Executive inhibition in mental arithmetic*

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Abstract Event-related potentials (ERPs) were measured to investigate the executive inhibitory processes in mental arithmetic. Subjects had to compute arithmetic expressions visually presented in four chunks. ERP analyses were conducted for the second chunk comparing the "NoCalculate" to the "Calculate" conditions. In the Calculate condition subjects could compute intermediate results. In the NoCalculate condition subjects had to withhold the computation. The results showed a negative effect (N380) over frontocentral regions at about 380 ms, probably reflecting the calculation inhibition demand in the NoCalculate condition. In addition, the dN380 (NoCalculate-Calculate difference) was more pronounced in the right hemisphere, which is consistent with the findings of previous fMRI and PET studies that the right prefrontal cortex is closely associated with response inhibition. The results support the generalization of the frontocentral N2 as a neurobehavioral tool for investigating inhibitory executive control.

Keywords: event-related potentials, mental arithmetic, executive inhibition.

In a series of studies focused on inhibitory executive control, a frontocentral N2 was suggested as an ERP correlate reflecting response inhibition. For instance, in the Go/NoGo tasks, subjects are required to respond to certain stimuli (Go stimuli) but to withhold their responses to other stimuli (NoGo stimuli). It has been repeatedly reported that ERPs elicited by NoGo trials compared to those by Go trials produce a frontocentral negative component peaking around 200—400 ms (called as NoGo-N2)[1—5]. Kopp et al.[6,7] suggested the frontocentral N2 as a neurobehavioral tool for investigating inhibitory executive control. Moreover, it has been proved that the NoGo-N2 can be elicited by inhibition of overt motor response as well as control of covert response such as silent counting of target stimuli[1,8]. However, previous studies concerning response inhibition were mainly restricted to Go/NoGo tasks, flanker tasks and Stroop tasks, a question is raised that whether the modulation of the frontocentral N2 amplitude is present in other cases of response competition as well.

The present study used a mental arithmetic task to extend the understanding of the frontocentral N2. Arithmetic expressions were visually presented chunk by chunk (each chunk comprised a number followed by an operator), subjects were required to calculate the expression silently and then select the correct solution from the two options. The analyses were focused on the second stimulus chunk of each expression. In the Calculate condition, e.g., $9-2+3-1=$, the arithmetic expressions contained only addition and subtraction which had identical priority, therefore at the second stimulus chunk subjects could calculate the first operation. While in the NoCalculate condition, e.g., $9-2\times3+1=$, the operator of the second stimulus chunk was a multiplication mark meaning the second operation had higher priority than the first one, so that subjects had to hold the first two chunks in mind and cannot calculate the first operation until the third stimulus chunk. We predicted that a frontocentral N2 effect would occur in the NoCalculate condition compared to the Calculate condition, reflecting the executive inhibition of calculations during processing the NoCalculate expressions.

1 Method

1.1 Participants

Data of 17 right-handed subjects (nine males) were analyzed (mean age: 27.8 years, range: 24.2—30.9 years). All were native speakers of German and had normal or corrected-to-normal vision. They were paid for their participation (Totally 25

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subjects were recruited. After the experiment, they were divided into two groups according to behavioral performance. Only the high performance group whose mean accuracies of the 8 blocks were all above 75% was included in the ERP analyses).

1.2 Material and procedure

Examples of the arithmetic expressions are presented in Table 1. Of the 320 (80 for each condition1)) arithmetic sequences were created in line with the following rules: (1) Natural numbers 1—9 were pseudorandomly distributed in all expressions. All four numbers in a single expression were different from each other. (2) For all stimulus chunks, the frequencies of "+" and "−" were equal, as well as the frequencies of "×" and "/". The Calculate condition never contained more than two "+" or "−". (3) 1 and 0 never served as operands in multiplications and divisions. (4) The quotients were natural numbers. (5) Intermediate and final results in all conditions were within −50 and 50. They could be identical to the previous numbers in the same expression; 0 was excluded for intermediate results. (6) The expressions had at least two possibilities being continued at each of the first three chunks so that subjects cannot predict the upcoming stimulus chunk.

Table 1. Examples of the two conditions and fillers

	I	II	III	IV
Calculate	9 −	2 +	3 −	4 =
NoCalculate	9 −	2 ×	3 +	4 =
Filler	9 −	2 × (	3 +	4) =
	9 ×	2 +	3 −	4 =

I, II, III, IV: the four stimulus chunks in one expression

The experiment and the recordings were performed in a sound-attenuated, electrically-shielded, dimly lit room. Participants were seated in a comfortable chair located 80 cm in front of the computer screen. Participants were required to mentally calculate the arithmetic, and select the correct result from the two proposed solutions presented at the end of each trial by pressing the corresponding button of the response box, i.e., press the left button if the option in the left half of the screen is the correct answer, and press the right button if the option presented in the right half of the screen is the correct answer. The correct solution was presented equally frequent in both halves of the screen. The incorrect options deviated by ± 1 or ± 2 from the correct solutions. Before the experiment started, participants passed 40 randomly chosen practice trials (ten trials for each condition) to get familiar with the task.

The presentation procedure of one trial is displayed in Fig. 1. The four stimulus chunks of each arithmetic expression were visually presented at the center of a 17-in. screen in sequence. The size of the stimuli had the visual angle of 2.0° (horizontal) × 1.5° (vertical). The sequence of events began with a fixation cross presented at the center of the screen for 500 ms. Then, the first stimulus was presented for 2 seconds, followed by the other three stimuli presented with the same duration. Finally, two numbers appeared which corresponded to the two possible solutions to the problem lasting for 4 seconds. Subjects were required to select the correct answer within that time. The inter-trial interval (ITI) was 2 seconds. Expressions of all types were randomized and presented in eight blocks. Each block lasted for about 8 minutes, and subjects took a break between blocks.

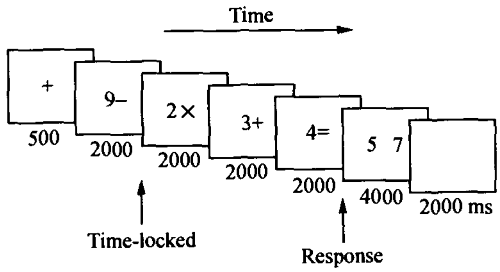

Fig. 1. The presentation procedure of one trial in the NoCalculate condition. The ERPs were time-locked to the second stimulus chunks of the expressions. Subjects' task was to choose a correct solution from the two options by pressing the corresponding left or right button.

1.3 ERP recording

The electroencephalogram (EEG) was recorded from 64 scalp sites using Ag/AgCl electrodes mounted in an elastic cap, with the reference at the nasion. The vertical electrooculogram (EOGV) was recorded with bipolar electrodes placed above and below the left eye. The horizontal electrooculogram (EOGH) was recorded from the outer canthi. All electrode impedances were maintained below 5 kΩ. The EEG and EOG were amplified using a DC to 80 Hz bandpass filter and continuously sampled at 250 Hz/channel for off-line analysis.

1)The filler contained two conditions. Originally the experiment was designed in a broader framework, while discussions about the other two conditions were beyond the current topic, we took them as fillers here.

1.4 Data analysis

Trials with EOG artifacts (standard deviation within a sliding window of 200 ms exceeding 50 μV) were excluded from averaging. The EEG and EOG were digitally filtered off-line with a 0.5—20 Hz bandpass filter. Only trials with correct responses were analyzed. ERPs were time-locked to the onset of the second stimulus chunk in each expression, and were epoched from −200 ms before the stimulus to 1000 ms post-onset and put to the −200 ms prestimulus baseline. ERPs of the two conditions were averaged separately. Only trials with "×" mark in the NoCalculate condition were averaged because a number of participants reported they were not used to the "/" sign representing the division mark and the results showed trials with "/" signs elicited different ERP effects from trials with "×" signs. Thus the maximum number of the trials averaged for the Calculate and NoCalculate conditions were 80 and 40 respectively, and the actual mean accepted trial numbers were 70 and 35 respectively.

Electrodes on which the ERP effects were most salient from visual inspection were selected for further analyses. For the early negative component peaking at about 290 ms (N290), peak-to-peak amplitude (from the preceding positive peak to the negative peak) and peak latency (the negative peak) were measured during 180—350 ms over the four anterior midline electrodes Afz, Fz, FCz, Cz. However, peak-to-peak amplitude measurement was not suitable for the late negative component peaking at about 380 ms (N380) because it only presented in the NoCalculate condition. Thus, mean amplitude during 350—450 ms was measured over the four anterior midline electrodes Afz, Fz, FCz, Cz. In order to test the potential hemisphere effect of the N380, mean amplitude during 350—450 ms was also measured over the ten anterior lateralized electrodes F3, F4, F5, F6, FC3, FC4, FC5, FC6, FT7, FT8. Mean amplitude of the late positive component (LPC) was measured over the five posterior midline electrodes Cz, CPz, Pz, POz, Oz in the time interval of 400—600 ms. The P value was corrected by Greenhouse Geisser method for violations in sphericity and Bonferroni method for multiple comparisons.

2 Results

Inspection of the grand averages and difference wave (NoCalculate-Calculate) (Fig. 2) and topographic maps (Fig. 3) showed a small frontocentral

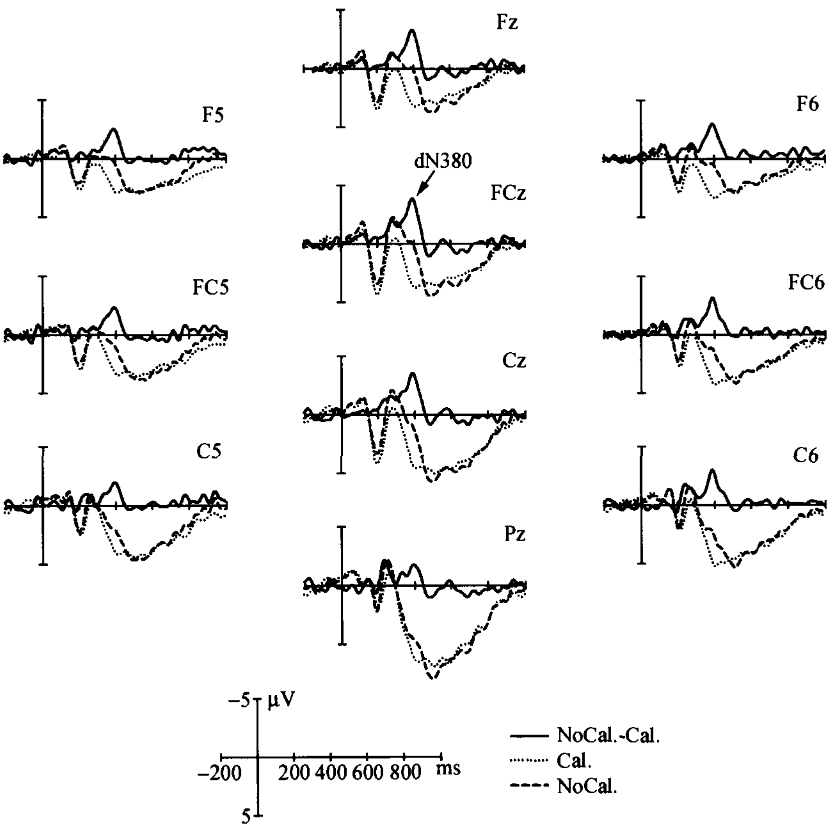

Fig. 2. Grand averaged ERPs for the two conditions and the difference wave (NoCalculate minus Calculate).

positive deflection at about 200 ms followed by a negative deflection at about 290 ms (N290) over frontocentral and bilateral temporal scalp regions was elicited by the NoCalculate condition compared to the Calculate condition within the time range of 180 ms and 350 ms. After that, a second negative deflection (N380) was presented for the same comparison during 350—450 ms over frontocentral scalp regions. Finally, a late positive component (LPC) was elicited in both conditions during 450—600 ms over parietal regions.

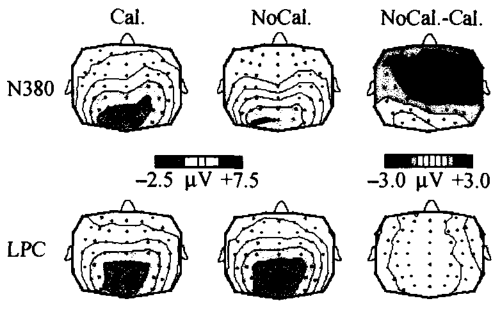

Fig. 3. Scalp topographies for the Calculate (left panel) and NoCalculate (middle panel) conditions and difference wave of NoCalculate minus Calculate (right panel) in the time ranges corresponding to the N380 (350—450 ms) and LPC components (450—600 ms).

2.1 N290 and N380

For the N290 (180—350 ms), an ANOVA of condition × electrode (Afz, Fz, FCz, Cz) was performed on the peak-to-peak amplitude and the peak latency respectively. Neither the main effect of condition nor the interaction effect of condition × electrode was significance ($p > 0.05$). It meant that the amplitude and latency of the N290 did not reliably differ between the two conditions.

For the N380 (350—450 ms), an ANOVA of condition × electrode (Afz, Fz, FCz, Cz) was conducted on the mean amplitude. The mean amplitude in the NoCalculate condition was more negative than in the Calculate condition (0.87 ± 0.59 vs. 3.09 ± 0.67 μV; $F(1,16) = 9.06$, $p < 0.05$). The N380 amplitude difference between the two conditions varied across the four electrodes (interaction condition × electrode: $F(3,48) = 3.61$, $p < 0.05$). The difference was maximal at FCZ (-2.57 μV). Both the N380 in the NoCalculate condition and the dN380 (the NoCalculate minus Calculate difference) were frontocentrally distributed except that the latter was somehow inclined to the right hemisphere (Fig. 3).

In order to test the potential hemisphere effect, another ANOVA of condition × hemisphere (left vs. right) × electrode (F3/4, F5/6, FC3/4, FC5/6, FT7/8) was conducted. The right hemisphere prepotency of the dN380 scalp distribution was supported by the significant interaction effect of condition × hemisphere ($F(1,16) = 7.25$, $p < 0.05$).

2.2 Late positive component (LPC)

An ANOVA of condition × electrodes (Cz, CPz, Pz, POz, Oz) was performed on the mean amplitude during 450—600 ms. Neither the LPC amplitude ($F(1,16) < 1$) nor its scalp distributions ($F(4,64) = 1.54$, $p > 0.05$) differed between the conditions. Topographic maps (Fig. 3) showed that the LPC is maximal over parietal areas for both conditions.

3 Discussion

Consistent with our expectation, a frontocentral negativity, N380 was elicited by the NoCalculate condition compared to the Calculate condition. It has been repeatedly reported that when comparing ERPs of NoGo trials and Go trials, a frontocentral negative wave is observed peaking around 200—400 ms (NoGo-N2), which has been suggested to reflect inhibition-related processes[5,9,10]. The mental arithmetic task is different from traditional tasks involving inhibitory control processes (e.g., the Go/NoGo task, the flanker task and the Stroop task). However, if priority means priority given to execute process A over process B then it is likely to induce response inhibition processing. We therefore think the N380 is comparable to the NoGo-N2 effect, corresponding to the general neurobehavioral mark of executive inhibition.

On the other hand, the N380 in our study is also similar to some other components. The first candidate is N270. It is a frontocentral negativity and was suggested to be associated with physical feature discrimination[11,12]. It seems possible that the enlarged N380 in the NoCalculate condition can be attributed to the "×" mark, which had different physical features from the more frequently presented "+" or "−" marks. However, the negativity in the present study peaked about 380 ms. Compared with N270, the latency of the N380 is relatively late. It is more likely that the N290 elicited in both conditions of our study is more alike the N270. The second alternative is N400. It was elicited in response to the processing of semantic incongruous words[13]. Despite the similar latencies, the N380 elicited in the NoCalculate condition can be differentiated from the classical N400 in two aspects. Firstly, a semantic violation or incongruence associated with the N400 was involved in neither condition of the present study. Secondly, the N400 usually shows a central or centroparietal distribution; in contrast, the N380 has a frontocentral distribution. Thus we think the N380 represents different processes from that of the N400.

The NoGo-N2 is suggested to be sensitive to the probability of the relevant conditions[5,8]. Whereas, with respect to the response type probability in our study, trials which can be calculated at the second chunk (Calculate condition and half fillers) and trials which cannot be calculate at the second chunk (NoCalculate condition and the other half fillers) had equal probability. Our results are in accord with the previous findings that the NoGo-N2 can be elicited in the equiprobable condition trials[1,14], and support the notion that the frequency of event type is not critical to the inhibition-related N2 per se[1].

A lot of evidences from functional magnetic resonance imaging (fMRI) and positron emission tomography (PET) have suggested that the right prefrontal cortex (PFC) is closely associated with response inhibition[15—19]. Our finding that the dN380 was more pronounced in the right hemisphere is consistent with these literatures. Due to the relatively low spatial resolution of the ERP technique, further research is needed to explore the exact localizations of the N380 in our arithmetic task.

The observed LPC cannot be unambiguously defined in its function. Some studies using Go/NoGo tasks have found that NoGo-P3 has a larger amplitude, later latency and more anterior scalp distribution compared to Go-P3[1,3,20,21]. Different from these results, the LPC elicited by the two conditions in our study did not differ in amplitude and topography. This is in agreement with Lavric et al.[22] who observed no P300 effect for matched frequency of Go and NoGo events. On the other hand, even though the LPC in the Calculate and the NoCalculate conditions shared some attributes, they do not necessarily depend on the same activation of brain systems. In the present study, calculations were only conducted in the Calculate condition. The LPC, however, was elicited in both conditions, suggesting that it may reflect different cognitive processing in the two conditions. Further research is needed to investigate what exact processes are underlying the LPC components in the present task.

4 Conclusion

To sum up, our arithmetic task contained two conditions which differed in the way whether the first operation could be calculated at the presentation of the second stimulus chunk. A frontocentral negativity was elicited by the NoCalculate condition compared to the Calculate condition at about 380 ms (N380). The N380 is distinguished from the N270 associated with physical feature discriminations and the N400 related to semantic violations. The N380 is very likely due to the calculation inhibition demand in the NoCalculate condition. The topography of the difference component dN380 was more pronounced in the right frontocentral areas. This is consistent with the findings of previous fMRI and PET studies that the right prefrontal cortex is closely associated with response inhibition. It demonstrates for the first time that calculation inhibition can be observed in the processing of complex arithmetic expressions. The frontocentral N2 can be evoked by various tasks recruiting inhibitory control, from simple motor response tasks to high demanding cognitive tasks. It can be used as a general neurobehavioral index of inhibitory executive functions.

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