had received their education (up to high school) in China but were currently living and studying in Belgium. Their first language was Chinese and their second language was English. Half of them (25 women and 15 men, mean age 27.7 years old) provided the answer to the arithmetic problems in their second language (English), whereas the other half (26 women and 14 men, mean age 28.8 years old) provided their answer in their first language (Chinese). All participants were paid €8 to €10.

On a paper-and-pencil measure of computational skill (addition, multiplication, and subtraction problems; French, Ekstrom, & Price, 1963), the performance of the Chinese groups was not different ($M = 54$ for those who answered in English and $M = 54$ for those who answered in Chinese, $t < 1$) and was significantly better than that of the Belgians ($M = 37$), $t(78) = 4.58$ and $t(78) = 4.81$, respectively. Thus, as in previous research with Chinese-educated participants, the Chinese participants' computational skill was much superior to that of other groups (Campbell & Xue, 2001; LeFevre & Liu, 1997; Imbo & LeFevre, 2009, 2010).

Materials

A computational estimation task was chosen where it was possible to construct problems that have a predefined 'best' strategy. Six sets of 24 computational estimation problems were constructed, resulting in a total of 144 different problems[1]. The six problem sets were balanced for problem size, sum of unit digits, and sum of decade digits. All problems consisted of two two-digit Arabic numbers between 20 and 90; one with a unit digit smaller than 5 and one with a unit digit larger than 5. All problems were also controlled for the following factors: (a) no operand had 0 or 5 as a unit digit, to avoid the application of rules (N x 0 = 0); (b) digits were not repeated in the same unit or decade positions (as in 41 x 47); and (c) digits were not repeated within operands (as in 33 x 57).

Half of the problems were labeled round-down (RD) problems, because on these problems the rounding-down strategy (in which both operands are rounded down to the closest decades) produces an answer that is numerically closer to the exact answer than the rounding-up strategy (in which both operands are rounded up to the closest decades). For example, 56 x 71 rounded down to 50 x 70 produces an answer of 3500, which is closer to the exact answer of 3976 [-476] than rounding up to 60 x 80 where the estimated answer would be 4800 [+824]. The other half were round-up (RU) problems, because the answer produced by the rounding-up strategy was closer to the exact answer than the answer produced by the rounding-down strategy (e.g., 49 x 63 = 3087; rounding up to 50 x 70 = 3500 [+413] whereas rounding down to 40 x 60 = 2400 [-687]).

Participants were not given any instruction in how to determine which strategy would produce the 'best' answer on any given problem. However, the choice of the most adaptive strategy usually could be based on the sum of the unit digits, because problems with smaller sums of unit digits are better estimated with the rounding-down strategy, whereas problems with larger sums of unit digits are better estimated with the rounding-up strategy. For the items used in the present research, problems with unit digits summing to 9 or less were best estimated with rounding down, whereas those with unit digits summing to 11 or more were best estimated with rounding up. Problems with unit digits summing to 10 were sometimes best rounded up (e.g., 27 x 83) and sometimes best rounded down (e.g., 76 x 54). Thus, there was no one definitive way to determine which strategy should be used on every problem, but the correlation between the sum of the unit digits and the best strategy was very high, $r(142) = .82$.

Procedure

The same experimenter tested each participant individually. The experiment took place in a quiet room and lasted for approximately one hour. The choice/no-choice method was used in order to obtain unbiased measures of strategy efficiency (Siegler & Lemaire, 1997; Luwel, Onghena, Torbeyns, Schillemans, & Verschaffel, 2009). In this method, participants are first tested in a choice condition, in which they can *choose* among the available strategies, and then in 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). Thus, in the present study, all participants solved the computational estimation problems in three conditions: first the choice condition (in order to exclude the influence of no-choice conditions on the choice condition), and then two no-choice conditions, the order of which was randomized across participants. In both choice and no-choice conditions, 7 practice problems and 24 experimental problems were presented. Each condition was further divided in two blocks: one with and one without working memory load. 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. The six problem sets were counterbalanced across choice/no-choice and no-load/load conditions such that each set appeared an equal number of times in each condition.

Estimation task. A trial started with a fixation point for 500 milliseconds. Then the computational estimation problem was presented horizontally in the center of the screen, with the “x” sign at the fixation point. Participants were told that they would see multiplication problems for which they had to give approximate answers without calculating the exact products. They were asked to work out the problem mentally (i.e., without use of pen-and-paper) and to state their answer aloud. 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 voice-activated relay.

In the choice condition, participants were explicitly asked to choose the best strategy for every problem; that is the strategy that yielded the closest estimate of the exact answer. They were instructed to use either the rounding down or the rounding-up strategy and no other strategies[2]. After each trial, they had to report verbally which strategy they had chosen. In the very few cases in which the strategy report did not match the participant's answer, the experimenter interfered so that the participant could correct this. In the no-choice/round-down condition, participants were asked to use the rounding-down strategy on all problems; they had to round both operands down to the closest smaller decades (e.g., 78 x 42 = 70 x 40 = 2800). In the no-choice/round-up condition, participants were asked to use the rounding-up strategy on all problems; they had to round both operands up to the closest larger decades (e.g., 78 x 42 = 80 x 50 = 4000). The rounding-up strategy is more difficult than the rounding-down strategy for two reasons: participants have to hold digits in memory that are not displayed on screen, and they have to calculate products of larger operands. Participants were instructed not to adjust the answer after having executed the strategy and not to use any other strategy (e.g., rounding one operand down and one operand up). In choice and no-choice conditions, the answer of the participant and the validity of the trial were recorded on-line by the experimenter. Answers were coded as incorrect when the respective strategy (rounding down or rounding up) was erroneously executed. 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 computational estimation task. Szmalec, Vandierendonck, and Kemps (2005) have shown that this task interferes with the central executive, whereas the load on the phonological and visual-spatial memory systems is negligible. The CRT task was also performed alone (i.e., without the concurrent solving of computational estimation problems) for 2 minutes.

Results

In total, 5.9% of trials were spoiled due to failures of the voice-activated relay. Because all these invalid trials returned at the end of the block, the loss was reduced to 0.7%. 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. All reported results were significant at $p < .05$, unless otherwise specified.

Secondary Task Performance

A 3 x 4 ANOVA was conducted on accuracies and correct latencies of the CRT task with Group (Belgian vs. Chinese/L1 vs. Chinese/L2) as a between-participants factor and Condition (Single, Choice, No-choice/round-down, No-choice/round-up) as a within-participants factor (see Table 1). The main effect of Condition was significant, $F(3,115) = 305.96$, $MSe = 130$, $\eta_p^2 = 0.72$, for accuracies and $F(3,115) = 180.34$, $MSe = 4670$, $\eta_p^2 = 0.61$ for latencies. Participants were more accurate and faster on the CRT task when it was performed alone (93.5% and 543 ms) then when it was performed in combination with the computational estimation task (49.8% and

692 ms), $F(1,117) = 691.80$, $MSe = 249$, $\eta_p^2 = 0.80$, and $F(1,117) = 526.68$, $MSe = 3772$, $\eta_p^2 = 0.75$, respectively. Performance on the CRT task in no-choice conditions (54.6% and 686 ms) was more accurate and faster than in the choice condition (40.1% and 705 ms), $F(1,117) = 186.12$, $MSe = 91$, $\eta_p^2 = 0.51$, and $F(1,117) = 5.84$, $MSe = 5068$, $\eta_p^2 = 0.03$, respectively. CRT task performance was equally fast in the no-choice/round-down condition (688 ms) as in the no-choice/round-up (683 ms) condition ($F<1$), but more accurate in the no-choice/round-down condition (58.9%) than in the no-choice/round-up condition (50.3%), $F(1,117) = 89.90$, $MSe = 49.6$, $\eta_p^2 = 0.34$. Rounding up is thus more demanding of executive working memory resources than rounding down.

The main effect of Group was not significant for either accuracies or latencies (each $p > .35$), and neither was the Group x Condition interaction for accuracies ($p = .15$). The Group x Condition interaction was significant for latencies though, $F(6,232) = 2.37$, $MSe = 4444$, $\eta_p^2 = 0.01$. The three groups were equally fast on the CRT task in the single-task condition, the choice condition, and the no-choice/round-up condition (each $p > .05$), but the Chinese groups (672 ms and 681 ms) were faster than the Belgian group (712 ms) in the no-choice/round-down condition, $F(1,117) = 4.55$, $MSe = 7461$, $\eta_p^2 = 0.03$ with no difference between the two Chinese groups ($F<1$).

In summary, participants were slower and more erroneous on the secondary task when it had to be solved simultaneously with the primary task than when it was done alone, and especially so when they had to make strategy choices in the primary task. The CRT results also show that Chinese need fewer working memory resources than do Belgians – albeit only when rounding down.

No-Choice Condition: Strategy Efficiency

Latencies on correctly executed strategies and percentage of errors were analyzed in separate 3 (Group: Belgian vs. Chinese/L1 vs. Chinese/L2) x 2 (Strategy: rounding down vs. rounding up) x 2 (Load: no load vs. load) ANOVAs, with repeated measures on the last two factors (see Table 2).

Latencies. Participants executed the rounding-down strategy (1.5 s) faster than the rounding-up strategy (3.1 s), $F(1,117) = 638.51$, $MSe = 455824$, $\eta_p^2 = 0.85$, and responded faster in no-load conditions (2.0 s) than in load conditions (2.6 s), $F(1,117) = 96.3$, $MSe = 418855$, $\eta_p^2 = 0.45$. Strategy and Load also interacted, $F(1,117) = 8.44$, $MSe = 206278$, $\eta_p^2 = 0.07$ because load effects were greater on the rounding-up strategy (0.7 s) than on the rounding-down strategy (0.5 s).

The main effect of Group was significant, $F(2,117) = 13.67$, $MSe = 2257252$, $\eta_p^2 = 0.10$. The Chinese/L1 participants (1.8 s) were faster than the Belgian participants (2.6 s), $F(1,117) = 21.72$, $MSe = 2257253$, $\eta_p^2 = 0.16$. The Chinese/L1 participants were also faster than the Chinese/L2 participants (2.6 s), $F(1,117) = 19.21$, $MSe = 2257253$, $\eta_p^2 = 0.14$. There was no difference between the Belgian group and the Chinese/L2 group ($F<1$).

Group further interacted with Strategy, $F(2,117) = 8.05$, $MSe = 455824$, $\eta_p^2 = 0.06$ (see Figure 1) and with Load, $F(2,117) = 3.19$, $MSe = 418855$, $\eta_p^2 = 0.03$. The effects of Strategy and Load were larger in the Chinese/L2 group than in the Chinese/L1 group, $F(1,117) = 15.86$, $MSe = 455824$, $\eta_p^2 = 0.08$ and $F(1,117) = 6.20$, $MSe = 418854$, $\eta_p^2 = 0.03$ respectively, indicating that responding in a non-preferred language interacted with strategy difficulty and increased the load on working memory. The effect of Strategy was also larger in the Belgian group than in the Chinese/L1 group, $F(1,117) = 5.78$, $MSe = 455824$, $\eta_p^2 = 0.03$. Load effects, in contrast, did not differ between the Belgian group and the Chinese/L1 group ($F<1$). Neither Strategy nor Load effects differed between the Belgian group and the Chinese/L2 group (each $p > .10$). The Group x Strategy x Load interaction did not reach significance, $F(2,117) = 2.71$ ($p = .07$).

In summary, the Chinese were faster than the Belgians when each were responding in their first language. The Chinese participants' efficiency advantage disappeared when they had to answer in their second language. Thus, answering in a non-preferred language slowed down estimation processes and increased the load on working memory.

Error rates. Participants made more errors when rounding up (8.1%) than when rounding down (2.7%), $F(1,117) = 67.14$, $MSe = 53$, $\eta_p^2 = 0.28$ and more errors in load conditions (5.9%) than in no-load conditions (4.9%), $F(1,117) = 4.26$, $MSe = 27$, $\eta_p^2 = 0.02$. Strategy and Load also interacted, $F(1,117) = 10.10$, $MSe = 117$, $\eta_p^2 = 0.05$: load effects were significant on the rounding-up strategy (2.2% more errors), $F(1,117) = 8.78$, but not on the rounding-down strategy (0.2%; $F<1$).

Errors varied with Group, $F(2,117) = 6.86$, $MSe = 90$, $\eta_p^2 = 0.06$: Belgians (7.6%) made significantly more errors than the Chinese/L2 group (3.9%) and the Chinese/L1 group (4.7%), $F(1,117) = 12.29$, $MSe = 90$, $\eta_p^2 = 0.06$ and $F(1,117) = 7.77$, $MSe = 90$, $\eta_p^2 = 0.04$, respectively, whereas the two Chinese groups did not differ ($F<1$). No other interactions reached significance. Thus, although responding in a second language slowed down the Chinese participants, they were able to maintain a higher level of accuracy than the less-skilled Belgians.

In sum, the Chinese participants were more accurate than the Belgians, extending previous results showing cultural differences in exact arithmetic accuracy (Imbo & LeFevre, 2009, 2010) to computational estimation. Both speed and accuracy results are also in agreement with an earlier study on computational estimation (Imbo et al., 2007), in which higher load effects on the rounding-up strategy than on the rounding-down strategy were observed. Indeed, when rounding up, more working memory resources are needed because participants have to hold digits in memory that are not displayed on the screen, and they have to calculate products of larger operands.

Choice Condition: Strategy Adaptivity

Participants were coded as adaptive when they chose the rounding-down strategy on those problems for which the rounding-down strategy provided the closest answer (i.e., RD problems) and the rounding-up strategy on those problems for which the rounding-up strategy provided the closest answer (i.e., RU problems). Percentage of adaptive strategy choices was analyzed in a 3 (Group: Belgian vs. Chinese/L1 vs. Chinese/L2) x 2 (Load: no load vs. load) mixed ANOVA. Participants were adaptive on 67.8% of all trials; that is, they chose the strategy that led to the answer that was closest to the exact answer. They were more adaptive in no-load conditions (70.0%) than in load conditions (65.6%), $F(1,117) = 11.26$, $MSe = 99$, $\eta_p^2 = 0.06$.

The main effect of Group was significant, $F(2,117) = 5.14$, $MSe = 294$, $\eta_p^2 = 0.04$. Belgians (72.5%) made more adaptive strategy choices than both the Chinese/L1 group (63.8%) and the Chinese/L2 group (66.9%), $F(1,117) = 10.01$, $MSe = 294$, $\eta_p^2 = 0.05$ and $F(1,117) = 4.17$, $MSe = 294$, $\eta_p^2 = 0.02$, respectively. There was no difference between the two Chinese groups ($p = .26$). Interestingly, Belgians' adaptive strategy choices did not differ between no-load and load conditions ($F<1$) whereas both the Chinese/L2 group and the Chinese/L1 group made significantly fewer adaptive strategy choices under load conditions than in no-load conditions, $F(1,117) = 5.33$, $MSe = 99$, $\eta_p^2 = 0.03$ and $F(1,117) = 9.68$, $MSe = 99$, $\eta_p^2 = 0.05$, respectively (see Figure 2).

In summary, on this problem-based measure of adaptivity the Chinese made fewer adaptive strategy choices than did the Belgians, and especially so under load conditions. These observations are in agreement with the results of Imbo and LeFevre (2009), in which person-based adaptivity analyses showed fewer adaptive strategy choices in the Chinese group, and suggest that Belgians and Chinese apply different strategy selection procedures. The load effects suggest that the Chinese participants use working memory resources in the strategy selection process whereas the Belgians do not.

Discussion

The goal of the present research was to test whether cultural differences in adaptive strategy selection occurred because strategy selection is (a) more resource demanding for Asians than for non-Asians or (b) more resource demanding for participants answering in a non-preferred language. We found support for the former interpretation. In particular, Belgians answering in their first language on a computational estimation task chose strategies more adaptively than Chinese-educated participants answering in either their first or second language. This effect could not be attributed to differences in arithmetic skill, because the Chinese were clearly more skilled than the Belgians. The role of working memory in strategy selection also differed across cultural groups. Chinese chose less adaptively when their working memory was taxed whereas Belgians' strategy selections were unaffected by working memory load.

A possible explanation for these cultural differences is that Belgians and Chinese differ in their educational experiences. Adults generally prefer to give exact answers rather than to estimate (e.g., LeFevre, Greenham, & Waheed, 1993). Due to different educational approaches, Asians might even have *less* tolerance for approximate solutions than people in other cultures. For example, Reys et al. (1999) found that the majority of Japanese students calculated the exact solution for 304.15 x 18.73, even though they were asked to estimate. The focus of Chinese traditional mathematics teaching on written algorithms and exact calculation may make it difficult for Asian students to consider rounding strategies, even when they are explicitly asked to estimate (Yang, 2005). Further, because educational approaches in Asia focus heavily on practice and training of arithmetic facts according to a single approach (e.g., memorization of multiplication tables; Zhang & Zhou, 2003), they might not focus as heavily on providing instruction on using a variety of strategies (Reys & Yang, 1998; Yang, 2005). Hence, when asked to perform rounding strategies, Asian students probably had to inhibit their tendency to perform exact calculations, which consumed working memory resources. In contrast, educational reform movements in European countries over the last 20 years have emphasized flexibility, adaptive expertise, and the use of meta-strategies as part of children's learning about arithmetic (Blöte, Klein, & Beishuizen, 2000; Verschaffel, Luwel, & Van Dooren, 2009). Thus, Belgian students are likely to be quite familiar with using a variety of strategies and with capitalizing on the most appropriate one.

It is, however, also possible that the Chinese chose adaptive strategies less frequently because they realized that both rounding strategies would yield relatively inaccurate estimates. Testing Belgians and Chinese on genuine approximate arithmetic (e.g., "56 x 71 is about 3900") rather than on exact arithmetic with rounded operands (e.g., "56 x 71 ≈ 50 x 70 = 3500") might address this issue, as would collecting self-reports on strategy selection methods.

Hence, whatever the reason was (i.e., being *unable* to determine the most adaptive strategy, or being *reluctant* to use inaccurate rounding strategies), the Chinese may have used exact answer calculations to guide their selection of the best estimation strategy. For example, they may have (1) calculated the exact answer or a better approximation of the exact answer (e.g., rounding one operand up and one down), (2) then calculated both estimates (i.e., for the rounding-down strategy and for the rounding-up strategy), (3) compared these estimates with the exact or the better answer, and (4) chosen the estimate that was closest to the exact or the better answer. Although it is unlikely that the Chinese participants used this multi-step approach on all trials (which would result in very high strategy adaptivity levels), it is obvious that this approach is very demanding of working memory resources, explaining their smaller frequency of adaptive strategy choices in load conditions. Also note that, even if the Chinese did not use this multi-step approach to strategy selection, they may have consumed working memory resources in order to suppress the tendency to do so. Further research in which participants report how they choose a strategy will be needed to determine whether this explanation for Chinese participants' lowered strategy adaptivity is accurate.

We also tested language effects on number processing. The Chinese/L1 group was faster (but not more accurate) than the Chinese/L2 group, in support of the view that bilinguals are faster in mental arithmetic when answers are produced in the preferred language (see also Campbell & Epp, 2004; McClain & Huang, 1982). Furthermore, load effects were larger in the Chinese/L2 group than in the Chinese/L1 group, indicating that responding in L2 involves executive working memory resources, and more specifically, requires inhibitory processes. Indeed, because L1 is the dominant language, stronger inhibitory processes are applied to L1 when responding in L2 than vice versa (e.g., Costa & Santesteban, 2004; Green, 1998; Meuter & Allport, 1999; Philipp & Koch, 2009; Philipp, Gade, & Koch, 2007). Furthermore, the difference between rounding down and rounding up grew larger when the Chinese had to answer in their second language. This interaction between response language and strategy difficulty can only be explained by models that propose an integrated calculation/estimation and language processing system. Because the Abstract Code model (McCloskey, 1992, McCloskey & Macaruso, 1994, 1995) and the Triple Code model (Dehaene, 1992; Dehaene & Cohen, 1995, 1997) postulate language-independent estimation strategies, they cannot account for our data. In contrast, in the Encoding Complex model (Campbell, 1992; 1994; Campbell & Epp, 2004), there are two different verbal response codes (one for L1 and one for L2), with stronger links from the magnitude code to L1 than to L2. According to this model, the links between the magnitude code and L2 become weaker as problem size increases. Because rounding up is more difficult to execute, participants in the Chinese/L2 group may have performed these calculations more frequently in their first language, and then have translated the results to English. Hence, this translation stage selectively increased the Chinese/L2 group's rounding-up latencies, explaining the interaction between strategy difficulty and response language. This result is also in agreement with an fMRI study (Wang, Lin, Kuhl, & Hirsch, 2007), in which calculation in L2 involved additional neural activation as compared to L1.

Conclusion

Even though the Chinese were faster and more accurate than the Belgians, they did not choose as adaptively between the strategies and they also used working memory resources to a greater degree when they were instructed to choose the best strategy. Thus, in the domain of computational estimation, Chinese rely on executive working memory both to select strategies and to execute them, whereas Belgians only use working memory resources to execute chosen strategies. We further showed that answering in a non-preferred language slows down estimation processes and consumes executive resources, resulting in a loss of strategy efficiency. Whether or not these conclusions hold in other mathematical tasks or in other cognitive domains is a challenge for future research.

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Footnotes

1. Our problem set was based on the problems constructed and previously used by Lemaire and collaborators (e.g., Lemaire & Lecacheur, 2002). We are grateful to these authors for providing us with the computational estimation problem set. Please note that Arabic numbers are the standard format learned and used in numerical tasks in Chinese; just as in Dutch, English, and many other languages.
2. The mixed rounding strategy (i.e., rounding one operand down and one operand up) was not allowed because including this strategy would make it very easy for the participants to be adaptive. Indeed, since this strategy is the 'best' strategy for all problems tested here, we assumed that participants would choose this strategy on (almost) all trials. Such ceiling effects would prevent us from detecting group differences in strategy adaptivity. Preventing participants from using the mixed rounding strategy makes the strategy selection process harder to execute. It forces participants to make a deliberate strategy choice (see also Imbo, Duverne, & Lemaire, 2007; Lemaire, Arnaud, & Lecacheur, 2004; Lemaire & Lecacheur, 2010).

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Table 1

Accuracy and latencies on the CRT task as a function of Group and Condition. Standard errors are shown in parentheses.

	Accuracy (%)			Latency (ms)		
	Belgian	Chinese/L1	Chinese/L2	Belgian	Chinese/L1	Chinese/L2
Single	91.6 (2.0)	94.4 (2.0)	94.4 (2.0)	551 (12)	523 (12)	555 (12)
No-choice/down	59.0 (2.9)	41.3 (2.9)	55.8 (2.9)	712 (14)	681 (15)	672 (14)
No-choice/up	53.2 (2.9)	62.0 (2.9)	45.3 (2.9)	685 (14)	696 (14)	668 (14)
Choice	41.7 (2.9)	52.4 (2.9)	37.1 (2.9)	706 (15)	690 (15)	718 (15)

Table 2

Latencies and error rates on the computational estimation task in no-choice conditions, as a function of Group, Strategy, and Load. Standard errors are shown in parentheses.

		Latencies (s)				Error rates (%)			
	Strategy	No load		Load		No load		Load	
Belgian	Rounding down	1.5	(0.1)	2.1	(0.1)	4.1	(0.7)	3.6	(0.6)
	Rounding up	3.1	(0.2)	3.7	(0.2)	10.2	(1.2)	12.6	(1.5)
Chinese/L1	Rounding down	1.0	(0.1)	1.4	(0.1)	2.9	(0.7)	2.5	(0.6)
	Rounding up	2.2	(0.2)	2.7	(0.2)	5.7	(1.2)	7.6	(1.5)
Chinese/L2	Rounding down	1.4	(0.1)	1.9	(0.1)	1.5	(0.7)	1.6	(0.6)
	Rounding up	3.0	(0.2)	4.0	(0.2)	5.0	(1.2)	7.5	(1.5)

Figure 1

Latencies on the computational estimation task in no-choice conditions, as a function of Group and Strategy. Error bars denote standard errors.

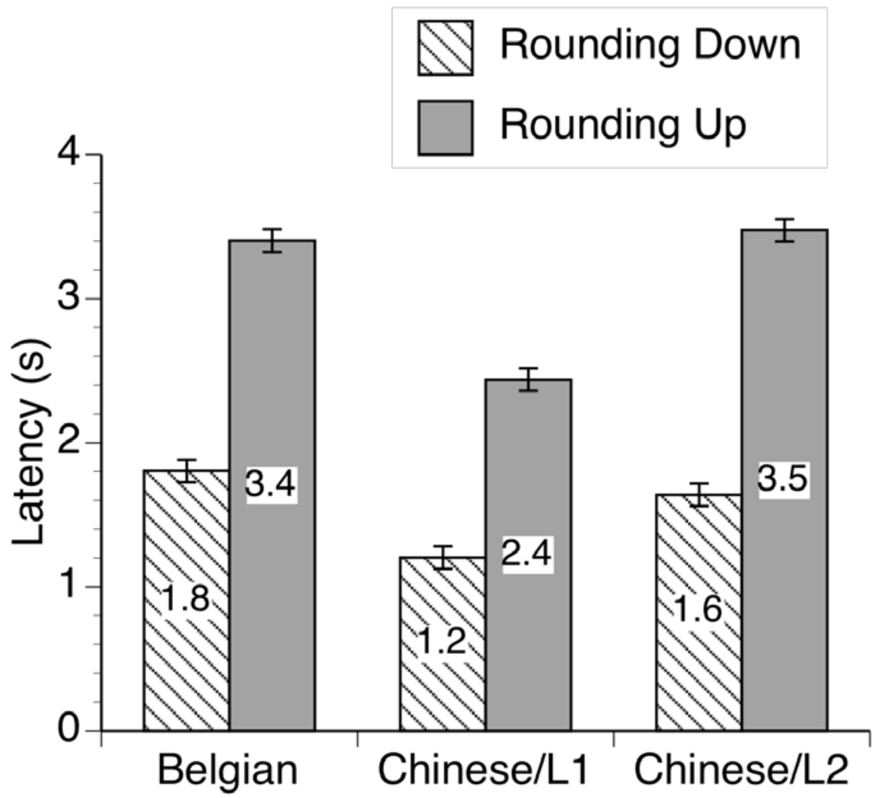

Figure 2

Percentage adaptive strategy choices on the computational estimation task in choice conditions, as a function of Group and Load. Error bars denote standard errors.