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Research Report

Event-related potentials for simple arithmetic in Arabic digits and Chinese number words: a study of the mental representation of arithmetic facts through notation and operation effects

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ABSTRACT

To test whether the retrieval of arithmetic facts is independent of numerical notations, this study investigated the event-related potentials elicited by single-digit addition and multiplication problems in Arabic digits and Chinese number words. The results showed that, in comparison with addition, multiplication elicited a greater N300-like component at the left anterior electrodes and greater late positive potentials at the right posterior electrodes, regardless of numerical notations. The operation effects lasted from 250 to 900 ms for Arabic digits, but from 250 to 1400 ms for Chinese number words when participants were asked to respond only to false arithmetic equations (experiment one), and lasted from 350 to 1400 ms for Arabic digits and Chinese number words when participants were asked to respond to both true and false arithmetic equations (experiment two). The consistency in the operation effects in ERPs (i.e., a dissociation of brain organization for different arithmetic operations) for different number notations suggests that mental representation and retrieval of arithmetic facts may be relatively independent of numerical notations.

1. Introduction

Single-digit arithmetic is fundamental to human number processing. Primary school children are required to learn and memorize the basic arithmetic facts (e.g., 8+7=15, 7×9=63). These facts, however, can be represented with different number notations (e.g., Arabic digits: 1, 2, 3, …; number words: one, two, three, …). Researchers have explored how numerical notations influence simple arithmetic (e.g., Campbell, 1994; McCloskey, 1992; McCloskey et al., 1992; McCloskey and Macaruso, 1995; Noël et al., 1997). One central question is whether the numerical codes or mental representations of arithmetic facts depend on their numerical notation.

Some theoretical accounts posit that numerical notation or the number surface form affects the way the numerical codes are activated (e.g., Campbell, 1994; Szücs and Csépe, 2004). For example, according to the encoding-complex model proposed by Campbell and colleagues (Campbell, 1994, 1998; Campbell

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et al., 1999; Campbell and Epp, 2005), the encoding process of a given task activates a network of associations (including numerical notation), which would then affect the subsequent retrieval or calculation. This perspective has received empirical support from behavioral and brain studies (e.g., Campbell, 1994; Campbell and Metcalfe, 2007; Szücs and Csépe, 2004). For example, Campbell (1994) found that arithmetic problems were more difficult to solve when they were presented in number words than when they were presented in Arabic digits, especially for “large” problems (i.e., problems with large operands). According to Campbell, the interaction between format and problem size was due to the influences of input format on the retrieval of arithmetic facts. To examine the notation effect using the ERP technique, Szücs and Csépe (2004) designed a simple addition verification task, in which the first operand was presented in one of three formats (an Arabic digit, a written number word, or phonological presentation of a number) and the second operand was an Arabic digit. Results showed that depending on the format of the first operand, the second operand (an Arabic digit) elicited different brain potentials. This result suggests that the access to numerical representations varies with the surface format (Szücs and Csépe, 2004).

In contrast with the notation-dependent perspective, another viewpoint assumes that the retrieval of simple arithmetic facts is independent of numerical notations (e.g., Blankenberger and Vorberg, 1997; Dehaene, 1992; Dehaene and Cohen, 1995; McCloskey, 1992; McCloskey and Macaruso, 1995; Noël et al., 1997). For example, according to the abstract code model (McCloskey, 1992; McCloskey and Macaruso, 1995; Sokol et al., 1991), arithmetic input is first encoded into abstract codes by the comprehension system, and then the abstract codes are used for the retrieval of arithmetic facts or complex arithmetic procedures in the calculation system. The abstract results are then sent to the production system and converted into Arabic, written, or spoken verbal number form, depending on the task requirements. According to this model, the numerical surface form exhibits no relation with the numerical codes. Similar to the abstract code model, Dehaene's triple code model (Dehaene, 1992; Dehaene and Cohen, 1995) states that arithmetic input is encoded into one of three specific codes: an analogue magnitude representation, a visual-Arabic number form, and an auditory–verbal code. Each code is used for a different type of numerical processing: The analogue magnitude representation is used for approximate calculation and numerical comparisons, the Arabic form for multi-digit operations and parity judgment, and the auditory–verbal code for simple addition and multiplication.

There is empirical evidence that numerical codes for arithmetic facts are independent of numerical notations (e.g., Noël et al., 1997; Sokol et al., 1991). For example, Noël et al. (1997) firstly asked participants to produce the solutions to multiplication problems presented either in Arabic digits or in English number words and then to perform a number-matching task on the same pair of digits or words. In the number-matching task, two canonical dot patterns and a pair of digits or a pair of number words were presented serially. Participants' task was simply to indicate whether the digits or words represented the same numerosities as those expressed by the dots. The results revealed a similar format-by-size interaction in both the arithmetic fact retrieval and the number-matching tasks. This result suggests that the format-by-size interaction originates in the encoding stage as shown by the number-matching tasks. Also consistent with this perspective, Sokol et al. (1991) found that multiplication errors produced by a patient were not affected by the stimulus format.

Based on the above review of the literature, there is evidence for both notation-dependent and notation-independent perspectives about the relations between numerical codes and their surface form. One reason for these conflicting results is that different studies might have tapped into different types of numerical codes. Arithmetic facts can be represented in the memory as one or more types of numerical codes, such as, abstract codes, analogue magnitude representation, visual-Arabic codes, and auditory–verbal codes (e.g., Campbell, 1994; Dehaene, 1992; Dehaene and Cohen, 1995; Dehaene et al., 1999; McCloskey, 1992; Zhou and Dong, 2003; Zhou et al., 2006, 2007a). It is possible that in previous studies, different types of codes were activated for different numerical notations (e.g., verbal codes for number words, visual-Arabic codes for Arabic digits). Furthermore, previous research did not clarify whether the interactions between numerical format and types of arithmetic operation occur at the encoding (of the operands and operation), retrieval (of arithmetic facts)/calculation, or reporting (the answer) stage of arithmetic problem solving.

The present study relied on some recent findings of differential involvement of verbal vs. visual codes in multiplication vs. addition among Chinese participants to effectively address the issue of notation effects on simple arithmetic. Several recent studies (e.g., Zhou et al., 2006, 2007a,b) have shown that addition and subtraction facts are typically represented in visuospatial memory (e.g., visual Arabic number form), but multiplication facts are typically represented in verbal memory. We have used the ERP technique to investigate the dissociated representations for addition, subtraction, and multiplication facts (Zhou et al., 2006). We found that, compared to addition and subtraction, multiplication elicited a greater N300 component peaking around 320 ms at the left anterior electrodes. These results suggest that multiplication involves more verbal processing than does addition and subtraction (we will return to this in greater depth in Discussion). No differences were found between addition and subtraction. Recently, we used the fMRI technique and found that single-digit addition had more activation in the parietal brain regions, especially in the right hemisphere, but single-digit multiplication had more activation in the language processing areas, including the precentral gyrus, the supplementary motor areas, and the posterior and anterior superior temporal gyrus in the left hemisphere (Zhou et al., 2007a). Evidence from lesion studies is also consistent with that conclusion. For example, patients with lesions in the left perisylvian language region and those with low verbal fluency had more difficulty in single-digit multiplication than in addition and subtraction (e.g., Cohen et al., 2000; Dehaene and Cohen, 1997; Delazer and Benke, 1997; Lemer et al., 2003; Pesenti et al., 1994; van Harskamp et al., 2002, 2005).

The present study aimed to directly test whether numerical notation (Arabic digits vs. Chinese number words) affected the neural correlates of arithmetic operation (addition vs. multiplication). Participants were asked to verify whether given arithmetic equations were true or false. According to the notation-independent hypothesis, arithmetic operation effect (i.e., differences in neural patterns between addition and multiplication) should be the same for both Arabic digits and Chinese number words conditions. According to the notation-dependent hypothesis, the operation effect should vary depending on the notation. The main neural correlate of the arithmetic operation effect to be used in this study is the N300 component at the left anterior electrodes, which was found to be greater for multiplication than for addition, as mentioned above. Two experiments were conducted to control for potential confounds of specific features of the arithmetic problems and response format (see below for details).

2. Results

2.1. *Experiment one*

2.1.1. *Behavioral data*

Reaction times data were collected only for the false arithmetic equations. Responses were recorded as incorrect when participants failed to press a key for false arithmetic equations or when they pressed the key for true arithmetic equations. Reaction times were trimmed by using the three-standard-deviation rule. That is, trials with reaction times that were three standard deviations above or below a participant's mean reaction time were treated as incorrect responses and discarded. Only 0.13% trials were discarded due to the three-standard-deviation rule. The mean reaction times for the correct responses (i.e., pressed the key) and error rates for all trials are displayed in Fig. 1. Two-factor repeated measures ANOVA with arithmetic operation and number notation as the within-subject factors showed a significant interaction effect for reaction times, $F(1, 22)=25.69$, $MSe=11656.23$, $p<0.001$. Further simple effects tests showed that participants took the same amount of time to respond to addition and multiplication problems presented in Arabic digits, but took longer to respond to addition problems than multiplication problems when they were presented in Chinese number words, $F(1, 22)=30.38$, $MSe=15520.25$, $p<0.001$. ANOVA on the error rates found that the participants made more errors when responding to the problems presented in Chinese number words than in Arabic digits, $F(1, 22)=39.00$, $MSe=1.37$, $p<0.001$.

2.1.2. *Event-related potentials*

The grand mean waveforms by arithmetic operation (addition and multiplication) and numerical notation (Arabic digit and number word) are displayed in Fig. 2. A P1/N1 component peaked about 100 ms at the bilateral posterior/anterior electrodes, and an N1/P1 component peaked about 150 ms at the bilateral posterior/anterior electrodes. A slow potential waveform from 300 ms to 2000 ms occurred at all electrodes. To examine whether and how numerical notations may affect arithmetic operation, we focused on the interaction between operation and numerical notation. A series of ANOVAs with operation, notation, and electrode position as within-subject factors were conducted on the mean amplitudes for several time windows, selected on the basis of the grand mean waveforms.

In the time window 250–300 ms, the interaction effect of operation and electrode position on mean amplitude was significant, $F(8,176)=2.34$, $MSe=2.75$, .$p<0.05$. No three-way interaction effect was found. Further tests of the two-way interaction effect found that multiplication elicited greater negative potentials than did addition at the left anterior electrodes, $F(1,22)=7.02$, $MSe=2.27$, $p<0.05$. This result means that there were greater negative potentials for multiplication than for addition for both Arabic digits and Chinese number words. Multiplication also had larger positive potentials than addition at the right central electrodes, $F(1,22)=8.72$, $MSe=2.23$, $p<0.01$. In the subsequent time window 300–350 ms, the interaction between operation and electrode position was significant, $F(8,176)=5.98$, $MSe=2.67$, $p<0.001$. Simple effects tests also demonstrated the same pattern of results as found for the 250–300 ms window (see above), that is, multiplication had larger negative potentials than addition at the left anterior electrodes, $F(1,22)=19.35$, $MSe=2.78$, $p<0.001$, and at the medial anterior electrodes $F(1,22)=11.81$, $MSe=1.09$, $p<0.005$. Multiplication had greater positive potentials than did addition at the right central electrodes, $F(1,22)=22.30$, $MSe=1.78$, $p<0.001$, and at the right posterior electrodes, $F(1,22)=6.90$, $MSe=2.36$, $p<0.05$. The same results were again found in the subsequent intervals 350–400 ms, 400–450 ms, and 450–500 ms. For a long interval from 500 to 900 ms, the interaction effect between operation and electrode position was significant, $F(8,176)=11.3$, $MSe=11.28$, $p<0.001$. Further tests showed that, compared to addition, multiplication had greater negative potentials at the left anterior electrodes, $F(1,22)=32.89$, $MSe=5.15$, $p<0.001$; and greater positive potentials at the left central electrodes, $F(1,22)=17.52$, $MSe=2.35$, $p<0.001$; and at the right posterior electrodes, $F(1,22)=11.13$, $MSe=1.22$, $p<0.005$.

From 900 to 1400 ms, there was a three-way interaction effect among operation, notation, and electrode position, $F(8, 176)=3.73$, $MSe=1.69$, $p<0.001$. Simple effects tests showed that multiplication had greater negative potentials than addition for the Chinese number words condition at the left anterior electrodes, $F(1,22)=30.48$, $MSe=5.01$, $p<0.001$, and at the medial anterior electrodes, $F(1,22)=29.02$, $MSe=0.64$, $p<0.001$. No such operation effect was found for Arabic digits at the same electrodes during this interval. For both Arabic digits and Chinese number words conditions, multiplication had greater positive potentials at the right posterior electrodes than did addition, $F(1,22)=6.19$, $MSe=0.67$, $p<0.05$, for Arabic digits; $F(1,22)=32.18$, $MSe=0.79$, $p<0.001$, for Chinese number words. Additionally, for the Chinese number words condition, the operation effect was also significant at the right central electrodes, $F(1,22)=16.15$, $MSe=1.76$, $p<0.005$. The topographies of difference waveforms for the operation effect (multiplication–addition) in serial time windows (i.e., 0–250, 250–500, 500–900, 900–1400 and 1400–2000 ms) are shown in Fig. 3.

In experiment one, we compared ERPs of doing addition and multiplication in Arabic digits and Chinese number words. Results showed significant differences between the two types of arithmetic operations, with multiplication eliciting a greater N300-like component at the left anterior electrodes and greater late positive potentials at the right posterior electrodes than addition. The operation effect was similar for both types of number notations. In this experiment, however, we used larger-operand-first addition problems and smaller-operand-first multiplication problems. As mentioned earlier, we used smaller-operand-first multiplication problems because Chinese subjects typically use an additional step to convert larger-operand-first multiplication problems into smaller-operand-first problems (LeFevre and Liu, 1997). We used larger-operand-first addition problems to avoid potential confusion between the two types of arithmetic problems. It is plausible, however, this systematic difference in the order of operands may contribute to the effects of arithmetic operation found in experiment one. In addition, we asked the subjects only to respond to false equations in experiment one. It is not clear whether this particular response format may also confound our results. experiment two was conducted to replicate the above results using a different response format and different addition problems.

2.2. Experimental two

2.2.1. Behavioral data

Reaction times were trimmed by using the three-standard-deviation rule. Only 1.1% trials were discarded due to the three-standard-deviation rule. Only trials with correct responses from the true arithmetic equations were analyzed, which was also the case for ERP data analysis in the next section. The mean reaction times and error rates are displayed in Fig. 4. The error rate for the false problems was 18.2%. Two-factor repeated measures ANOVA with arithmetic operation and number notation as the within-subject factors showed a significant interaction effect for reaction times, $F(1, 15) = 10.41$, $MSe = 1031.17$, $p < 0.01$. Further simple effects tests showed that participants took the same amount of time to respond to addition and multiplication problems presented in Arabic digits, but took longer to respond to addition problems than multiplication problems when they were presented in Chinese number words, $F(1, 15) = 21.88$, $MSe = 1702.83$, $p < 0.001$. This pattern of the interaction was the same as that found in experiment one. ANOVA on the error rates did not show any significant effects.

2.2.2. Event-related potentials

Event-related potentials for the true arithmetic equations with correct responses were analyzed. The grand mean waveforms by operation (addition and multiplication) and numerical notation (Arabic digit and number word) are displayed in Fig. 5. A P1/N1 component peaked about 100 ms at the bilateral posterior/anterior electrodes, and an N1/P1 component peaked about 150 ms at the bilateral posterior/anterior electrodes. A slow potential waveform from 300 ms to 2000 ms occurred at all electrodes.

As in experiment one, a series of ANOVAs with operation, notation, and electrode position as within-subject factors were conducted on the mean amplitudes for several time windows. There were neither operation effects nor operation-related interaction effects in the time windows 250–300 ms and 300–350 ms. In the time window 350–400 ms, the interaction effect between operation and electrode position was significant, $F(8,120) = 2.45$, $MSe = 2.11$, $p < 0.05$. No three-way interaction effects were found. Further tests on the two-way interaction effect found that multiplication elicited marginally greater negative potentials than did addition at the left anterior electrodes, $F(1,15) = 3.11$, $MSe = 3.43$, $0.05 < p < 0.10$. Multiplication also had larger positive potentials than addition at the right central electrodes, $F(1,15) = 9.42$, $MSe = 1.02$, $p < 0.01$. In the subsequent time window 400–450 ms, the interaction between operation and electrode position was significant, $F(8,120) = 4.53$, $MSe = 2.16$, $p < 0.001$. Simple effects tests also demonstrated that multiplication had larger negative potentials than addition at the left anterior electrodes, $F(1,15) = 9.13$, $MSe = 3.21$, $p < 0.01$, and at the left central electrodes $F(1,15) = 7.37$, $MSe = 1.59$, $p < 0.05$. Multiplication had greater positive potentials than did addition at the right central electrodes, $F(1,15) = 18.25$, $MSe = 1.01$, $p < 0.001$. The same results were again found in the subsequent interval 450–500 ms. For a long interval from 500 to 900 ms, the interaction effect between operation and electrode position was significant, $F(8,120) = 10.88$, $MSe = 2.02$, $p < 0.001$. Further tests showed that, compared to addition, multiplication had greater negative potentials at the left anterior electrodes, $F(1,15) = 18.42$, $MSe = 4.51$, $p < 0.001$, and at left central electrodes, $F(1,15) = 35.10$, $MSe = 1.40$, $p < 0.001$; and had greater positive potentials at the right central electrodes, $F(1,15) = 12.45$, $MSe = 1.52$, $p < 0.005$.

From 900 to 1400 ms, there still was a two-way interaction effect of operation and electrode position, $F(8, 120) = 8.38$, $MSe = 1.69$, $p < 0.001$. Simple effects tests showed that multiplication had greater negative potentials than addition at the left anterior electrodes, $F(1,15) = 15.28$, $MSe = 4.09$, $p < 0.001$, at the medial anterior electrodes, $F(1,15) = 11.79$, $MSe = 1.74$, $p < 0.005$, and at the left central electrodes, $F(1,15) = 24.06$, $MSe = 1.63$, $p < 0.001$. Multiplication had greater positive potentials than addition at the right central electrodes, $F(1,15) = 9.80$, $MSe = 0.89$, $p < 0.01$.

The topographies of difference waveforms for the operation effect (multiplication–addition) in serial time windows (i.e., 0–350, 350–500, 500–900, 900–1400 and 1400–2000 ms) are shown in Fig. 6.

The current experiment replicated the main finding from experiment one, that is, multiplication relative to addition had greater negativities at the left anterior electrodes. However, the operation effects first occurred in the time window 350–400 ms rather than 250–300 ms as found in experiment One. This delay might be associated with the greater cognitive load resulted from the bimanual responses in experiment two as compared to the single-hand responses to false equations only in experiment one.

3. General discussion

To test whether numerical notation affects the retrieval of numerical codes for arithmetic facts, the present study compared the event-related potentials elicited by single-digit addition and multiplication presented either in Arabic digits or Chinese number words. We found that, compared to addition, multiplication elicited a greater N300-like

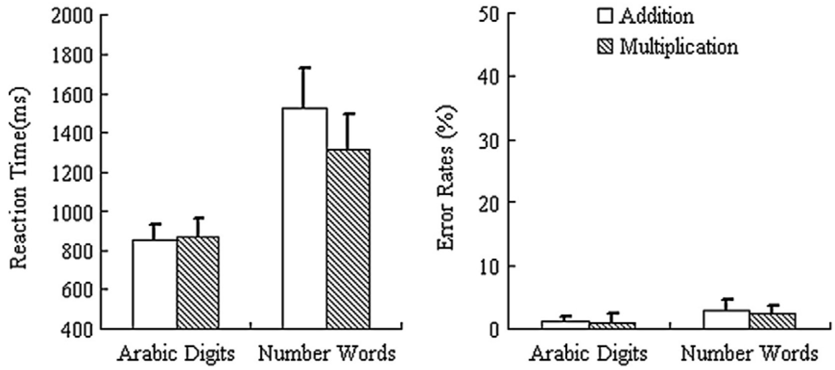

Fig. 1 – Reaction time (ms) and error rates (%) for single-digit addition and multiplication presented with Arabic digits and complex Chinese number words (the lines above the bars represent the standard error) (experiment one).

component at the left anterior electrodes and greater late positive potentials at the right posterior/central electrodes, regardless of numerical notations. The operation effects lasted from 250 to 900 ms for Arabic digits, but from 250 to 1400 ms for Chinese number words when participants responded only to false arithmetic equations (experiment one), and lasted from 350 to 1400 ms for Arabic digits and Chinese number words when participants responded to both true and false arithmetic equations (experiment two). Taken together, the neural dissociation between addition and multiplication was similar for Arabic digits and Chinese number words, suggesting that the retrieval of numerical codes for arithmetic facts is relatively independent of numerical notations.

3.1. *The operation effects*

The operation effects were observed in two aspects of the ERP. First, relative to addition, multiplication had greater negative potentials or a larger N300-like component at the left anterior electrodes. This operation effect replicated the results of our previous study (Zhou et al., 2006). In that study, participants were asked to firstly think of a solution to a given arithmetic problem (e.g., 2+3) and then to judge if the solution matched the presented answer (e.g., 5). Results showed a greater N300 component at the left anterior electrodes for multiplication than for addition and subtraction. The operation effect in both the present and the previous studies had the same onset of about 300 ms, although the effect lasted for various durations (more than 600 ms in the current study and 100 ms in the previous study), perhaps due to differential task demands (simultaneous presentation in the present study and serial presentation in the previous study).

Results of the current study should be interpreted together with the findings from a recent fMRI study of ours on the brain organization for simple arithmetic (Zhou et al., 2007a). In that study, we found that, compared to addition, single-digit multiplication elicited more activation in the language processing areas, including the precentral gyrus, the supplementary motor areas, and the posterior and anterior superior temporal gyrus at the left hemisphere. The current ERP study used the same paradigm(verification of single-digit arithmetic equations) as in the fMRI study. The samples in both experiments were undergraduate students. The greater N300 component at the left anterior electrodes for multiplication than for addition in the current study might originate from the language-processing regions, reflecting more verbal processing for multiplication. As discussed in Introduction, this notion that multiplication facts are represented as phonological codes is consistent with previous neuropsychological findings (e.g., Delazer and Benke, 1997; Lemer et al., 2003; van Harskamp et al., 2002) and an fMRI study (Richard et al., 2000).

Previous studies on language processing have found left anterior negative potentials during verbal or phonological processing, such as phonological judgment (Rugg, 1984a,b), synonym generation (Altenmüller et al., 1993; Thomas et al., 1997), word or sentence decision with a homophonic target (Niznikiewicz and Squires, 1996), and verb generation (Rowan et al., 2004). The lateralized negative potentials are typically in the fronto-central regions and greater over the left than the right hemisphere. Researchers, however, have given them different terms depending on the researchers and the experimental task. For example, Niznikiewicz and Squires (1996) termed such negative potentials as the N200 component peaking at around 293 ms in their word or sentence decision tasks, and Rowan et al. (2004) described them as slow cortical potentials in the time window 1250–3000 ms in their verb generalization task. We believe the N300-like component in the current study corresponded to the lateralized negative potentials in phonological processing in language tasks because of the similarity in their topographies and of the involvement of phonological processing in all of these tasks.

Relative to multiplication, addition had more negative potentials at the right posterior/central electrodes. In our recent fMRI study, addition elicited more activation than did multiplication in the intraparietal sulcus and middle occipital gyri at the right hemisphere, and the superior occipital gyri in both hemispheres (Zhou et al., 2007a). The more rightward lateralization of the negative potentials might have originated from these brain regions. These regions are involved in visual perception, visual mental imagery, visuospatial working memory, and spatial attention (e.g. Corbetta et al., 1998, 2000; Diwadkar et al., 2000; LaBar et al., 1999; Linden et al.,

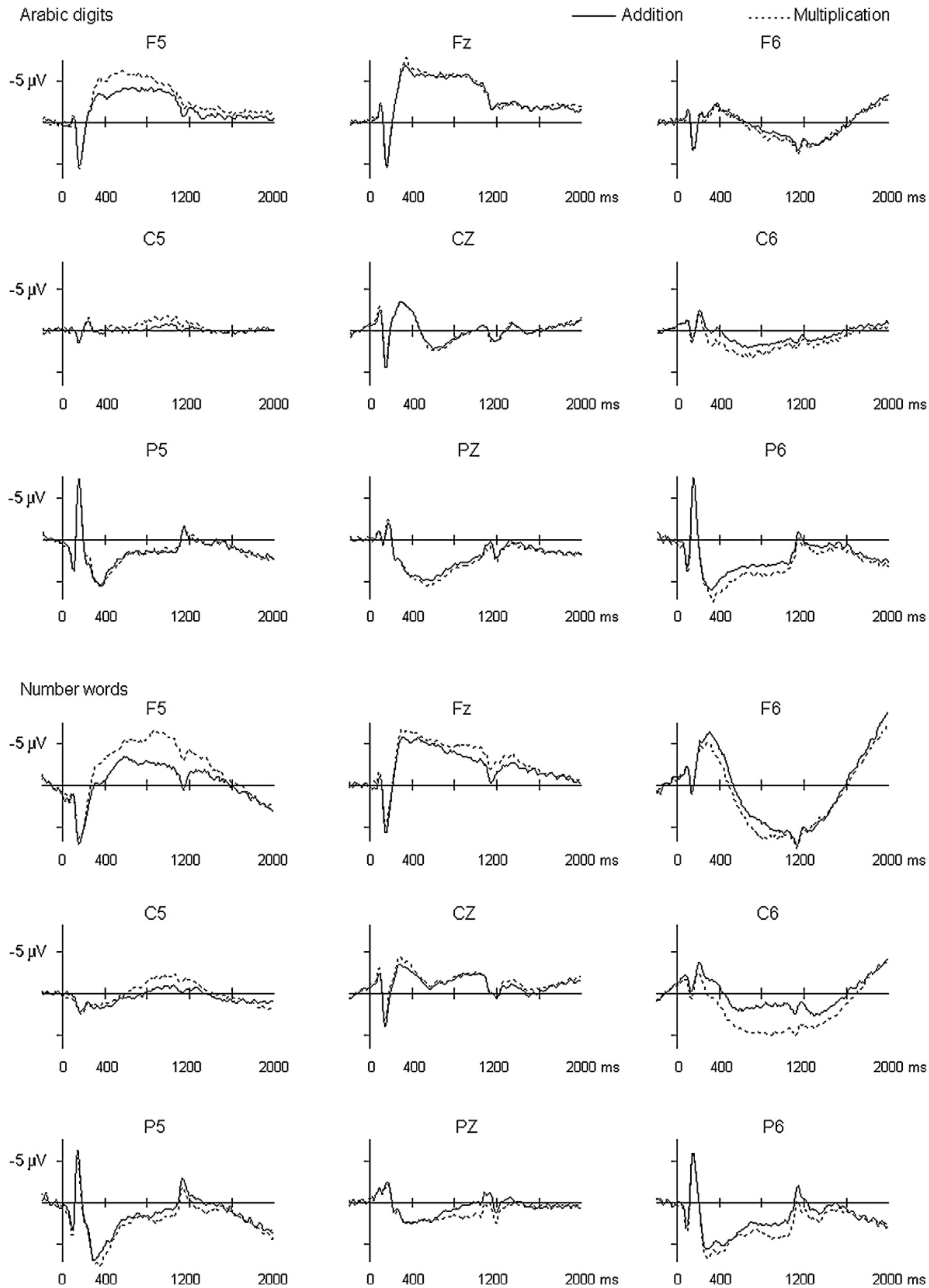

Fig. 2 – Event-related potentials for single-digit addition and multiplication at the left and right anterior, posterior scalps (experiment one). The top panel is for the Arabic digits condition, and the bottom panel is for the Chinese number words condition.

2003; Nystrom et al., 2000; Postle et al., 2004; Thomas et al., 1999; Zurowski et al., 2002). The more negative potentials at the right posterior/central electrodes for addition than for multiplication suggest that addition might involve more visuospatial processing to support the manipulation of numerical magnitude (Dehaene et al., 1999).

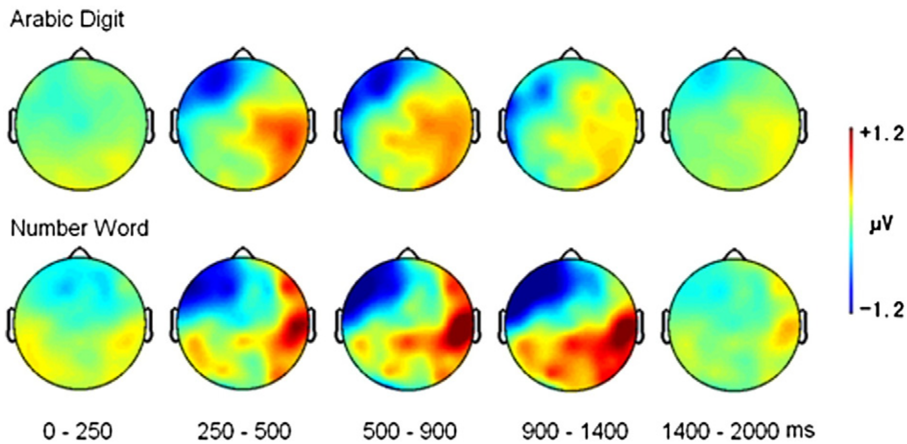

Fig. 3 – Topographies for the operation effects (multiplication–addition) in the Arabic digits and Chinese number words conditions (experiment one).

3.2. *The interaction between operation and numerical notation*

In our previous behavioral research (Zhou and Dong, 2003), we observed an interaction between operation and numerical notation. In that study, operands of single-digit arithmetic problems were serially represented either in Arabic digits or in Chinese number words. Results showed that participants took longer and gave more incorrect answers in multiplication than in addition under the Arabic digits condition, but the pattern was reversed under the number words condition. In the present study, behavioral data also showed a similar interaction between operation and numerical notation. That is, there was no difference in difficulty between addition and multiplication under the Arabic digits condition, but addition was more difficult than multiplication under the number words condition. Although the reaction time data were collected from only a small number of trials (i.e., 40 false equations of all 320 equations for each participant) in experiment one and from all valid trials in experiment two, results from both experiments replicated the interaction between arithmetic operation and number notation. These results showed that, when Chinese financial number words were compared with Arabic numbers, the interaction between arithmetic operation and number notation was consistently found.

A similar interaction between operation and number notation had been reported by Blankenberger and Vorberg (1997). In their study, addition and multiplication problems were displayed with Arabic digits and German number words. To our knowledge, no study has shown an interaction between operation and number notation when English number words are used (e.g., Campbell, 1994). When one operand was held in memory, Blankenberger and Vorberg (1997) also did not find the interaction. When the simple Chinese number words (e.g., 二 *two*, 三 *three*, 四 *four*, 五 *five*, 六 *six*, 七 *seven*, 八 *eight*, 九 *nine*) were used, there also were no interactions between notation and operation (Campbell, et al., 1999). These results suggest that the operation-by-notation interaction effect may depend on the familiarity of the number notation and the presentation mode.

There has been a long-standing debate about the locus of the interaction between arithmetic processing and numerical notation (e.g., Blankenberger and Vorberg, 1997; Campbell, 1998; Campbell and Epp, 2005; Campbell and Fugelsang, 2001; Noël et al., 1997). It could occur in any of the three processing stages presumably involved in simple arithmetic: encoding operands and operation, retrieving or calculating the answer, and reporting the answer. Some researchers believe that it originates at the encoding or reporting stage (e.g., Dehaene, 1992; McCloskey et al., 1992), whereas others attribute it to the retrieval or calculation stage (e.g., Campbell and Epp, 2005). The present ERP study seemed to show that the retrieval of arithmetic facts is independent of notations, supporting the idea that the interaction found in behavioral performance could be related to the encoding or reporting stage. Meanwhile, we found that the operation effects for both types of number notations occurred in the time window 250–500 ms or 350–500 ms in the two experiments, suggesting that the interaction between operation and number notation in behavioral performance might be related to the encoding stage. To retrieve the specific codes for addition or multiplication facts, participants had to encode operation-specific number notations. That is, they typically generated visuospatial or magnitude codes during the encoding of the addition problems, and typically generated verbal codes during the encoding of the multiplication problems (because multiplication tables are typically recited verbally).

3.3. *Conclusions*

This study compared the event-related potentials elicited by single-digit addition and multiplication problems. Multiplication elicited a greater N300 component at the left anterior electrodes and greater late positive potentials at the right posterior/central electrodes than did addition, and this was true for both the Arabic digits and Chinese number words conditions. In other words, the dissociation of brain organization for simple arithmetic (between addition and multiplication) in the Arabic digits condition is replicated for simple arithmetic in the Chinese number words condition, suggesting that the retrieval of numerical codes for arithmetic facts is relatively independent of numerical notations.

4. Experimental procedures

4.1. Experiment one

4.1.1. Participants

Twenty-four undergraduate students (12 males and 12 females) were recruited from Beijing Normal University for this experiment. They were native Chinese speakers and obtained their elementary and secondary education in Mainland China. The average age of the participants was 20.9 years, ranging from 18.6 to 23.4 years. All participants were right-handed and self-reported to have normal or corrected-to-normal eyesight. They had not participated in any experiments similar to the present one (i.e., involving simple arithmetic tasks of addition and multiplication) during the past half a year. Participants gave written informed consent before the experiment. After the experiment, each participant was paid RMB 50.

4.1.2. Materials

Twenty eight one-digit addition from 2+3 to 8+9 and 28 one-digit multiplication problems from 2×3 to 8×9, with an exception of "tie" problems for both operations, were used. Problems with 0 and 1 as an operand (e.g., 1+5, 0+5, 1×5, 0×5) were also not used in this study because they are rule-based problems (e.g., LeFevre et al., 1996).

Previous studies on Chinese multiplication (typically Mainland Chinese) found that smaller-operand-first multiplication was easier than the larger-operand-first multiplication (LeFevre and Liu, 1997; Zhou et al., 2007b; Zhou and Dong, 2003). Chinese participants typically had to reorganize the larger-operand-first multiplications into smaller-operand-first ones in order to solve them (LeFevre and Liu, 1997). To avoid the additional step, we used only smaller-operand-first multiplication problems. Because different operations (e.g., addition, multiplication) with the same digits could interfere with each other within the same experiment (e.g., Winkelman and Schmidt, 1974), we used only larger-digit-first addition problems to reduce the possible interferences between addition and multiplication.

From the 28 addition facts and 28 multiplication facts, four were randomly selected from each group to form false arithmetic equations. This yielded a total of 32 addition and 32 multiplication problems. For the false arithmetic equations, the false answers were generated by adding 1 to or subtracting 1 from one of the two operands and then adding or multiplying the two operands for addition and multiplication, respectively. Meanwhile, they had to have the same number of digits (either one or two digits) as the true answers of the same arithmetic problems would have (e.g., 2×5=12). With these constraints, the false answers closely resemble the true answers.

To allow for enough trials for the ERP recording, we had to present each problem five times, totaling 320 trials or problems (280 with correct answers and 40 with false answers). The operands of these problems were presented either in Arabic digits or Chinese number words. The complex financial Chinese number words were used. The nine digits (from 1 to 9) and their pronunciation in Mandarin are 壹 *yi*, 贰 *er*, 叁 *san*, 肆 *si*, 伍 *wu*, 陆 *liu*, 柒 *qi*, 捌 *ba*, 玖 *jiu*. These words are not typically used in mathematics classes. As mentioned earlier, previous behavioral studies (Zhou and Dong, 2003; Zhou et al., 2004) had shown a significant interaction between operation and number notation when the complex Chinese number words were used. In the current study, we used the ERP technique to determine whether such an interaction occurred early during the encoding and retrieval stage. Because we focused on the early encoding and retrieval stage and because we wanted to reduce the amount of time it takes to read the unusually long solutions when the complex Chinese number words are used, we presented the answers to these problems in Arabic digits.

4.1.3. Procedure

Participants were asked to determine whether an arithmetic equation was true or false. They only needed to respond when the equation was false. Half of the participants responded with their left hand, the other half with their right hand. Participants were encouraged to respond as accurately and fast as possible. No responses were required for true equations to simplify the mental processes during the arithmetic-equation verification.

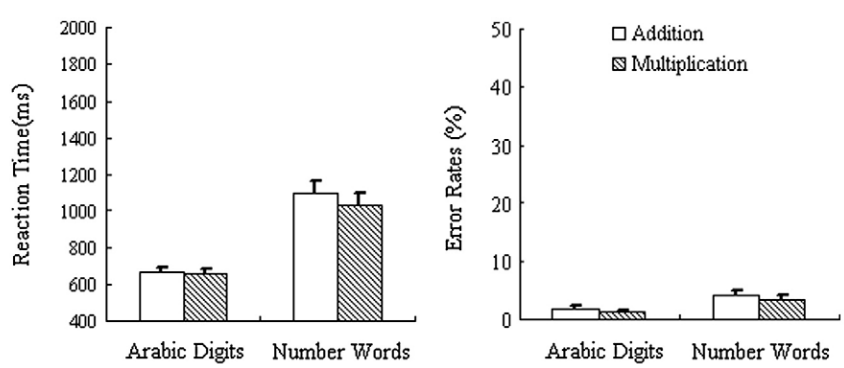

Fig. 4 – Reaction time (ms) and error rates (%) for single-digit addition and multiplication equations presented with Arabic digits and complex Chinese number words (the lines above the bars represent the standard error) (experiment two).

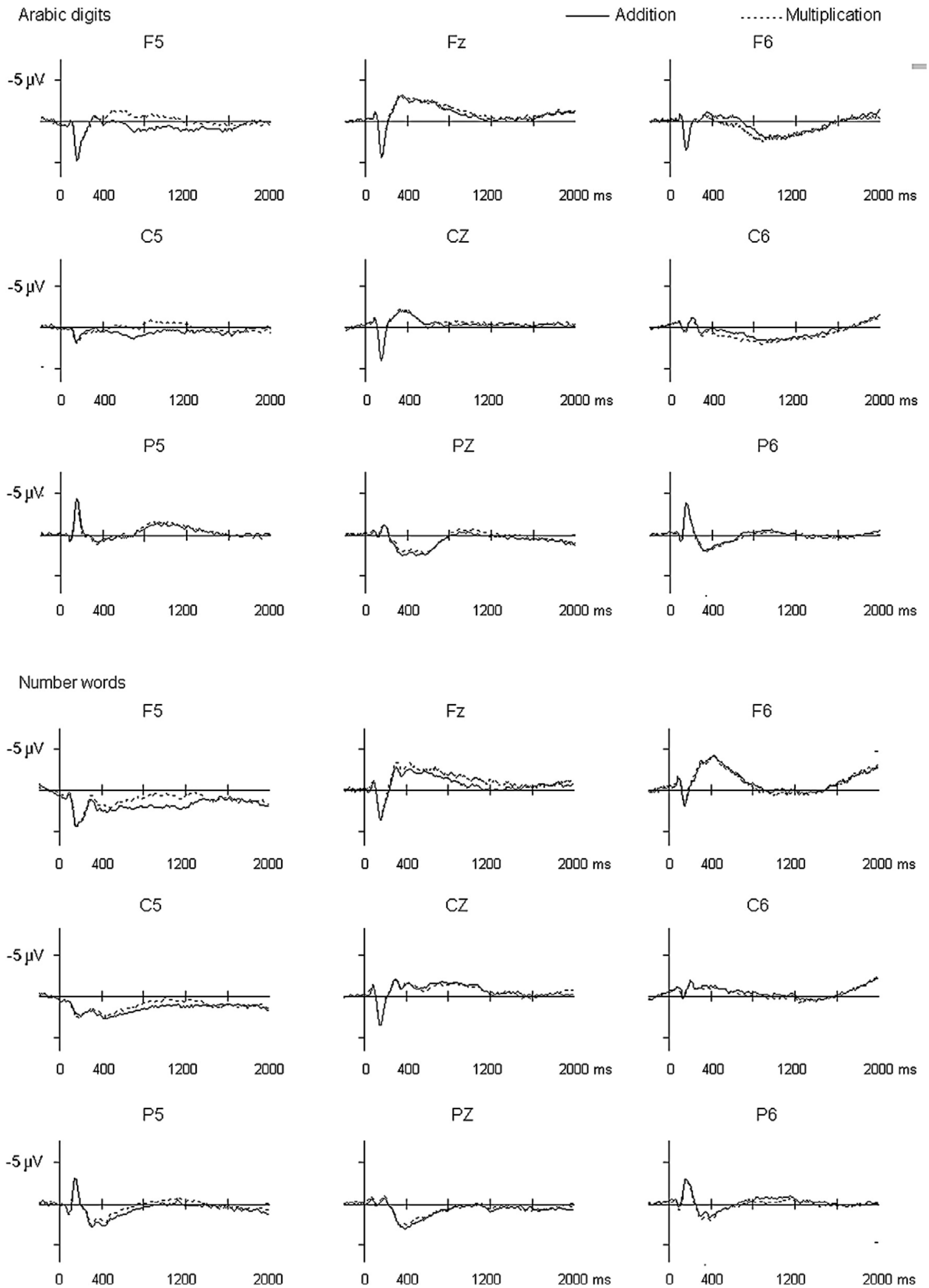

Fig. 5 – Event-related potentials for single-digit addition and multiplication at the left and right anterior, posterior scalps (experiment two). The top panel is for the Arabic digits condition, and the bottom panel is for the Chinese number words condition.

Participants were seated 105 cm away from the computer screen in a dimly lit, sound-attenuated room. All stimuli were presented visually in white against black background at the center of the screen. For each trial, an equation was first presented for 1000 ms, followed by a blank screen for 1500 ms. Each digit for the operands and

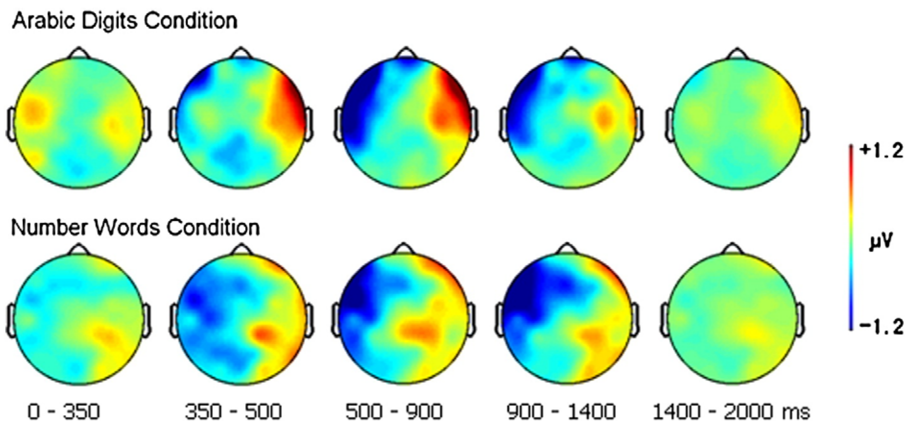

Fig. 6 – Topographies for the operation effects (multiplication–addition) in the Arabic digits and Chinese number words conditions (experiment two).

solution was about 1×1.5 cm in size. The vertical visual angle was 0.82 degrees, and the horizontal visual angle was 3.55 degrees when the solution was a one-digit number or 4.15 degrees when the solution was a two-digit number. During the presentation of the two operands and the blank screen, participants would perform addition and multiplication and make a judgment by pressing a key if they judged the equation to be false. If they judged the equation to be true, they just wait for the next trial.

We used a verification task rather than a production task in the ERP experiment for several reasons. First, in verbal-production tasks, the tongue movement and muscle activities are likely to add artifacts to the EEG recording. For this reason alone, many other similar studies have used the delayed verification task (e.g., Galfano et al., 2004; Niedeggen and Rosler, 1999; Szücs and Csépe, 2004). Second, multiplication problems generally involve larger numbers as their answers (ranging from 6 to 72) than do addition problems (5 to 17). Consequently, verbal production might result in more verbal processing for multiplication than for addition. The verification paradigm helps to minimize the confounding effect of verbal production. It should also be pointed out that the present study used the standard verification task rather than the delayed verification task as used in some previous ERP studies. In the delayed verification task, the operands and answers are sequentially presented and participants have some time to think about the answer. However, in the standard arithmetic-equation verification task, operands and answers are simultaneously presented, which may lead to plausibility judgment (e.g., Campbell and Tarling, 1996; Lemaire and Fayol, 1995). To reduce plausibility judgment, we selected false equations with solutions very close to the true solutions.

Previous research has shown strong evidence of interference among arithmetic operations when participants had to switch between them (e.g., Campbell and Oliphant, 1992). To reduce such interference, problems were presented in separate blocks. Each type of operations had two blocks (about 4 min each). Problems were randomly presented within a block, with the constraint that consecutive problems did not have a common operand or the same solution. At the beginning of each block, the arithmetic operation to be performed was cued on the screen. Participants had a 1-min rest between blocks.

Before the formal test, there were practice trials with problems with 0 and 1 as one of the operands (e.g., 0×2, 1×2). During the practice stage, participants were instructed to avoid eye-blinks. Participants were given feedback if they made two many eye blinks and response errors, took too long to respond, or had obvious head movement.

4.1.4. *Electroencephalography (EEG) recording and analysis*

Scalp voltages were recorded by a NeuroSCAN system, using a 64-channel Quick-cap with silver chloride electrodes (Neurosoft, Inc. Sterling, USA). All electrodes in the cap are placed according to the international 10-20 electrode placement standards. The unlinked ears were used as reference during recording. The middle of the forehead served as ground. Two channels were placed at the outer canthi of both eyes to record the horizontal electrooculogram (HEOG), and another two channels above and below the left eye for vertical electrooculogram (VEOG). The sampling rate was 1000 Hz. The impedance of all electrodes was kept below 5 kΩ.

Offline, trials were rejected for movement artifacts or amplifier saturation. A DC correction was applied, and ocular artifacts were then corrected with NeuroScan EDIT (Version 4.3). The trigger threshold for ocular artifacts was set to 10%. The minimum number of sweeps that were required to construct an averaged VEOG artifact was 20. The duration of the average artifacts was 400 ms. After the correction of ocular artifacts, the continuous EEG data were segmented into epochs from 200 ms prestimulus (i.e., 200 ms before the onset of arithmetic equations) until 2000 ms post stimulus-onset. The 200 ms prestimulus served as the baseline. EEG was detrended and baseline-corrected. Epochs exceeding the range of −100–100 μV at any channel except HEOG and VEOG were rejected as artifacts. The remaining trials were averaged for each operation and notation separately for each participant. One participant's data were not further analyzed because there were less than 50% valid trials in all conditions. The percentages of valid trials used for averaging were 87.9% (±13.7%, standard deviation) for addition and 85.7% (±20.1%) for multiplication in the Arabic digits condition, and 88.1% (±19.4%) for addition and 86.6%(±19.6%) for multiplication in the Chinese number words condition. The averaged waveform was filtered with a low pass of 30 Hz (zero-phase, 12 dB/octave). The grand average was obtained by averaging across the participants' averages separately for each arithmetic operation by each number notation. We re-referenced the grand average waveforms with the average reference.

The event-related potentials to be analyzed were time-locked to the onset of arithmetic equations. According to the grand mean waveforms in four conditions (addition in Arabic digits, addition in Chinese number words, multiplication in Arabic digits, and multiplication in Chinese number words), the electrodes were selected and combined into nine types: left anterior electrodes (F7, F5, F3), medial anterior electrodes (F1, FZ, F2), right anterior electrodes (F4, F6, F8), left central electrodes (T7, C5, C3), medial central electrodes (C1, CZ, C2), right central electrodes (C4, C6 and T8), left posterior electrodes (P7, P5, P3), medial posterior electrodes (P1, PZ, P2), and right posterior electrodes (P4, P6, P8). We conducted ANOVAs on the mean amplitude for several time windows, selected on the basis of the grand mean waveforms. Within-subject factors included arithmetic operation, number notation, and electrode position. Scalp topographies of difference potentials between addition and multiplication (multiplication–addition) were visualized with EEGLAB (http://sccn.ucsd.edu/eeglab/).

4.2. *Experiment two*

The goal of this experiment was to replicate the main findings from experiment one after controlling for two potential confounds. In this experiment, we used smaller-operand-first problems for both addition and multiplication and participants needed to respond bimanually to both true and false arithmetic equations.

4.2.1. *Participants*

Sixteen undergraduate students (8 males and 8 females) were recruited from Beijing Normal University for this experiment. The average age of the participants was 21.2 years, ranging from 19.3 to 25.2 years. Like those in experiment one, these participants were right-handed, had normal or corrected-to-normal eyesight, and had no recent experience with similar studies. They also gave informed consent and were paid RMB 50.

4.2.2. *Materials*

Thirty six one-digit addition from 2+2 to 9+9 and 36 one-digit multiplication problems from 2×2 to 9×9 were used. Problems with 0 or 1 as an operand were excluded just as in experiment one, but "tie" problems were included in this experiment because they helped reduce the repetition of the same problems and were not as problematic as the rule-based 0- or 1-operand problems. From the 36 addition facts and 36 multiplication facts, five were randomly selected from each group to form false arithmetic equations. This yielded a total of 41 addition and 41 multiplication problems. For the false arithmetic equations, the false answers were generated by adding 1–2 to or subtracting 1–2 from one of the two operands for addition; and by adding 1 to or subtracting 1 from one of the two operands for multiplication. The false answers had to have the same number of digits (either one or two digits) as the true answers of the same arithmetic problems would have (e.g., 2×5=12). With these constraints, the false answers closely resemble the true answers. To allow for enough trials for the ERP recording, we had to present each problem two times, totaling 164 trials or problems (144 problems with true answers and 20 with false answers).

4.2.3. *Procedure*

The procedure was the same as that used in experiment one except for one major change and one minor change. The major change involved response format. In experiment one, participants were asked to make a response only when an arithmetic equation was false, but in this experiment, they were asked to respond bimanually to indicate whether an arithmetic equation was true or false. Half of the participants used their left hand to press a key to indicate a true equation and their right hand to indicate a false equation, whereas the other half responded in the opposite way. The minor change was to lengthen the blank screen from the original 1500 ms to 2500 ms to allow subjects more time to respond and to prepare for the next trial.

4.2.4. *Electroencephalography (EEG) recording and analysis*

The procedures for the electroencephalography recoding and analysis were the same as those used in experiment one. The percentages of valid trials used for averaging were 90.7% (±10.3%, standard deviation) for addition and 89.2%(±9.4%) for multiplication for the Arabic digits condition, and 89.3% (±12.4%) for addition and 90.4% (±10.8%) for multiplication in the Chinese number words condition.

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