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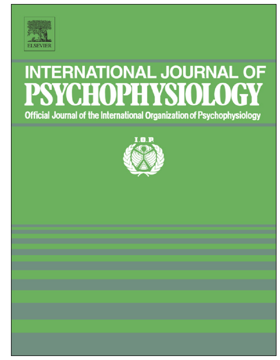


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# Differential recruitment of brain networks in single-digit addition and multiplication: evidence from EEG oscillations in theta and lower alpha bands

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## Abstract

Previous neuroimaging research investigating dissociation between single-digit addition and multiplication has suggested that the former placed more reliance on the visuo-spatial processing whereas the latter on the verbal processing. However, there has been little exploration into the disassociation in spatio-temporal dynamics of the oscillatory brain activity in specific frequency bands during the two arithmetic operations. To address this issue, the electroencephalogram (EEG) data were recorded from 19 participants engaged in a delayed verification arithmetic task. By analyzing oscillatory EEG activity in theta (5-7 Hz) and lower alpha frequency (9-10 Hz) bands, we found different patterns of oscillatory brain activity between single-digit addition and multiplication during the early processing stage (0-400 ms post-operand onset). Experiment results in this study showed a larger phasic increase of theta-band power for addition than for multiplication in the midline and the right frontal and central regions during the operator and operands presentation intervals, which was extended to the right parietal and the right occipito-temporal regions during the interval immediately after the operands presentation. In contrast, during multiplication higher phase-locking in lower alpha band was evident in the centro-parietal regions during the operator presentation, which was extended to the left fronto-central and anterior regions during the operands presentation. Besides, we found stronger theta phase synchrony between the parietal areas and the right occipital areas for single-digit addition than for multiplication during operands encoding. These findings of oscillatory brain activity extend the previous observations on functional dissociation between the two arithmetic operations.

**Key words**: Numerical cognition; Dissociation between simple mental arithmetic operations; EEG analysis; Brain functional networks

## 1. Introduction

Exploration of different cognitive processes across basic arithmetic operations such as single-digit addition and multiplication has been the focus of numerous studies in the domain of numerical cognition (Arsalidou and Taylor, 2011; Rosenberg-Lee et al., 2011; Zhou, 2011; Zhou et al., 2007a). The prevailing models for numerical processing, both the triple-code model (Dehaene, 1992) and the encoding-complex model (Campbell, 1994; Campbell and Epp, 2004), suggest that the internal code used to process numerical information is non-abstract, i.e., dependent upon the processing task. Event-related potential (ERP) and functional magnetic resonance imaging (fMRI) studies exploring the dissociation between single-digit addition and multiplication have suggested that the former engaged predominantly the visuo-spatial Arabic code whereas the latter recruited the verbal code to a larger extent (Zhou, 2011; Zhou et al., 2006; Zhou et al., 2007a). However, there has been little exploration into the disassociation in EEG oscillations between single-digit addition and multiplication, although EEG signatures in specific frequency bands could provide more detailed and accurate spatiotemporal information with respect to the issue than the corresponding measures based on broadband electrophysiological signals or the blood oxygen level-dependent (BOLD) fMRI signals (Siegel et al., 2012).

To solve an arithmetic problem, the visually presented operands need to be mentally represented using verbal code, visuo-spatial Arabic code or analog magnitude code. After brief presentation of operands, the numerical representation is maintained for further processing if necessary. Since operands are suggested to be encoded into visuo-spatial Arabic code in single-digit addition and verbal code in multiplication, it is still unclear whether the recruitment of brain functional network is modulated by arithmetic type during the early encoding stage, related to the control of attention and stimulus encoding. Additionally, some research has suggested that both arithmetic operations are solved by direct retrieval of arithmetic facts (Chen and Campbell, 2015, 2016), whereas some research has argued that single-digit multiplication depends on direct fact retrieval but single-digit addition is solved by procedural strategies (Fayol and Thevenot, 2012; Metcalfe and Campbell, 2011; Uittenhove et al., 2016). If the latter assumption is valid, greater recruitment of executive function will be observed for single-digit addition, due to the fact that numerical information will be manipulated in effortful procedural manipulation (Geary et al., 1999).

EEG oscillations in the theta frequency range have been consistently reported to be related to different cognitive processes, e.g., the control of attention, information encoding and mental manipulation, etc. (Clayton et al., 2015; Deiber et al., 2007; Harmony et al., 1999; Moeller et al., 2010; Sauseng et al., 2010; Sauseng et al., 2007; Ward, 2003). Theta power is associated with the allocation of attention resources in cognitive processes, and phasic power increase in theta band following target onset is interpreted to reflect encoding of the stimulus information in visuo-spatial tasks (Bastiaansen et al., 2002). Furthermore, interregional phase synchronization in theta rhythms reflects functional integration among neuronal populations during information encoding (Gorisek et al., 2015; Klimesch, 1996; Sauseng et al., 2010; Sauseng et al., 2007; Sauseng et al., 2004). Specially, the fronto-parietal theta network has been proved to be modulated by the demands on information manipulation in the working memory system (Griesmayr et al., 2014; Mizuhara et al., 2005; Sauseng et al., 2005). On the other hand, synchronized alpha responses, comprising phase and amplitude responses, reflect the processes of accessing and retrieving information stored in a complex long-term memory system, which is termed knowledge system (Klimesch, 2012; Klimesch et al., 2011). The knowledge system is a storage system, which comprises not only traditional long-term memory but any type of knowledge, including procedural and implicit-perceptual knowledge. Evoked phase responses (e.g., phase locking) in alpha frequency band in an early post-stimulus interval reflects a specific type of attention that is related to the knowledge system. In other words, alpha-band phase-locking activity "directs the flow of information" to those neural structures which represent information that is relevant for encoding (Klimesch, 1997, 2011, 2012). Alpha power desynchronization in a later stage reflects a processing mode that controls the retrieval of stored information in memory (Klimesch, 1997, 1999).

In order to explore how brain functional networks are differentially involved in single-digit addition and multiplication, this study focuses on investigating theta and alpha activities across the solution stages of the arithmetic tasks, by using a delayed verification paradigm. It is expected that EEG oscillations will bring new evidence about the differential neural basis for single-digit addition and multiplication and extend the range of areas that are known to contribute to the dissociation between the two arithmetic operations, from which the different cognitive processes implicated in the two arithmetic operations could be understood in more depth.

## 2. Materials and methods

### *2.1. Subjects, stimuli, and task*

Nineteen college students (11 males and 8 females, aged 19-31 years, with mean = 23.42 and standard deviation = 2.55) whose major is biomedical engineering without known calculation difficulties were recruited as subjects for this experimental study. Exclusion criteria included left handedness (based on subject's self-report), neurological illness, and history of brain injury. All subjects were asked to read and sign an informed consent form before experiments and the study was approved by the Academic Committee of the School of Biological Science and Medical Engineering, Southeast University, China. All participants were native speakers of Mandarin Chinese and obtained their elementary and secondary education in Mainland China. All the subjects passed National College Entrance Examination and none of them declared himself/herself as a calculating prodigy. Therefore, they were considered to be individuals with average-level arithmetic performance.

Recent behavioral research has revealed that presenting the operator prior to the operands facilitates both types of arithmetic operations, but the recruitment of brain networks during the priming stage, i.e., the presentation of the operator, in the two arithmetic operations is still unclear (Chen and Campbell, 2015). Therefore, a delayed verification paradigm with the operator presented prior to the operands was employed to explore differential brain oscillation activities between single-digit addition and multiplication. We chose a delayed verification task over a standard verification task (i.e., operands and proposed solution are presented simultaneously, e.g., “2+3=8”) due to the fact that the latter is suggested to involve a plausibility judgment rather than retrieval or calculation (Campbell and Tarling, 1996; Lemaire and Fayol, 1995). Each trial began with the presentation of a fixation point for 500 ms, followed by a blank screen randomly jittered between 0.8 and 1 second. Then the two operands of each arithmetic type were presented simultaneously for 200 ms after the 150 ms presentation of an operator (a plus or multiplication sign). Subsequently a blank screen was displayed for 1300 ms, during which participants silently produced the solution of the single-digit multiplication or single-digit addition problem, until the presentation of a solution for the subjects to judge. By pressing a key with their middle finger, the subjects indicated whether the presented solution was the same as their own solution. Response hands were counterbalanced across subjects. Hence, there was no motor cortex activation related to button press responses in the crucial calculation interval. Smaller-operand-first problems (e.g., 3×4 or 7+8) are exclusively involved in this study owing to a preferred operand order for multiplication observed in Mainland Chinese subjects (Zhou et al., 2007b). Thus, non-zero problems consist of 28 possible combinations of operands ranging from 2 to 9 in each operation (i.e., problems ranging from 2×9 to 8×9 in multiplication or 2+9 to 8+9 in addition, with ties being excluded, e.g., 3×3 or 3+3). Each combination was repeated 4 times, resulting in 112 trials for each arithmetic operation. Previous research has shown the asymmetrical costs of mixing addition and multiplication when the arithmetic operations are assigned in one block (e.g., (Campbell and Arbuthnott, 2010; Campbell and Oliphant, 1992)). To reduce such interference, different types of arithmetic operations were presented in separate blocks and arithmetic type was alternated blockwise, with the order counterbalanced across subjects. Then to ensure that the prior presentation of the operator still takes effect with only one arithmetic type in each block, a control task (retention of two numbers) was included in each block. The procedure and materials of the control task were the same as those of the two arithmetic operations, with an exclamation mark indicating retention of two numbers. Participants retained the numbers until the presentation of a probe number. They had to judge whether the probe number had been shown as a part of the previously presented two numbers. At the beginning of each block, type of arithmetic operations and the control task to be performed were cued on the screen. Each type of arithmetic operations had two blocks (about 5 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.

### *2.2. EEG recording*

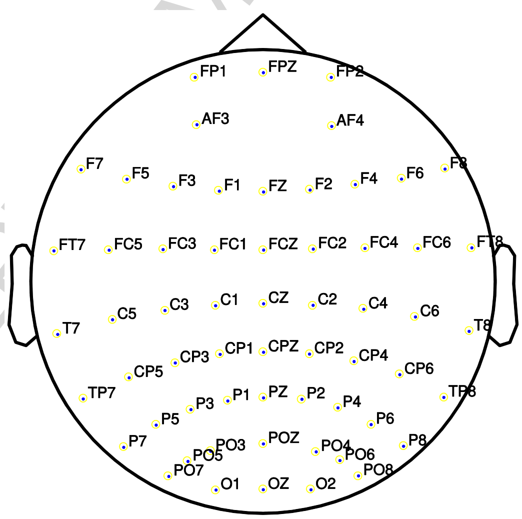



**Fig. 1.** Placement of 60 EEG sensors according to the International 10–20 system.

Continuous EEG data were recorded by a 60-channel Neuroscan using the international 10-20 system (see head scheme in Fig. 1), with the reference on the left mastoid. The sampling rate was 1000 Hz with an analog passband filter of 0.1-100 Hz.

Electro-oculographic (EOG) signals were simultaneously recorded by four surface electrodes to monitor eye movements.

*2.3. Data preprocessing*

The preprocessing of EEG data consists of the following steps. First, the preprocessing procedures in Scan 4.5 were carried out, such as rejecting unsuitable portions (e.g., paroxysmal) of the continuous data, reducing the ocular artifact using signals recorded by EOG electrodes, band-pass filtering the continuous data between 1-60 Hz, trial segmentation into 3.5s epochs lasting from 1.4s before operands onset until 2.3s post-operands, offline re-reference to the linked mastoid electrodes, artifact rejection with the threshold of ±75μV. Only the trials with correct response were kept for further analysis. Subsequently, the sample rate of EEG data was sub-sampled from 1000 Hz to 250 Hz and further artifact reduction was performed using independent component analysis (ICA) twice. The first implementation of ICA aims to reject bad epochs through semi-automated rejection (e.g., threshold on power spectrum and the cumulant of the distribution) coupled with visual-inspection. The purpose of the second ICA on the pruned data is for component rejection. All the artifact reduction using ICA was implemented by the EEGLAB toolbox (Delorme and Makeig, 2004), and the component rejection was performed by using ADJUST (Mognon et al., 2011), a plug-in of the EEGLAB software. As a result, the preprocessing procedures resulted in 46–105 (88±15) trials for the addition task, 43-103 (83±16) trials for the multiplication task and 87-203 (171±29) trials for the control task.

Further analyses, such as the wavelet transform, event-related power change, inter-trial phase coherence, and permutation tests were performed using FieldTrip

(Oostenveld et al., 2011), an open-source MATLAB toolbox for neurophysiological data analysis. Figure 2 shows the processing pipeline for EEG time-frequency analysis using Fieldtrip.

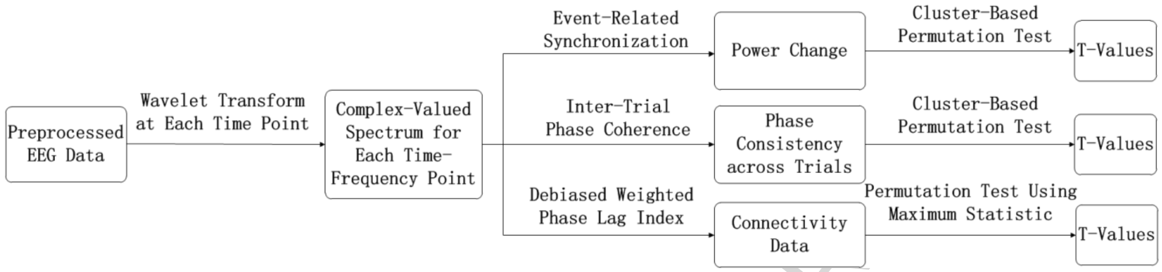



**Fig. 2.** Flow chart of EEG time-frequency analysis steps. For details, refer to the Materials and methods section.

### *2.4. Wavelet transform and power analysis*

The segmented data (-1400 to 2,300 ms in respect to onset of operands) were wavelet-transformed using a Morlet wavelet, $\omega(t,f_0) = A \exp(-t^2/2\sigma_t^2) \exp(2i\pi f_0 t)$, with width of the wavelet being set to 7 (Handy, 2005; Sinkkonen et al., 1995). The resulting complex-valued spectrum for each time-frequency point was used to calculate power change, phase consistency across trials and connectivity between electrode pairs. The power at each time-frequency point was given by the squared norm of the complex-valued spectrum. The resulting power spectrum at each time-frequency point was expressed relative to a reference interval (-650 ms to -350 ms relative to the onset of the operands), to highlight stimulus-induced changes in the magnitude of oscillations. Then power spectrum at each electrode was averaged across 2 frequency bands (theta: 5–7 Hz; upper alpha: 11-12Hz) and 9 time windows: the time window covering whole length of the time interval of interest (i.e., -150 – 1500 ms), a 150 ms time window during which the operator presents (i.e., -150 – 0 ms relative to the onset of the operands) and seven consecutive non-overlapping 200 ms time windows spanning 0 to 1400 ms relative to the onset of the operands. The sliding window length (200 ms) was chosen to span at least one cycle period of the lowest frequency of our interest (5 Hz) (Asada et al., 1999; Greenberg et al., 2015; Mullen et al., 2015).

*2.5. Inter-trial phase coherence*

Inter-trial phase coherence is a measure of phase consistency between trials (Delorme and Makeig, 2004). The inter-trial phase coherence takes values ranging from 0 (absence of synchronization across EEG trials) to 1 (their perfect synchronization and the time-locking events). We averaged the spectrum of inter-trial phase coherence at each electrode across 2 frequency bands (theta: 5–7 Hz; lower alpha: 9-10 Hz) and 9 time windows: the whole length of the time interval of interest (i.e., -150 – 1500 ms), a 150 ms time window during which the operator presents (i.e., -150 – 0 ms relative to the onset of the operands) and seven consecutive non-overlapping 200 ms time windows spanning 0 to 1400 ms relative to the onset of the operands.

*2.6. Phase coupling analysis*

To elucidate the different brain networks recruited in the two arithmetic operations, inter-electrode phase synchrony between the signals from each two scalp sites under each condition was computed through debiased weighted phase lag index for each frequency and time point (Vinck et al., 2011). Weighted phase lag index is an extension of phase lag index that indexes the asymmetry in the distribution of phase differences calculated from the instantaneous phases of two signals over trials (Stam et al., 2007). By weighting each phase difference according to the magnitude of the lag, phase differences around zero only marginally contribute to the calculation of weighted phase lag index. This procedure reduces the probability of detecting "false positive" connectivity in the case of volume conducted noise sources with near zero phase lag and increases the sensitivity in detecting phase synchronization. A further advantage of the weighted phase lag index is that it is invariant to a linear mixing of two dependent sources, and is hence more sensitive in detecting interactions when the interacting sources are spatially close (Haufe et al., 2013). In addition, the debiased weighted-phase-lag-index-square estimator addresses the positively biased issue of weighted phase lag index caused by sample-size bias. Finally, the debiased weighted phase lag index for each electrode pair was averaged across 3 frequency bands (theta: 5–7 Hz; lower alpha: 9-10 Hz; upper alpha: 11-12Hz) and 9 time windows: the whole length of the time interval of interest (i.e., -150 – 1500 ms), a 150 ms time window during which the operator presents (i.e., -150 – 0 ms relative to the onset of the operands) and seven consecutive non-overlapping 200 ms time windows spanning 0 to 1400 ms relative to the onset of the operands. Note that the debiased weighted phase lag index is an estimate of the squared weighted phase lag index, that is, a value of 0.1 for the debiased weighted corresponds to a value of the unbiased weighted phase lag index of about 0.3.

### *2.7. Inferential statistics*

Instead of restricting to regions of interest, a cluster-based permutation test, using a test statistic based on clustering of spatial adjacency, was applied to assess the degree of statistical significance of the arithmetic type effect (i.e., addition vs. multiplication) on the power and inter-trial phase coherence in selected EEG frequency bands (Maris and Oostenveld, 2007). The dependent samples t-statistic was applied to evaluate the effect at each electrode, and the electrodes with p-values smaller than the threshold 0.01 were selected to be clustered. For a two-sided test applied here, the clustering, based on adjacency of spatial dimension, was performed separately for electrodes with a positive t-vale and those with a negative t-value. The cluster-level statistics thereupon were calculated by taking the sum of the t-values within every cluster, and the absolute maximum value of the cluster-level statistics is taken as the test statistic by means of which we evaluate the arithmetic operation effect in this study. An important motivation for the selection of this test statistic is the fact that cluster-based test statistics turn out to be more sensitive to multiple comparisons than traditional methods, such as Bonferroni correction (Maris and Oostenveld, 2007). After 6000 random partitions, the clusters with t-values larger than the 97.5th percentile value were considered as significant.

Cluster-based approach is unsuitable for statistics on functional connectivity, due to the fact that debiased weighted phase lag index is calculated between electrode pairs. Therefore, to account for the problem of multiple comparisons for the large number of electrode pairs (1770), the maximum t value across electrode pairs in each permutation was used to construct the maximum t-value distribution. After 6000 random partitions, the 97.5th percentile value was taken as a threshold for significance.

To further investigate whether the observed oscillatory activity is operation-specific or is involved in general functions in numerical processing, a one-way repeated measures analysis of variance (ANOVA) was conducted on power change, inter-trial phase coherence or debiased weighted phase lag index across the electrodes within the significant cluster or significant electrode pairs, for each interval during which the effect of arithmetic type was observed, with task type (addition, multiplication, and control) serving as within subjects factor. Mauchly's test was applied to assess the possible violations of sphericity. The Greenhouse–Geisser correction was conducted when sphericity assumptions were violated ($p < 0.05$), and, in these cases, the uncorrected degrees of freedom, ε values, and the corrected probability levels are reported. When the main effect of the ANOVA was significant, post-hoc comparisons were made to determine the significance of pairwise contrasts, using Tukey's one-factor HSD procedure (alpha = 0.05).

## 3. Results

### *3.1. Behavioral results*

The duration of the trials (from the onset of fixation point until participants pressing a key) was 3727±242 ms, 3679±177 ms and 3755±177 for addition, multiplication and control trials, respectively. Response accuracy was 98.73%±1.04%, 99.02%±0.93% and 97.91%±1.53% for addition, multiplication and control task, respectively. The error rates were low and thus were not further analyzed. Reaction time (RT) was measured from the moment the solution was presented until the participant made a correct response. Reaction time was 674±241 ms, 617±159 ms and 700±175 ms for addition, multiplication and control task, respectively. RT were then entered into a one-way repeated measures ANOVA, with task type (addition, multiplication, and control) serving as within subjects factor. The results indicated that there was no main effect of task type ($F_{2,18} = 2.016$, $\varepsilon = 0.545$, $p = 0.171$).

### *3.2. Addition induces larger theta power increase than multiplication over midline and right hemisphere*

Figure 3 presents the grand average of time-frequency plots for power change and inter-trial coherence during single-digit addition (Fig. 3A and 3C) and multiplication (Fig.

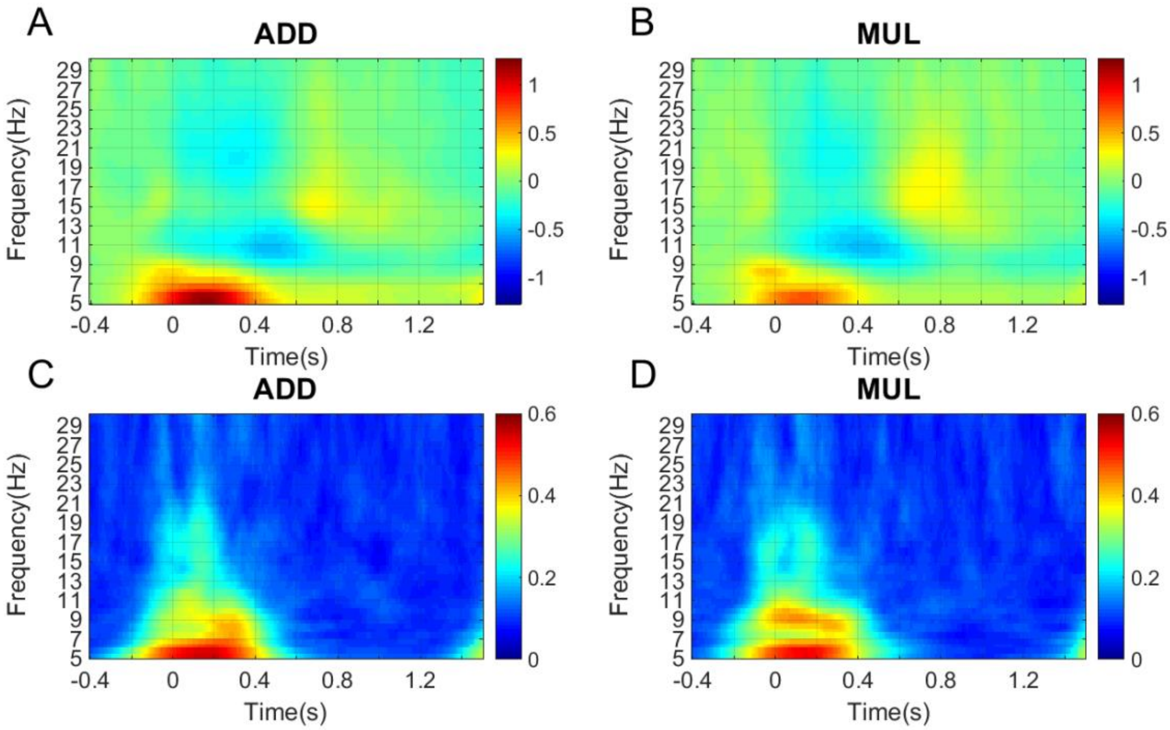



**Fig. 3.** Grand average time-frequency plots of oscillatory activity in single-digit addition (ADD) and multiplication (MUL) for a representative electrode CZ. Zero point denotes onset of the operands. Time-frequency plots of power changes for single-digit addition (A) and multiplication (B). Time-frequency plots of inter-trial phase coherence values for single-digit addition (C) and multiplication (D). Mean data of 19 subjects.

3B and 3D) at the representative electrode CZ (Fig S1 shows grand average time-frequency plots of power changes for addition and multiplication for all sensors and Fig S2 shows grand average time-frequency plots of inter-trial phase coherence for addition and multiplication for all sensors). Thereafter, theta (5-7 Hz) and upper alpha (11-12 Hz) frequency ranges were selected for power analysis, whereas theta (5-7 Hz) and lower alpha (9-10 Hz) were selected for inter-trial phase coherence analysis, given that in these frequency bins brain oscillations show the most pronounced responses. Figure 4 presents the grand average topography of event-related power change in theta frequency band for addition and multiplication during 9 time intervals of interest. The cluster-based

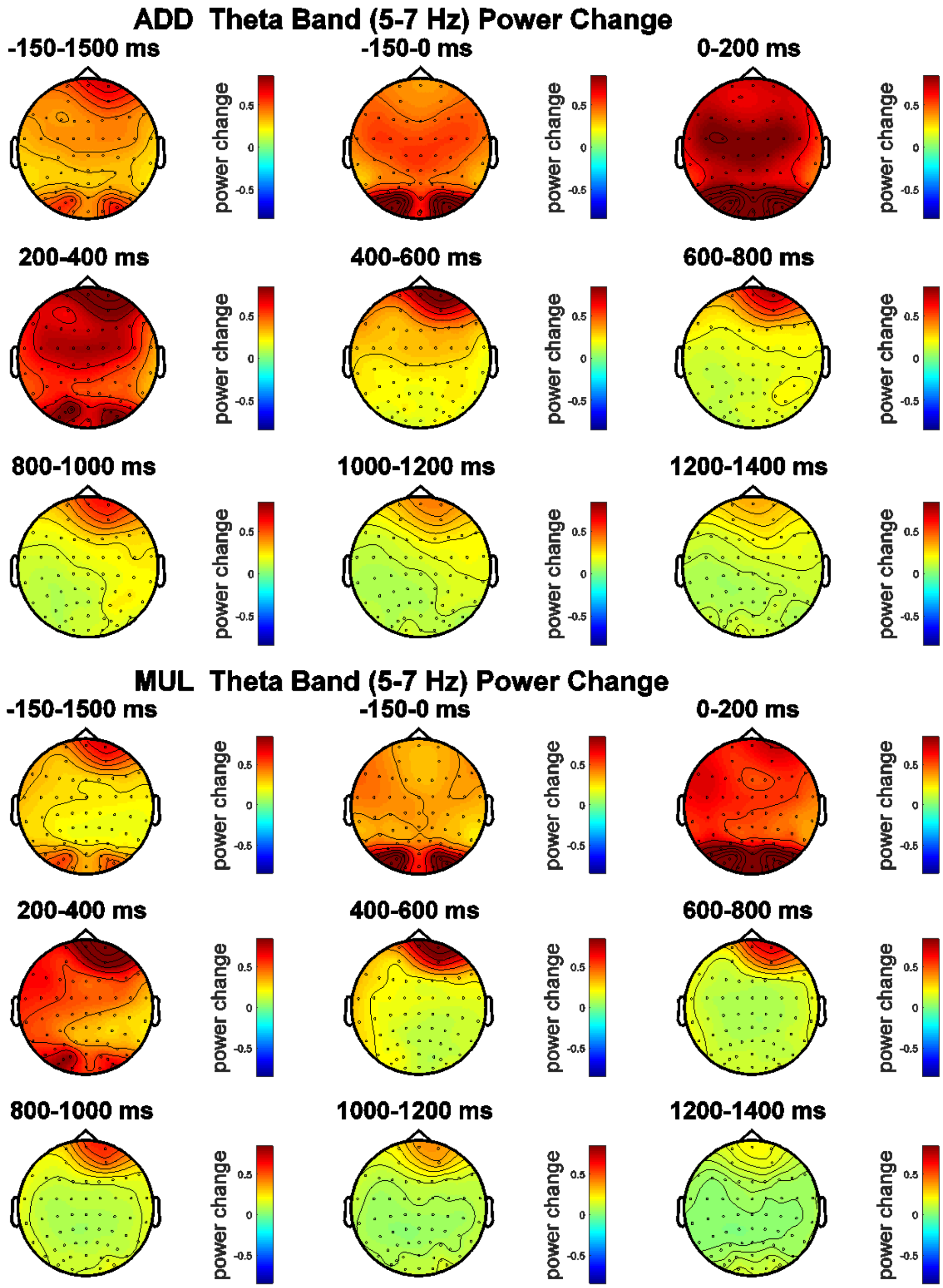



**Fig. 4.** Topography of event-related power change in theta frequency band (5-7 Hz) for addition (ADD) and multiplication (MUL) during 9 time windows: the whole length of the time interval of interest (i.e., -150 – 1500 ms), a 150 ms time window during which the operator presents (i.e., -150 – 0 ms relative to the onset of the operands) and seven consecutive non-overlapping 200 ms time windows spanning 0 to 1400 ms relative to the onset of the operands. Mean data of 19 subjects.

permutation tests on the type of arithmetic operations discovered significant difference in theta power between single-digit addition and multiplication in four time intervals: -150 – 1500 ms, -150-0 ms, 0-200 ms and 200-400 ms, during which the addition task elicited greater theta power increase in the midline and the right hemisphere ($t_{\text{cluster}}$ = 24.627, $p_{cluster}$ = 0.030, $t_{\text{cluster}}$ = 24.865, $p_{cluster}$ = 0.031, $t_{\text{cluster}}$ = 44.086, $p_{cluster}$ = 0.015 and $t_{\text{cluster}}$ = 63.603, $p_{cluster}$ = 0.007, respectively) (Fig. 5). Furthermore, the effect in the 3 time windows, i.e. during the entire period of task (-150 – 1500 ms), the operator presentation (-150 - 0 ms) and the operands presentation (0 – 200 ms), was mainly restricted to anterior part of midline and the right hemisphere and extended to the right parietal areas and the right occipito-temporal areas during the interval immediately after operands presentation (200 - 400 ms). For each of the four time intervals, the one-way repeated measures ANOVA on theta power change averaged across the electrodes within the significant cluster indicated a significant main effect of task type on theta power change in each of the four time intervals ($F_{2,18}$ = 6.436, $p$ = 0.004, $F_{2,18}$ = 5.255, $p$ = 0.01, $F_{2,18}$ = 5.52, $p$ = 0.008 and $F_{2,18}$ = 6.669, $p$ = 0.003). Post hoc comparisons showed that, for all four intervals, theta power change under multiplication was significantly lower than both addition ($p$ = 0.028, 0.023, 0.017 and 0.005, respectively) and control tasks ($p$ = 0.002, 0.015, 0.012 and 0.014, respectively). However, the difference between addition and control tasks was not significant in each of the four intervals ($p$ = 1). Despite a significant difference of theta power change was observed between addition and multiplication using the entire length of the task period (-150 ms – 1500 ms), the effect was attributed to the operation effect in the early stage (-150 – 400 ms) since no operation effect was observed during the intervals later than 200 – 400ms time intervals. Besides, although desynchronization of upper alpha frequency band was observed at a later stage for both arithmetic operations, there was no significant power difference observed between the

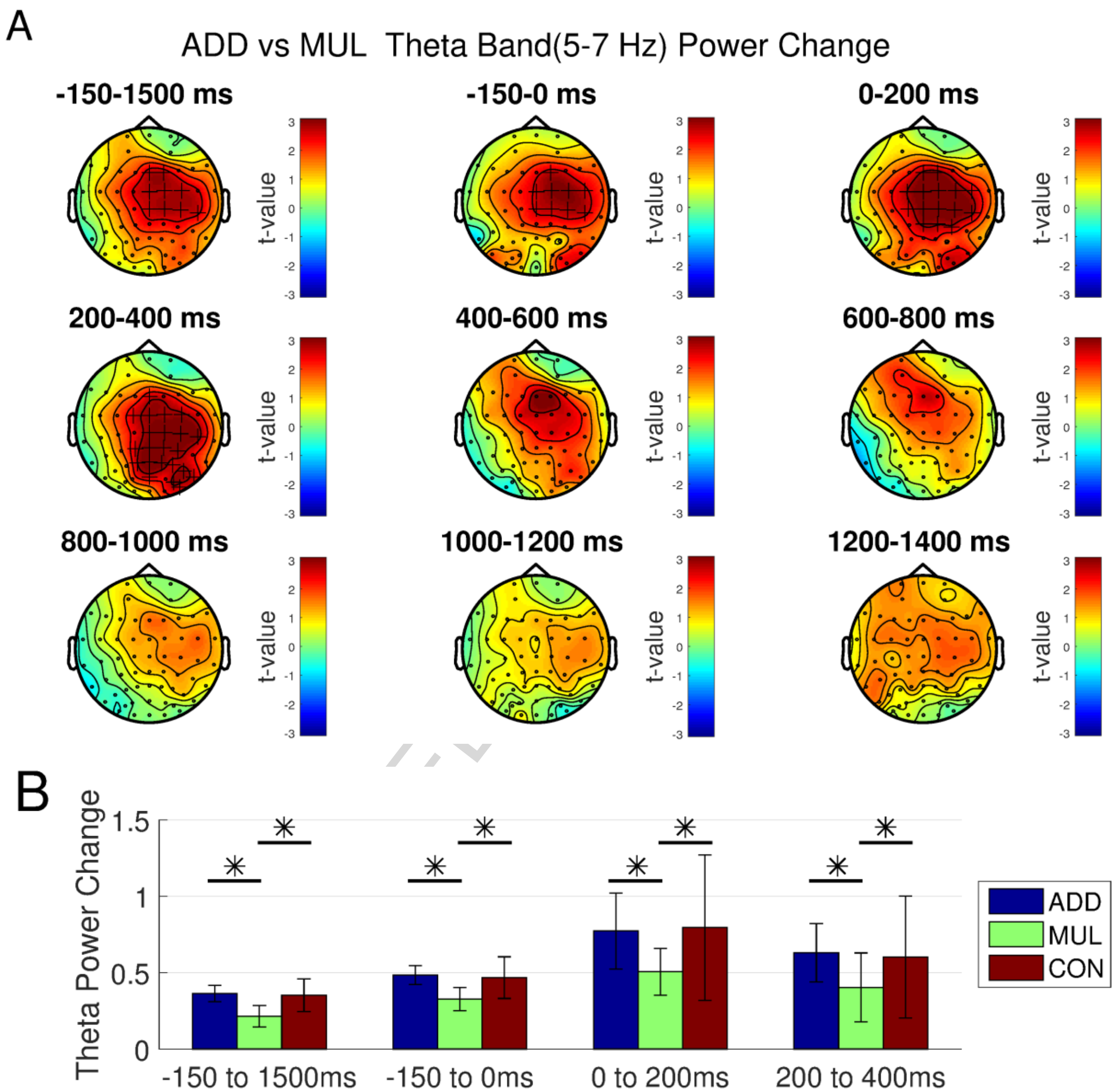
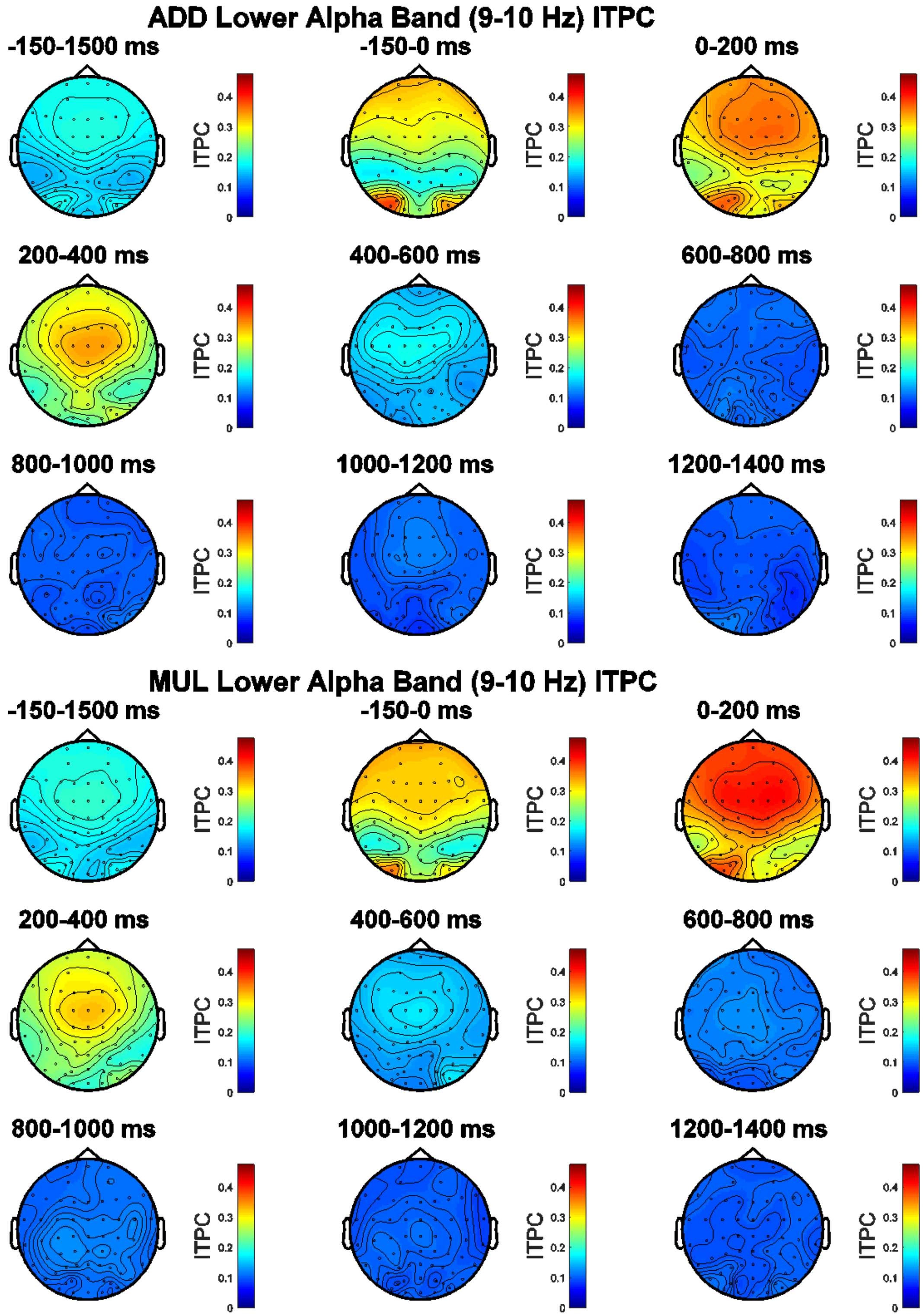



**Fig. 5.** Comparison of induced theta activity (5-7 Hz) between single-digit addition and multiplication through cluster-based permutation test using 9 time windows: the whole length of the time interval of interest (i.e., -150 – 1500 ms), a 150 ms time window during which the operator presents (i.e., -150 – 0 ms relative to the onset of the operands) and seven consecutive non-overlapping 200 ms time windows spanning 0 to 1400 ms relative to the onset of the operands. (A) Topography of t-value for testing the difference in theta activity between single-digit addition (ADD) and multiplication (MUL) during the 9 time windows, in which plus signs indicate electrodes within clusters showing significant difference between the two types of arithmetic operations (corrected p = 0.030, 0.031, 0.015 and = 0.007, respectively). (D) Bars per condition (i.e., addition (ADD), multiplication (MUL) and control (CON)) for power change relative to baseline averaged over electrodes in the time-frequency cluster highlighted in A. Error bars indicate standard error of mean (SEM) for normalized data.

two arithmetic operations in upper alpha frequency band (Fig. S3 in the Supplemental Material). Thereafter, based on the grand average of time-frequency plots for inter-trial phase coherence (Fig. 3C and 3D), we analyzed phase-locked activity of both theta and lower alpha band.

### 3.3. *Multiplication induced larger inter-trial phase coherence in lower alpha band than addition*

Figure 6 presents the grand average topography of inter-trial phase coherence in lower alpha frequency band for addition and multiplication during 9 time intervals of interest. The cluster-based permutation tests reflected significant effect of arithmetic type on inter-trial phase coherence of lower alpha band in the -150-0 ms and 0-200 ms time intervals, within which greater phase-locking activities in the centro-parietal regions was elicited by multiplication ($t_{\text{cluster}}$ = -20.1, $p_{cluster}$ = 0.034) and then extended to the left fronto-central and anterior sites ($t_{\text{cluster}}$ = -42.349, $p_{cluster}$ = 0.011, respectively) (Fig. 7). For each of the two time intervals, the one-way repeated measures ANOVA conducted on the phase-locking values of lower alpha band, which were averaged across the electrodes within the significant cluster, revealed a significant main effect of task type on the inter-trial phase coherence of lower alpha band for the both time intervals ($F_{2,18}$ = 5.463, $p$ = 0.008 and $F_{2,18}$ = 6.421, $p$ = 0.004, respectively). Post hoc comparisons showed that, in the -150-0 ms interval, the inter-trial phase coherence under the single-digit addition was significantly lower than multiplication ($p$ = 0.02), while no significant difference was found for other comparisons ($p$ > 0.1). In the 0-200 ms interval, the inter-trial phase coherence under multiplication was significantly larger than both single-digit addition ($p$




interest (i.e., -150 – 1500 ms), a 150 ms time window during which the operator presents (i.e., -150 – 0 ms relative to the onset of the operands) and seven consecutive non-overlapping 200 ms time windows spanning 0 to 1400 ms relative to the onset of the operands. Mean data of 19 subjects.

= 0.007) and control tasks ($p$ = 0.02), while the difference between addition and control tasks was not significant ($p$ = 1). There was no significant difference of inter-trial phase coherence observed between the two arithmetic operations in theta frequency band (Fig. S4).

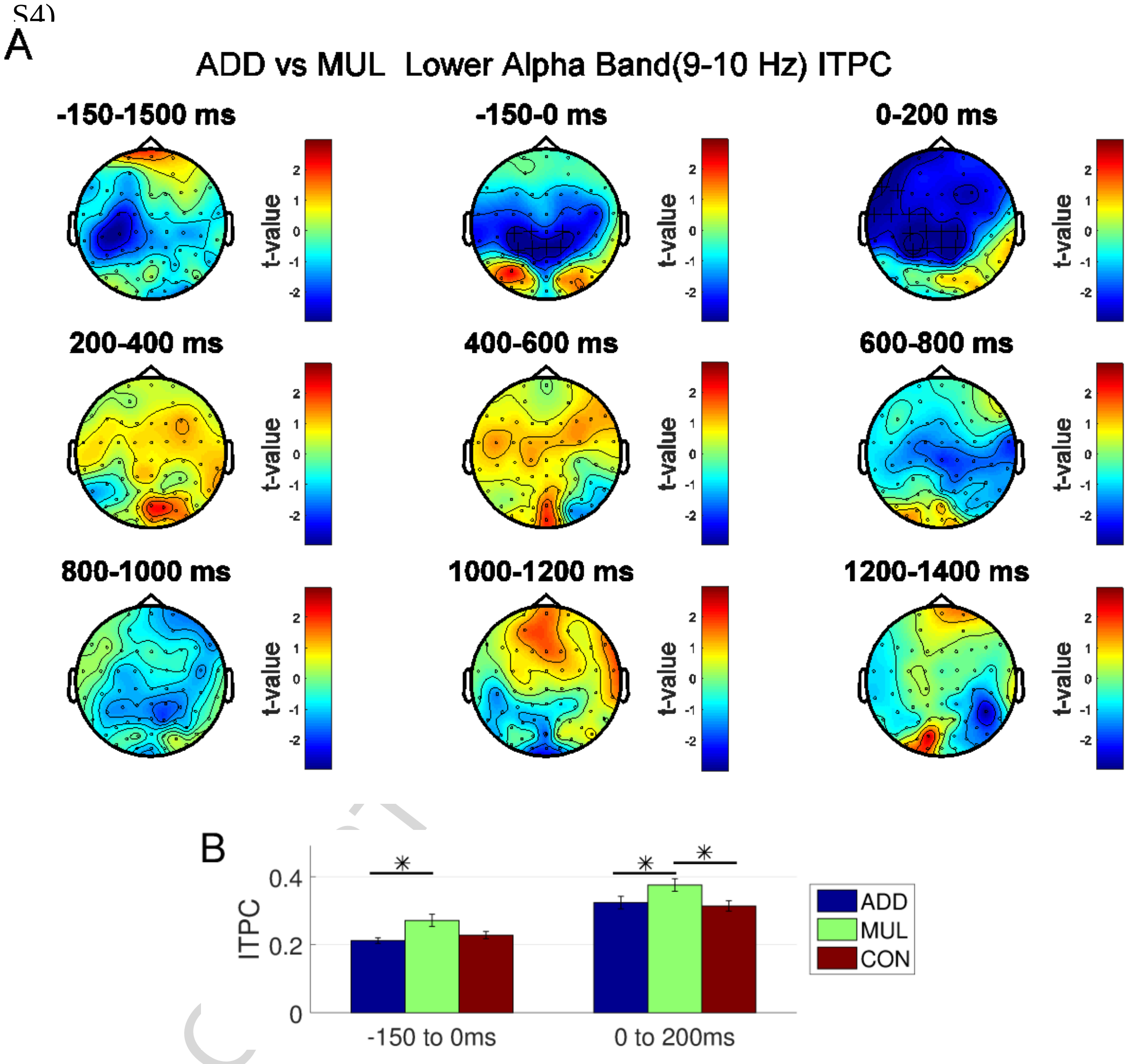



**Fig. 7.** Comparison of inter-trial phase coherence (ITPC) of lower alpha frequency band (9-10 Hz) between single-digit addition and multiplication through cluster-based permutation test using 9 time windows: the whole length of the time interval of interest (i.e., -150 – 1500 ms), a 150 ms time window during which the operator presents (i.e., -150 – 0 ms relative to the onset of the operands) and seven consecutive non-overlapping 200 ms time windows spanning 0 to 1400 ms relative to the onset of the operands. (A) Topography of t-value for testing the difference in inter-trial phase coherence of alpha frequency band between single-digit addition (ADD) and multiplication (MUL) during the 9 time windows, in which plus signs indicate electrodes within clusters showing significant difference between the two types of arithmetic operations (p = 0.034 and = 0.011, respectively). (B) Bars per condition (i.e., addition (ADD), multiplication (MUL) and control (CON)) for inter-trial phase coherence averaged over the time-frequency cluster highlighted in A. Error bars indicate SEM for normalized data.

*3.4. Increased theta phase synchrony in parieto-occipital cortex for single-digit addition during operands presentation*

The phase coupling analysis has been conducted on all the three bands, i.e., theta, lower alpha and upper alpha frequency bands. In the tests for the effect of arithmetic type on all the possible electrode pairs (1770), there was no significant difference in each of the nine selected time windows for all 3 frequency bands (Fig. S5, S6 and S8). Thereafter, we selected the regions of interest which may increase the sensitivity of the statistical test (Maris and Oostenveld, 2007). Previous results in this study (Section 3.1) have demonstrated that larger theta power increase was involved in single-digit addition than multiplication during the early stage (0 – 400 ms), probably suggesting greater attentional demands on spatial representation of operands (see Discussion). Moreover, the parieto-occipital cortical activation has been found to be closely linked to visuo-spatial processing of stimuli (Babiloni et al., 2006) and to the spatial representation of numbers (Gobel et al., 2006). Therefore, we restricted the regions of interest to 378 electrode pairs at the posterior parietal and occipital regions probably involved in spatial representation of the numbers (Fig. 8B).

Only in the 0-200 ms time window, i.e., the presentation of operands, the permutation test revealed a significant effect of arithmetic type on two electrode pairs CP5/P8 ($t$ = 4.317, $p$ = 0.04) and PZ/PO4 ($t$ = 4.336, $p$ = 0.038), which suggested higher parietal-occipital theta phase synchrony for single-digit addition compared to multiplication (Fig. 8A). Thereafter, the one-way repeated measures ANOVA for debiased weighted phase lag index averaged across electrode pairs CP5/P8 and PZ/PO4 indicated a significant main effect of task type during the 0-200 ms interval ($F_{2,18}$ = 8.787,

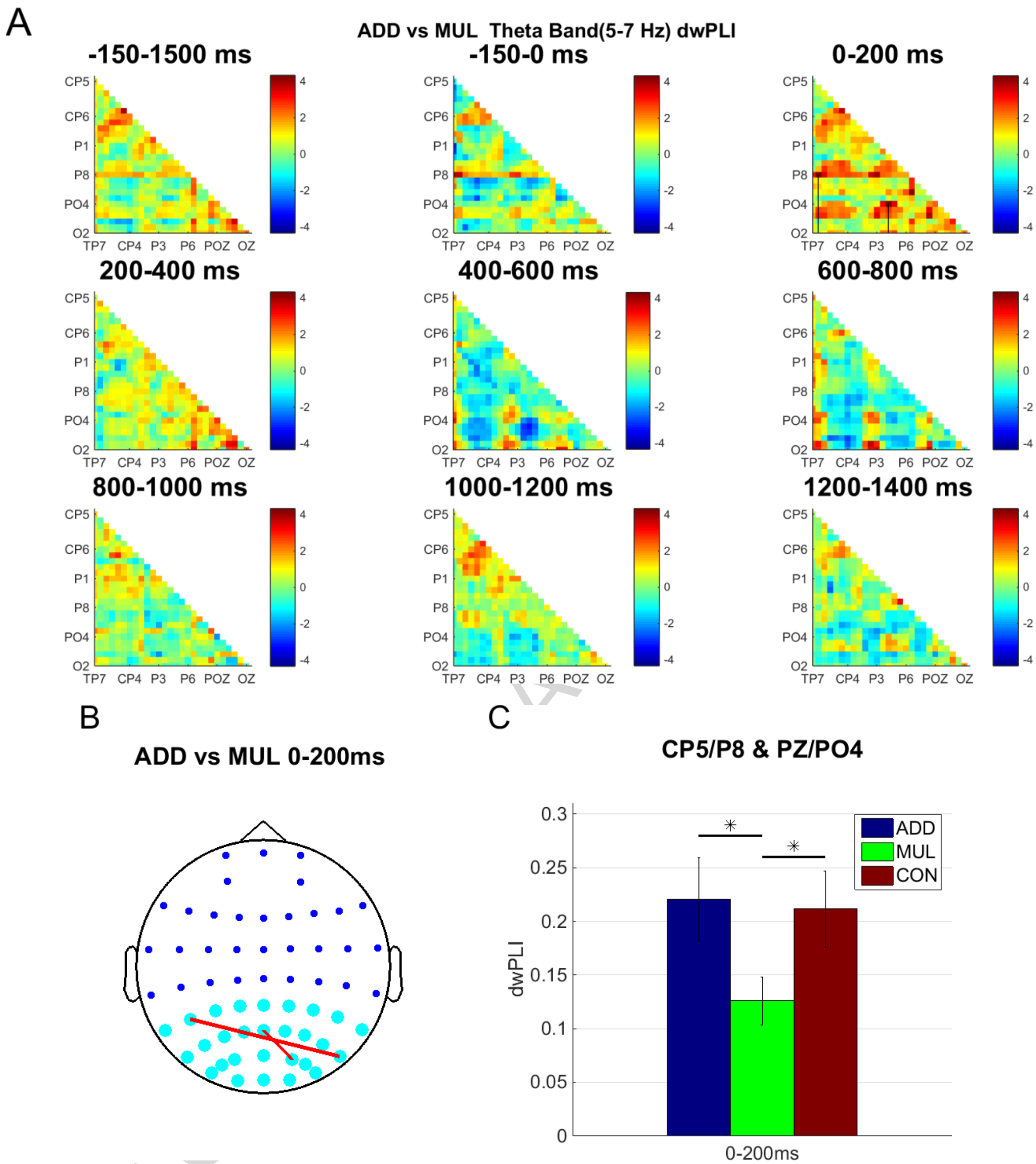



**Fig. 8.** In the regions of interest (marked by cyan points in B), comparison of debiased weighted phase lag index (dwPLI) of theta frequency band (5-7 Hz) between single-digit addition and multiplication through permutation test using 9 time windows: the whole length of the time interval of interest (i.e., -150 – 1500 ms), a 150 ms time window during which the operator presents (i.e., -150 – 0 ms relative to the onset of the operands) and seven consecutive non-overlapping 200 ms time windows spanning 0 to 1400 ms relative to the onset of the operands. (A) Plot of t-value for testing the difference in dwPLI of theta frequency band (5-7 Hz) between single-digit addition and multiplication during the 9 time windows, in which the upper end of each vertical line indicates electrode pair showing significant difference between the two types of arithmetic operations (corrected p = 0.04 and 0.038, respectively). (B) In the regions of interest, the electrode pairs (marked by red line) CP5/P8 and PZ/PO4 showed significant difference between single-digit addition (ADD) and multiplication (MUL) during 0 – 200 ms. (C) Bars per condition (i.e., addition, multiplication and control (CON)) for dwPLI averaged over electrode pairs marked in B. Error bars indicate SEM for normalized data.

$p$ = 0.001). Post hoc comparisons showed that theta phase synchrony for multiplication was smaller than those for single-digit addition ($p$ = 0) and control ($p$ = 0.01), but no difference can be observed between addition and control tasks (p = 1). Besides, there was no significant effect of arithmetic type on phase synchrony observed for both the lower and upper alpha frequency bands (Fig. S7 and S9).

## 4. Discussion

The present study investigated the differential neural responses and brain functional networks recruited in single-digit addition and multiplication through analyzing EEG oscillations in theta, lower and upper alpha frequency bands. As a result, our study revealed disassociated brain responses and interregional connections between the two arithmetic operations. Single-digit addition induced larger theta power increase over the midline and the right hemisphere compared to multiplication during the early intervals, whereas single-digit multiplication induced larger lower alpha phase locking in the postcentral regions and the left fronto-central and anterior areas compared to single-digit addition during the early intervals. Besides, single-digit addition implicates stronger theta phase synchrony in the parieto-occipital regions compared to multiplication during operands encoding.

### *4.1. Theta power increase suggests stronger visuo-spatial processing in single-digit addition*

The effect of arithmetic type on theta power increase was first observed over the midline and the right frontal and central areas during both operator and operands presentation intervals, with larger theta power increase elicited by single-digit addition.

Despite significant difference between addition and multiplication was observed for theta power analysis using the whole length of trials, the effect is attributed to the operation effect in the early stage since no operation effect was observed during the intervals later than 200 – 400ms. The phasic power increase in theta band following target onset is interpreted to reflect encoding of the target information (Bastiaansen et al., 2002). Especially, briskly started increase in theta power over frontal and central regions has been proved to primarily reflect the activation of neural networks involved in an attentional system, with enhanced theta response for tasks requiring more attention resources (Deiber et al., 2007; Missonnier et al., 2006). Furthermore, the previous research using repetitive Transcranial Magnetic Stimulation has suggested that the right frontal areas are involved in covert attentional orienting to the use of a spatial representation of numbers when it is relevant to the numerical processing task (Rusconi et al., 2011). Combined with the fact that single-digit addition places stronger reliance on the spatial presentation of numbers, i.e., visuo-spatial Arabic code, which is actually an image of the Arabic digit positioned on a mental number line (Zhou, 2011), the findings suggest that stronger attention, especially visuo-spatial attention, is required for single-digit addition compared to multiplication. The effect of arithmetic type reached statistical significance even before the presentation of operands, i.e., during the presentation of an operator, suggesting the initiation of task-related brain networks by preview of the operator. Then in the 200-400 ms time window, the differential oscillatory network was extended to the right parietal and the right occipito-temporal areas, which were suggested to be involved in visual mental imagery and visuo-spatial working memory (Linden et al., 2003; Postle et al., 2004; Zurowski et al., 2002). This finding implies the recruitment of visual-spatial sketch pad to maintain the operands in the working memory after operands disappeared, which is consistent with the previous studies suggesting the maintenance of visuo-spatial information in mind during addition (Hubber et al., 2014). Since the observed effect of arithmetic type on theta oscillatory activity was restricted to the early stage of mental arithmetic, it was assumed to be attributed to the encoding difference between the two arithmetic operations rather than calculation-related processes. This interpretation was supported by further exploration taking control task into consideration. First, no significant task type effect (arithmetic vs. control) on theta power was observed during the early time intervals (-150 – 400 ms) (Fig. S10), during which significant difference of theta power was observed between addition and multiplication. Therefore, the operation effect on theta power at an early stage could probably be caused by general functions in numerical processing such as encoding rather than calculation. Second, in the regions within which difference between addition and multiplication was most pronounced, control task significantly differed from multiplication but not from addition. In summary, the findings of stronger induced theta power over the midline and the right hemisphere during single-digit addition compared to multiplication in the early stage are consistent with previous research suggesting that more visuo-spatial processing is implicated in encoding of the operands during single-digit addition (Zhou, 2011). Moreover, our findings extend the previous observations, by suggesting that, with a preview of the operator, the neural network related with visuo-spatial attention is already primed before the presentation of the operands and demonstrating the role of theta oscillatory activity in the early cognitive stages.

### 4.2. *Alpha lateralization reflects stronger attention to knowledge system in single-digit multiplication*

The effect of arithmetic type was also found in the phase-locking oscillations of lower alpha band. In contrast to addition, multiplication induced larger lower alpha phase locking across trials, which was evident in the centro-parietal regions during operator presentation and was extended to the left fronto-central and anterior areas during operands presentation. It is suggested that the lower alpha band activity reflects unspecific processing demands such as attention (Klimesch et al., 1997a). Additionally, previous research has shown that alpha oscillations control early categorization of stimulus encoding through a phase response of alpha oscillations at around 100 ms to enable precisely timed cortical activity in task relevant neuronal structures (Freunberger et al., 2009; Klimesch, 2012; Klimesch et al., 2011). On the other hand, previous research has suggested that the centro-parietal areas are involved in the semantic priming tasks (Sachs et al., 2008). Furthermore, the left-hemispheric fronto-central and anterior activation is believed to reflect implicit lexical access (Sass et al., 2009) and verbal processing (Zhou, 2011). Therefore, the stronger phase-locked lower alpha activity for multiplication reflects higher “semantic orientation” to access information (e.g., phonological information) used for operands encoding. The interpretation is consistent with the common belief that, for single-digit multiplication, the verbal code is the obligatory entry code for accessing stored tables of multiplication arithmetic facts (Zhou, 2011; Zhou et al., 2006). Since the phase-locked alpha activity in the early stage reflects the access to memory system rather than the processes operating within the memory system (e.g., retrieval) (Klimesch, 2012), it is proposed to reflect a specific type of attention that is related to knowledge system. Further exploration taking control task into consideration found that multiplication recruited the language-related neural networks to a larger extent than both addition and control tasks, suggesting that attention to knowledge access plays a more important role in multiplication. In contrary to our results, a recent study exploring change of evoked EEG frequencies induced by learning divisibility rules found activation in frontal and centro-parietal scalp areas of the right hemisphere, but no evidence of activation of left fronto-central and anterior regions (Skrandies and Klein, 2014). However, the inconsistency between the two studies was in good accord with Dehaenes' view (Dehaene, 1992). According to his triple-code model, retrieval of multiplication tables are executed via verbal code whereas multi-digit calculation are performed using the Arabic code. Since the study used more complex mathematical tasks (4-digit division), probably resulting in stronger recruitment of the Arabic code rather than verbal code. Our results on theta power change provided support for the interpretation by demonstrating similar activation profile (frontal and centro-parietal scalp areas of the right hemisphere) in response to single-digit addition, which is believed to be performed using the Arabic code (Zhou, 2011).

Compared to phase-locked lower alpha responses, there was no significant effect of arithmetic type observed in upper alpha desynchronization, which reached maximum during 200-600 ms, for both arithmetic operations (Fig. 3). It is suggested that event-related power shifts in the upper alpha band are specifically related to semantic memory processes (Klimesch et al., 1997a). Additionally, the time period of maximum upper alpha desynchronization is believed to reflect retrieval of semantic information (Klimesch, 2011, 2012; Klimesch et al., 2011). If the hypothesis holds true, it is reasonable to assume that greater demands on semantic retrieval are required for arithmetic compared to control condition. Comparison of upper alpha desynchronization between arithmetic (both addition and multiplication) and control supported the notion by demonstrating a significant effect of task type (arithmetic vs. control) during 200 - 400 ms interval. For the 200- 400 ms interval, arithmetic task elicited greater upper alpha power decrease than control condition, in the left parieto-occipital sites (Fig. S11). The upper alpha power decrease, which has a left hemispheric advantage and is most pronounced over parieto-occipital sites, has been suggested to be related with semantic memory demands (Klimesch, 1997; Klimesch et al., 1997b). The results provided support for the notion that the time period of maximum upper alpha desynchronization reflects retrieval of semantic information. Despite a significant effect of task type on upper alpha band was also observed during the 1200- 1400 ms interval, it was caused by stronger upper alpha synchronization rather than desynchronization in control condition. Thus, it is assumed to reflect stronger inhibitory control processes rather than memory retrieval in control condition. In sum, the lack of the effect of arithmetic type on upper alpha desynchronization does not favor different strategies involved in the two arithmetic operations. As a result, encoding difference (visuo-spatial Arabic code vs. verbal code) between the two arithmetic operations is seemingly contradictory to the assumption that both operations are solved by direct retrieval. As a matter of fact, the results are consistent with the network interference model on storage and retrieval of arithmetic facts (Campbell, 1995), suggesting that digits could be represented as verbal, visual Arabic or magnitude format in the association network. Besides, previous research found differential codes for the representation of arithmetic facts (Zhou, 2011). Therefore, encoding difference does not necessarily indicate differential strategies involved in the solution, but implies the different codes for representation of arithmetic facts in the two arithmetic operations due to the early learning experience in the childhood (learning by procedural strategies vs. learning by rote) (Zhou, 2011; Zhou et al., 2007a). Alternatively, the lack of difference in later stages could be due to the fact that only a fraction of addition problems are solved by procedural strategies while most simple addition problems are solved by direct retrieval. Future research could make further exploration through grouping addition problems based on the verbal report of the solution strategies. In summary, our results are in agreement with stronger verbal processing involved in single-digit multiplication, but further demonstrated the role of phase-locked lower alpha response in the early encoding stage of mental arithmetic. In addition, with a preview of the operator, our study suggests that the neural network related with attention to knowledge access is initialized before the presentation of the operands.

### *4.3. Theta phase synchrony in the parieto-occipital regions suggests stronger involvement of spatial representation for numbers in single-digit addition*

If procedural strategies, which involve manipulation on the numerical information, are involved in addition, it is reasonable to assume that greater demands on executive function are required for addition compared to multiplication that are often solved by direct memory retrieval. However, in the current study, no significant effect of arithmetic type was observed on the fronto-parietal theta network, which underlies executive function of the working memory (Cooper et al., 2015; Griesmayr et al., 2014; Hanslmayr et al., 2008; Moeller et al., 2015). The result is not in support of the hypothesis that procedural strategies are implicated in single-digit addition. The interpretation, i.e., both arithmetic operations are solved by the retrieval of arithmetic facts, is consistent with our previous results on upper alpha power change as well as previous research investigating operator priming effect in single-digit addition and multiplication (Chen and Campbell, 2015, 2016).

When the regions of interest were restricted to the parietal and occipital regions, we observed enhanced phase synchrony in the 5-7 Hz theta band between the intra-parietal areas and the right occipital areas during the operands presentation for single-digit addition in comparison with multiplication. In previous studies, inter-regional phase synchronization of theta oscillations has been suggested to reflect integration of different neural circuits during information encoding (Gorisek et al., 2015; Klimesch, 1996; Sauseng et al., 2010; Sauseng et al., 2004). Parietal cortex plays an important role in spatial representation of number magnitude (Dehaene et al., 2003; Eger et al., 2003; Gobel et al., 2001). In addition, identifying Arabic numerals is related with the activation of the right visual areas, e.g., the fusiform gyrus (Pinel et al., 2001; Zarnhofer et al., 2012). Therefore, in the present study, the increased functional connectivity between the intra-parietal areas and right visual areas for single-digit addition reflects higher demands for binding numerical symbols with their corresponding position on mental number line, thereby transcoding the visual stimuli into the visuo-spaital Arabic code (Dehaene, 2009). Further exploration taking control task into consideration supports that the phase synchrony reflects encoding difference rather than actual computation.

In summary, the differential brain networks observed in single-digit addition and multiplication in this study are restricted to the early stage of the solution of the arithmetic problems, probably relating to the encoding difference between the two arithmetic operations. The interpretation is broadly consistent with the assumption that a preview of the operator might simply help to facilitate operation-specific encoding of the operands (Campbell and Arbuthnott, 2010; Chen and Campbell, 2015). One limitation is that although the results indicated that a preview of the operator primed differential brain networks in single-digit addition and multiplication, the relation between the recruitment of brain networks and the behavioral performance of arithmetic operation improved by the operator preview (e.g., reduction in reaction time) is unknown.

## 5. Conclusion

To explore the differential recruitment of brain networks in single-digit addition and multiplication, this study investigated dissociated patterns of oscillatory activity between the two arithmetic operations using EEG oscillations in theta, lower and upper alpha frequency bands. With respect to theta oscillations, the experimental results in this study have extended the previous research, by suggesting that in single-digit addition higher theta amplitude at midline and right frontal and central areas is due to the stronger attentional orientation to use of spatial representation of number magnitude. Besides, phase synchrony in theta frequency band suggests stronger functional connectivity between the parietal and right occipital regions for the encoding of addends, which supports the stronger recruitment of spatial representation for operands in addition. By contrast, inter-trial phase coherence in lower alpha band reflects stronger phase locking for single-digit multiplication in the centro-parietal regions and the left fronto-central and anterior areas, suggesting stronger attention to knowledge system for multiplication compared with addition. Furthermore, with a preview of the operator, differential brain networks recruited in the two arithmetic operations were initialized even before the presentation of the operands. From an educational perspective, investigating how different networks (language vs. visuo-spatial) are involved in different arithmetic operations is very useful to understand cognitive processes involved in participants performing arithmetic operations, thus providing profound implications for the pedagogy of arithmetic.

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Highlights:

- Single-digit addition induced higher theta amplitude compared to multiplication over midline and certain regions of the right hemisphere during the early processing stages of a delayed verification task.
- Stronger theta-band phase synchronizations in the parieto-occipital regions were involved in addition compared to multiplication during the encoding of operands.
- Stronger lower alpha-band inter-trial phase coherence was found in multiplication compared to addition in the centro-parietal regions and the left fronto-central and anterior regions during the early processing stages.
- Significantly differential brain networks recruited in the two arithmetic operations were initialized by the preview of the operators.