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The operand-order effect in single-digit multiplication: An ERP study of Chinese adults

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Abstract

Unlike those used in the West, a typical Chinese multiplication table includes only smaller-operand-first entries (e.g., 3 × 7 = 21, but not 7 × 3 = 21). Due to this unique feature, multiplication for Chinese subjects has been found to show an operand-order effect. The present study aims to investigate the neural bases of the operand-order effect. Subjects were 20 Mainland Chinese subjects who learned as children the half multiplication table (i.e., smaller-operand-first entries only) and 20 Hong Kong and Macao Chinese subjects who learned as children the whole multiplication table (i.e., both smaller- and larger-operand-first entries) under the British and Portuguese educational systems, respectively. ERP data showed that, for those who learned the half table (Mainland Chinese), but not for those who learned the whole table (Hong Kong and Macao Chinese), the larger-operand-first problems elicited greater negative potentials across representative electrodes of the whole scalp, emerging at about 120 ms after the onset of the second operand and lasting until around 750 ms. These results suggest that the particular experience of acquiring multiplication facts had pronounced impact on their representations in the brain.

Keywords: Numeral cognition; Arithmetic facts; Multiplication; Operand-order effect; Event-related potentials (ERP)

Many researchers have focused their attention on the mental processes involved in arithmetic problem solving. Among the various documented effects (e.g., the problem size effect, the tie effect, and the distance effect), there is one that appears to be specific for Chinese subjects: the robust operand-order effect in single-digit multiplication. Studies with both Chinese students in North America [2,7,9] as well as those in Mainland China [14] found that, for single-digit multiplication, subjects took shorter time to respond to smaller-operand-first problems (e.g., 3 × 7) than to larger-operand-first problems (e.g., 7 × 3). This effect has been attributed to the early learning experience of Chinese multiplication table that contains only smaller-operand-first problems (with a total of 45 facts, 1 × 1 = 1, 1 × 2 = 2, ..., 1 × 9 = 9; 2 × 2 = 4, 2 × 3 = 6, ..., 8 × 8 = 64, 8 × 9 = 72; and 9 × 9 = 81). This operand-order sensitivity appears to stay with Chinese people for a lifetime. When encountering a larger-operand-first multiplication problem, it appears that Chinese people tend to reverse the order of the two operands to form a familiar smaller-operand-first problem.

Recently, researchers have begun to explore the neural bases of simple arithmetic. Within the domain of multiplication, for example, several studies have used the ERP technique to study the neural activation pattern of number facts [5,6,12]. Of most relevance to the current study, Kiefer and Dehaene [6] studied the time course of the operand-order effect in multiplication. Although previous behavioral data did not show an operand-order effect for English-speaking subjects [7,9], Kiefer and Dehaene's ERP study actually revealed some operand-order effects in selected electrodes for one of two experimental conditions. During the period of 290–370 ms after the onset of the second operand (presented for 150 ms) in the auditory condition, ERPs for smaller-operand-first problems were more positive than those for larger-operand-first problems on the temporal electrodes (0.466 μV difference), and ERPs for smaller-first problems were more negative than those for larger-first problems on the frontal electrodes (0.438 μV difference). The operand-order effect in the auditory condition was also observed in the intervals of 630–1013 and 1014–1399 ms on the central

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electrodes. The negativity was bilaterally more pronounced for smaller-operand-first problems than for larger-operand-first problems (0.624 and 0.304 μV difference). No significant differences were found for the visual condition.

One possible reason for their sporadic findings of the operand-order effect in terms of temporal sequence, brain regions, and method of presentation is that their American sample may have shown very little behavioral difference (e.g., reaction times) between smaller- and larger-operand-first problems. Although Kiefer and Dehaene did not measure RT in their study, their subjects are expected to be similar to Canadian subjects studied by LeFevre et al. [7,9]. The present study aims to replicate and extend Kiefer and Dehaene's [6] study by comparing two samples of Chinese subjects: Mainland Chinese and Hong Kong and Macao Chinese. As mentioned above, previous research has shown clear evidence of the operand-order effect for Chinese who learned the half multiplication table. It is expected that such an operand-order effect should be minimal for Chinese who as children learned the whole multiplication table. Chinese educated under the British and Portuguese educational systems in Hong Kong and Macao fall into that category. They learned 81 facts including both smaller- and larger-operand-first entries. Therefore, we expected that Mainland Chinese subjects should show a more consistent pattern of the operand-order effect in their ERP, whereas Hong Kong and Macao Chinese subjects should show little or no operand-order effect in their ERP.

Forty healthy graduate and undergraduate students (mean age = 21.2 years) were recruited from universities in Beijing for this study. Half of the sample received their primary and secondary education in Mainland China, and the other half in Hong Kong and Macao. Half of the Mainland Chinese subjects were male and the other half female. Eight of the Hong Kong and Macao subjects were male and the other 12 female. All subjects had normal or corrected-to-normal vision.

All problems used in the present study were single-digit multiplication, from 2×3 to 8×9. The tie problems (problems with the same operands, e.g., 3×3) were excluded. There were 56 problems. Each problem was followed by a correct or an incorrect solution, yielding 112 trials. These trials were presented twice. For each participant, these trials were randomly allocated into two blocks, and within each block, the trials were randomly presented with the constraint that no two successive trials shared the same operand.

Experiments were conducted in a dimly lit, electrically shielded, and sound-attenuated room. Subjects were asked to close their eyes during the experiment. All the materials were aurally presented with two speakers, one on each side of the participant. The pronunciations of operands from 2 to 9 were presented in Mandarin for the Mainland Chinese subjects and in Cantonese (their native dialect) for Hong Kong and Macao subjects. Each operand was presented for 200 ms. For each trial, the first operand was first presented, followed by a 50 ms silence and then by the second operand. In order to avoid the influence of electromyography (EMG) generated by oral response and to distinguish the calculation stage and the response stage, a delayed verification paradigm was used. After the stimulus presentation, the subjects were given 1300 ms to think of the solution. Then they were presented with either a correct solution or an incorrect solution for 400 ms. Participants had to judge whether the proposed solution was correct (i.e., the product of the two foregoing operands) or incorrect by pressing a key with their left or right index finger. The response hand was counterbalanced across participants. After 2000 ms allowed for response, the next trial would be presented.

A Neuroscan quick-cap with 64 channels (Neurosoft, Inc., Sterling, USA) was used to record the electroencephalogram (EEG). All EEG channels were referenced to linked earlobes. Two channels were placed at the outer canthi to record the horizontal electrooculogram (HEOG), another two channels on the sub- and supra-orbital ridges of the left eye for vertical electrooculogram (VEOG). Data were recorded by dc with 50 Hz notched. The digit sample was 1000 Hz.

Offline a dc correction was applied first and then ocular artifacts were corrected with NeuroScan EDIT (Version 4.3). Epoch of a trial was 1950 ms long, starting 200 ms before the onset of first operand and ending with the onset of the proposed solution. Trials exceeding the range of −100 to 100 μV at any channel except VEOG and HEOG were rejected as artifacts. Data of one subject (a Mainland Chinese) were discarded because too few sweeps (8%) were accepted after artifacts were rejected. The mean percentage of accepted sweeps for the remaining subjects was 92%. These accepted trials were corrected by a baseline of −200 to 0 ms before the onset of the first operand and filtered with a low pass of 30 Hz (12 db/oct). Because our interest was on the time window during calculation, which occurred before the presentation of the solution, we averaged the ERP across trials regardless of whether the proposed solution was correct or not.

Fig. 1 shows the raw waveform for smaller- and larger-operand-first problems on representative electrode F6. The first

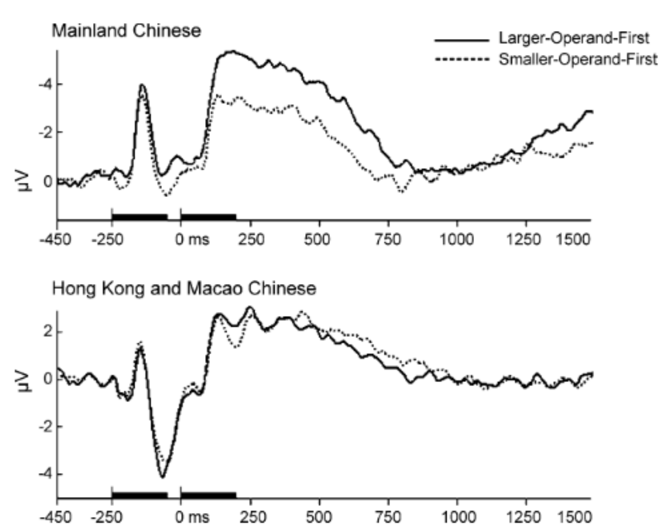

Fig. 1. Grand average waveforms at representative electrode F6 for single-digit multiplication. The two black bars indicate two operands. The first operand evoked typical P50 and N100 components, and the second operand evoked a long-lasting negative component. There was no operand-order effect during the presentation of first operand. A significant operand-order effect was found for Mainland Chinese, but not for Hong Kong and Macao Chinese, starting around 120 ms after the onset of the second operand and lasting until around 750 ms.

operand evoked typical P50 and N100 components observed in many auditory ERP experiments [10,11] and the second operand evoked a long-lasting negative component. We conducted a repeated measures analysis of variance (ANOVA) on the averaged amplitude in each time window with laterality (left, middle, right), caudality (anterior, central, posterior), and operand order (smaller-operand-first versus larger-operand-first) as within-subject factors, and the type of subjects (Mainland versus Hong Kong and Macao Chinese) as a between-subject factor. Three electrodes were selected from each region, resulting in the following 27 electrodes: F7, F5, F3, F1, FZ, F2, F4, F6, F8, T7, C5, C3, C1, Cz, C2, C4, C6, T8, P7, P5, P3, P1, Pz, P2, P4, P6, and P8. Results showed no significant operand-order effect in the interval from the onset of first operand to 120 ms after the onset of the second operand. For the interval between 120 and 500 ms after the onset of the second operand, corresponding to the "peak" of the negative component, there was a significant interaction effect between operand order and the type of subjects, $F(1, 37) = 6.00$, $p < 0.05$. Further simple tests revealed that, as hypothesized, only Mainland Chinese subjects showed the operand-order effect, $F(1, 37) = 7.27$, $p < 0.05$. No other interactions related to the operand order were significant. For the interval between 500 and 750 ms after the onset of the second operand, roughly corresponding to the descending part of the negative component, the three-factor interaction of caudality, operand order, and the type of subjects reached significance, $F(2, 74) = 4.70$, $p < 0.05$. Further tests revealed that only Mainland subjects showed the operand-order effect at the frontal and central electrodes, $F(1, 18) = 6.22$, $p < 0.05$, and $F(1, 18) = 4.40$, $p = 0.05$. No other interactions involving the operand order were significant. For the remaining epochs (i.e., 750–1500 ms), there were no significant operand-order effects.

The difference potentials were computed by subtracting the smaller-operand-first condition from the larger-operand-first condition (see Fig. 2). Consistent with the ANOVA results, the difference potentials distributed across a broad region during 120–500 and 500–750 ms, but not before 120 or after 750 ms.

As anticipated, we found a consistent operand-order effect in multiplication for Chinese who learned the half multiplication table. As compared to Kiefer and Dehaene's sporadic finding [6], the operand-order effect in ERP for Mainland Chinese subjects occurs earlier, exists in a longer time interval, and is more consistent (i.e., greater negativity for larger-first problems) across different regions. We attributed these differences to the more consistent and obvious operand-order effect found for Chinese subjects in chronometric studies [9,10,14]. Another factor that may exacerbate the operand-order effect is that Mainland Chinese adults consistently solve the single-digit multiplication problems via direct retrieval [7–9], instead of using any other strategies (e.g., multi-step addition, or a combination of multiplication and addition such as solving 6×7 as $6 \times 6 = 36$, $36 + 6 = 42$). In other words, the retrieval of smaller-operand-first entries is direct, whereas the retrieval of larger-operand-first entries may involve the reversal of the two operands. The greater mental load when retrieving larger-operand-first entries would account for the greater negativities in ERP. In contrast, Hong Kong and Macao Chinese who learned the whole multiplication table did not show the operand-order effect in ERP.

Our finding of the whole-scalp distribution and long-lasting difference potentials for the operand-order effect may appear to differ from previous research that showed topographical differences in single-digit arithmetic (e.g., specific to the electrodes of regions such as the parietal electrodes) [3,4,13]. Based on the classic model of the neural bases of number processing (e.g., Dehaene's triple-code model [3,4]), it would make sense that the operand-order effect should occur in the parietal lobe (perhaps even more specifically at the IPS) because solving larger-operand-first problems may involve number manipulation for Chinese who do not store them as verbal codes. Some research, however, has shown that number processing may be more spread out than previously assumed. For example, Niedegen and Rosler [12] found a broad distribution (frontal, central, parietal electrodes) for the numerical distance effect during the retrieval of number facts. Kiefer and Dehaene [6], as mentioned

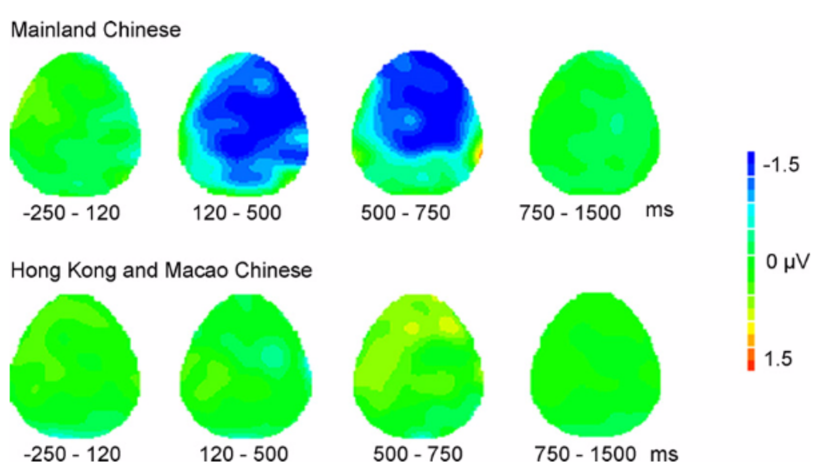

Fig. 2. The topography of difference potentials ("larger-operand-first minus smaller-operand-first") for single-digit multiplication. −250 ms is the onset of the first operand, and 0 ms is the onset of the second operand. The operand-order effect emerged only for Mainland Chinese during 120–750 ms after the presentation of the second operand.

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earlier, found an operand-order effect in the frontal, central, as well as parietal electrodes (depending on the epochs). Zhou et al. [15] have also recently discovered that the numerical distance effect is localized in the anterior–central part of the brain. It should be acknowledged that source localization with the ERP technique is not precise. The broader distribution may be due to multiple neural sources. Future research needs to use high-resolution neuroimaging techniques, such as fMRI, to localize specific brain regions for the operand-order effect.

The operand-order effect appears as early as about 120 ms after the onset of the second operand, suggesting that the retrieval process might begin that early. This is plausible because all digits in Chinese are mono-syllable words and have a unique beginning sound, so participants can recognize and process them even before the sound is finished. Moreover, we believe that the beginning of the operand-order effect may correspond to the beginning of the retrieval process. The encoding stage is not likely to differ between smaller- and larger-operand-first problems because the same sounds were used in these two conditions. But the retrieval stage may be different because it is easier to retrieve products of smaller-operand-first problems.

Finally, it should be noted that there are variations within the Western multiplication tables. Some include 81 facts (9 × 9), whereas others include 144 facts (12 × 12). Furthermore, in some countries such as the United States and the United Kingdom, children recite tables with the table name in the second position: e.g., the two-times table begins, “once two is two, two twos are four, etc.” In contrast, Italian children use the opposite order: “due per uno e due, due per due e quattro, etc.” This differential experience within Western learners may also have an effect on the mental storage of multiplication facts. The memory of multiplication tables may be further complicated by the reorganization of the memory due to children’s growing understanding of commutativity and perhaps other properties of multiplication during the course of development [1]. For example, Butterworth et al. have found that Italian children learn 5 × 7 before 7 × 5 as part of the five-times table, but end up responding faster to 7 × 5 than to 5 × 7 [1]. Future research should explore the impact of these variations and developmental changes on neural functions.

In summary, our ERP study showed a consistent (temporally and topographically) operand-order effect in simple multiplication by Mainland Chinese subjects who memorized only the smaller-operand-first multiplication problems, but not by Hong Kong and Macao Chinese who learned both smaller- and larger-operand-first multiplication problems. These results suggest that the neural basis of the memory and retrieval of multiplication facts is shaped by particular cultural/educational experience involved in the learning of multiplication.

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