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RESEARCH ARTICLE

The neural basis of breaking mental set: an event-related potential study

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Abstract Event-related brain potentials (ERPs) were recorded to explore the electrophysiological correlates of breaking mental set when subjects performed the Chinese character-generation task. A new experimental paradigm (learning–testing model) was adopted in order to make subjects find a solution actively by using a fixed way (Rep: repetition) or a new method (BMS: breaking mental set). Results showed that BMS elicited a more positive ERP deflection (P500-700) than did Rep between 500 and 700 ms after onset of the test stimuli. The P500-700 was possibly involved in the successful breaking of mental set and the initial forming of new associations during problem solving. Furthermore, BMS also elicited a more positive ERP deflection (P900-1300) than did Rep between 900 and 1,300 ms. The P900-1300 might reflect searching and generating a new character after breaking mental set.

Keywords Mental set · Problem solving · ERPs (event-related potentials)

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Introduction

Gestalt psychologists thought that insight problem solving was a process of reconstructing the whole situation as an "Aha" experience. The occurrence of an "Aha" experience means rethinking some basic assumptions about the problem content, which is thought to happen in a relatively sudden and unpredictable manner (Köhler 1925; Scheerer 1963). During the last century, cognitive psychologists have studied the processes involved in insight—with respect to problem solving skills—on human and animal subjects (e.g., Kaplan and Simon 1990; Köhler 1925; Scheerer 1963; MacGregor et al. 2001). However, the cognitive mechanisms underlying the occurrence of insight remain unknown, and there are different theories that attempt to explain it. For instance, Kaplan and Simon (1990) pointed out that an element of representation change was involved in insight problem solving (the Representation Change Theory). Another approach, the Progress Monitoring theory (MacGregor et al. 2001; Ormerod et al. 2002), attempted to explain insight into a framework based on means-ends analysis heuristics.

Of greater importance and interest, these different theories both pointed out a similar, key cognitive process—breaking mental set—during insight problem solving. For example, Knoblich et al. (1999, 2001) proposed that two cognitive processes underlie the process of representation change: constraint relaxation (breaking mental set) and chunk decomposition (i.e., the separation of the components of a perceptual chunk). Similarly, Chronicle and Ormerod (2001) proposed two influential factors in insight problem solving, including (a) various kinds of constraints and (b) the dynamic in how individuals attempt to seek alternative solutions (relaxation of constraints). As Ölinger et al. (2008) also said, "Mental set is the tendency to solve certain problems in a fixed way based on previous solutions to similar problems. The moment of insight occurs when a problem cannot be solved using solution methods suggested by prior experience and the problem solver suddenly realizes that the solution requires different solution methods." In other words, breaking mental set requires reconstruction.

Brain imaging techniques such as functional magnetic resonance imaging (fMRI) and positron emission tomography (PET) have made it possible to record precisely the brain activity associated with insight problem solving. For example, Luo and colleagues recorded neural activity using fMRI and correlated this activity with cognitive insight by providing a trigger (the solution) to catalyze insightful riddle-solving processes (Luo and Niki 2003; Luo et al. 2004). Results showed that insight riddle solving was associated with activity primarily in the anterior cingulate cortex (ACC) and the prefrontal cortex (PFC). In a series of studies using the compound remote associates problem (CRA, e.g., boot, summer, ground; solutions: camp), fMRI results revealed an increased signal in the right anterior superior temporal gyrus for insight but not noninsight solutions (Bowden et al. 2005; Jung-Beeman et al. 2004). Luo and Knoblich (2007) indicated that the two experimental approaches seem promising in the laboratory at the present stage, because both approaches should elicit restructuring (breaking mental set), generate multiple insight events, and provide accurate onset times, which are required for laboratory fMRI and ERPs researches.

Moreover, some research has also applied the study of event-related potentials (ERPs) to examine the electrophysiological correlates of riddle solving when the answers were provided (Mai et al. 2004; Qiu et al. 2006). For example, using the solution as a trigger, Mai et al. (2004) found that the ERP difference wave (Aha minus No-aha answer) showed the maximum amplitude over the central site with a peak latency period of 380 ms (N380). The dipole analysis localized the N380 generator to the ACC. Thus, they proposed that the N380 likely reflected an "Aha" effect, and that it may be involved in the breaking of mental set. Qiu et al. (2008) also investigated the electrophysiological correlates of successful insight problem solving (Chinese logographs) using ERPs. Their results showed that "successfully guessed" logographs elicited a more positive ERP deflection (P200-600) and a more negative ERP deflection (N1500-2000, N2000-2500) than did "unsuccessful" logographs. Together with dipole analysis, they proposed that the P200-600 might be involved in forming rich associations in the early stage of successful logograph solving, and the N1500-2000 might play an important role in the breaking of mental set and the forming of novel associations. In Wang et al. (2009), the same group of authors used a different reference condition (routine problem solving) to explore the neural basis of successful Chinese logograph solving. However, their findings were not similar to the previous work (Qiu et al. 2008). They found that insight problems elicited more negative ERP deflections (N300-800 and N1200-1500) over fronto-central scalp regions and more positive ERP deflections (P300-800 and P1200-1500) over parieto-occipital scalp regions than did routine problems. Furthermore, Lang et al. (2006) found several early ERP precursors of insightful behavior; these ERP components were larger in solvers than in nonsolvers from the outset.

So, available research findings appear inconsistent, which might be due to the different materials (e.g., riddles and puzzles, the CRA), or different reference states (routine problem, unsuccessful insight problem solving, no-Aha experience) used in these previous studies. Luo and Knoblich (2007) concluded that there is no reason to believe that all kinds of insights will recruit exactly the same brain networks, and it is relatively difficult to come up with good reference states in studies of insight problem solving. They also said, "Insight requires a restructuring of the problem situation that is relatively rare and hard to elicit in the laboratory. One way of dealing with this problem is to catalyze such restructuring processes using solution hints." Given that restructuring is a key step in insight—which is rare and hard to elicit in the laboratory—why not explore the neural basis of insight problem solving through decomposing the complex cognitive process (e.g., breaking mental set, forming novel association, and Aha experience) using other paradigms to simplify these processes and make them easier to elicit?

To this end, in the present study, we adopted a relatively novel model that uses a learning–testing experimental paradigm to explore the brain mechanisms related to breaking mental set when subjects perform the Chinese character-generation task (see Qiu et al. 2007). The model is designed to make subjects generate a new character by using one method. The paradigm induces subjects to fixate on the method or strategy that had been used successfully during previous tests, but that no longer provides an effective solution to a second test (breaking mental set condition). As determined in previous studies (Ölinger et al. 2008; Luo and Knoblich 2007; Ash and Wiley 2006), three factors play a key role in breaking mental set: (1) the tendency to attempt to solve a problem in a fixed way, in other words, inappropriately representing the problem, (2) unsuccessfully attempting to solve a problem using methods suggested by prior experience, leading to impasse, and (3) realizing that the solution requires different methods (reconstructing). The three factors were present in our paradigm just as in other paradigms. Furthermore, we surmised that a related ERP index of attention and decision might be the P3 (P300) component. In general, P300 amplitude reflects the amount of attentional resources employed in a given task (Donchin and Coles 1988) and has been shown to provide information about differing amounts of mental effort required for character generation under the breaking of mental set condition (BMS) and the repetition condition (Rep). Based on previous studies (e.g., Luo and Niki 2003; Luo et al. 2004; Jung-Beeman et al. 2004; Bowden et al. 2005; Mai et al. 2004; Qiu et al. 2008; Wang et al. 2009), we hypothesized that it should be more difficult for subjects to generate a new character under BMS compared to Rep condition, and that this should be reflected in the ERP activation pattern. Specifically, breaking mental set effect should be related to a late positivity in BMS compared to Rep condition. By recording and analyzing high-density ERPs elicited by character generation under different conditions, ERP data should therefore allow for more precise examination of the time course of breaking mental set during problem solving.

Methods

Subjects

As paid volunteers, 13 adults (7 women, 6 men) aged 18–26 years (mean age, 21.9 years) from Southwest University in China participated in the experiment. The study was approved by the appropriate ethics committee and was carried out after informed consent obtained by the subjects. All subjects were right-handed, had no history of current or past neurological or psychiatric illness, and had normal or corrected-to-normal vision.

Stimuli

Stimuli were 180 familiar Chinese characters selected from The Contemporary Chinese Dictionary (see Qiu et al. 2007). Chinese characters are composed of strokes [e.g., horizontal (–) and vertical (|) strokes]. Thus, a new word can be formed by adding, subtracting, changing or shifting a stroke to a pre-existing Chinese character. Specifically, some characters could be transformed into another character by adding one stroke; for example, 问 can be changed into 间 by adding a stroke (e.g., adding the '—'). Some characters could be transformed into another character by subtracting one stroke; for example, 师 can be changed into 帅 by subtracting a stroke (e.g., subtracting the '—'). Some characters could be transformed into another character by changing one stroke; for example, 归 can be changed into 旧 by changing one stroke (e.g., changing the 'ノ'). Some characters could be transformed into another character by shifting one stroke; for example, 玉 can be changed into 主 by shifting one stroke (e.g., shifting the '丶'). All Chinese characters were composed of 3–10 strokes and were randomly displayed in the center of a 17-inch screen at a font size of 20, using the font face Song.

Procedure

There were two learning phases and two test phases in each trial. The solution in the first test phase was completely analogous to the solutions in the learning phases. The solution in the second test phase could be achieved either in the same way as in the first test phase (Rep condition) or by a variant, e.g., inserting a horizontal line rather than a vertical line (BMS condition). In detail, the sequence of events was as follows (see Fig. 1).

First, a fixation point appeared for 200 ms in the center of the screen and was followed by an example that displayed a Chinese character generation for 5,000 ms (first learning phase: e.g., 问–间, Method: adding a '—'). Participants were instructed to press the SPACE key with their left thumb if they understood the generation method as soon as possible. Next, another example using the same generation method was displayed again (second learning phase: e.g., 非–韭, Method: adding a '—'). After a 300–500 ms interval with an asterisk appearing in the center of the screen, a character, which could be transformed into another character easily with the previous generation method (e.g., adding a '—'), was presented for 5,000 ms (first testing phase: e.g., 冉–再, Method: adding a '—'). Participants were asked to generate another character and to press the '1' key with the right index finger if they could actually generate it. Then, a correct answer was displayed for 3,000 ms, and participants were asked to press the "1" key with the right index finger if their answer was the same as the character displayed on the screen or press the "2" key with the right middle finger if it was not

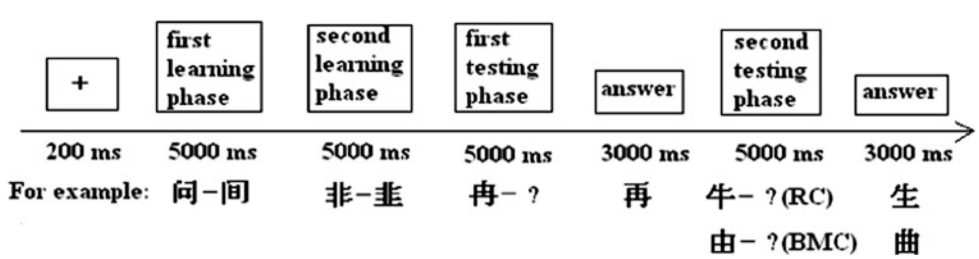


Fig. 1 The flow of learning–testing character-generation task in the repetition condition (Rep) and the breaking mental set condition (BMS)

the same. Once again, after a 300–500 ms interval with an asterisk, another character was presented for 5,000 ms (second testing phase). Participants were again asked to generate another character. Under the repetition condition (Rep), they could generate another character by using the previous generation method easily (e.g., 牛–生, Method: adding a '—'). In contrast, under the breaking of mental set condition (BMS), they had to use a different method to arrive at the answer; that is, the previous method was invalid (e.g., 由–曲, Method: adding a '|'). Again, a correct answer was displayed for 3,000 ms, and participants were asked to press the "1" key if their answer was the same as the character displayed on the screen or press the "2" key if it was not the same. The number keys were on the number pad, and the "1" and "2" keys were balanced across subjects. In our experiment, some examples were used twice in the learning phase. However, the characters appeared only once in the testing phase.

The whole test was divided into two parts. First, to familiarize the subjects with the procedure and pace of the task, they were trained with 10 items using the same procedure, before the actual ERP experiment. Then, the actual ERP experiment started. There were 4 blocks and each one had 14 BMS and 14 Rep trials. The different conditions in each block were displayed randomly. In addition, the stimulus–response key assignments were counterbalanced across subjects. Between blocks, subjects could take a rest. Subjects were seated in a quiet room facing a screen placed at approximately 60 cm distance from the eyes and were instructed to respond as fast and accurately as possible by pressing the corresponding key on the keyboard. Subjects were asked to try to make as few movements and to limit eyeblinks.

ERP recording and analysis

Brain electrical activity was recorded from 64 scalp sites using tin electrodes mounted in an elastic cap (Brain Product), with the reference on the left and right mastoids. The vertical electrooculogram (VEOG) was recorded with electrodes placed above and below the left eye, and the horizontal electrooculogram (HEOG) with electrodes placed on the right side of the right eye and the left side of the left eye. All interelectrode impedance was maintained below 5 kΩ. The EEG and EOG were amplified using a 0.05–80 Hz bandpass and continuously sampled at 500 Hz/channel for off-line analysis. Eye movement artifacts (blinks and eye movements) were rejected offline. Trials with EOG artifacts (EOG voltage exceeding ± 80 μV) and those contaminated with artifacts due to amplifier clipping, bursts of electromyographic activity, or peak-to-peak deflection exceeding ± 80 μV were excluded from averaging.

The ERP waveforms were time locked to the onset of the second test stimuli. The averaged epoch for ERP, including a 200-msec pre-items baseline, was 1,800 ms. Correctly responded trials were separately averaged for the two task types (BMS and Rep). At least 30 trials were available for each subject and condition. Based on inspection of the ERPs grand-averaged waveforms and topographic map (see Figs. 2 and 3), the ERP component amplitudes were analyzed in a series of two-way repeated-measures ANOVAs using the factors task type (BMS and Rep) and anterior/posterior electrode sites separately (10 sites for anterior: F3, F1, Fz, F2, F4, FC3, FC1, FCz, FC2, FC4; 15 sites for posterior: C3, C1, Cz, C2, C4, CP3, CP1, CPz, CP2, CP4, P3, P1, Pz, P2, and P4). Because using data from multiple electrode sites may lead to a violation of the sphericity assumption, all ANOVA results were corrected using the Greenhouse–Geisser procedure.

Results

Behavioral data

The reaction times (RTs) for BMS and Rep were 1,759 ± 705 and 1,589 ± 420 ms, respectively. Repeated-measures analyses of variance for RTs showed that RTs for BMS were significantly slower than for Rep ($F(1,12) = 4.82$, $P < 0.05$). The results indicated that subjects were indeed influenced by the mental set effect and needed to spend more mental resources to generate characters under BMS compared to Rep. In addition, the proportions of correct responses to BMS and Rep were 90 ± 20% and 93 ± 8%, respectively. The results of the ANOVAs showed that there was no main effect of task type for these proportions ($F(1,12) = 1.53$, $P > 0.05$).

Electrophysiological scalp data

The grand-average waveforms and topographic maps of difference wave (BMS minus Rep) showed the following spatiotemporal distribution for the ERP data (see Figs. 2 and 3). As shown in Fig. 2, N100 and P250 were elicited by both conditions; the results of the ANOVAs showed no main effect of task type for these components. The results thus indicated that early visual processing was similar between the two conditions for the N100 and P250 ERP components.

Most importantly, we found that BMS elicited a more positive ERP deflection than did Rep after about 500 ms. The mean amplitudes in the time windows of 500–700 and 900–1,300 ms were analyzed using two-way repeated-measures ANOVAs, with task type and electrode site as factors. Over the centro-parietal scalp regions (15 electrode

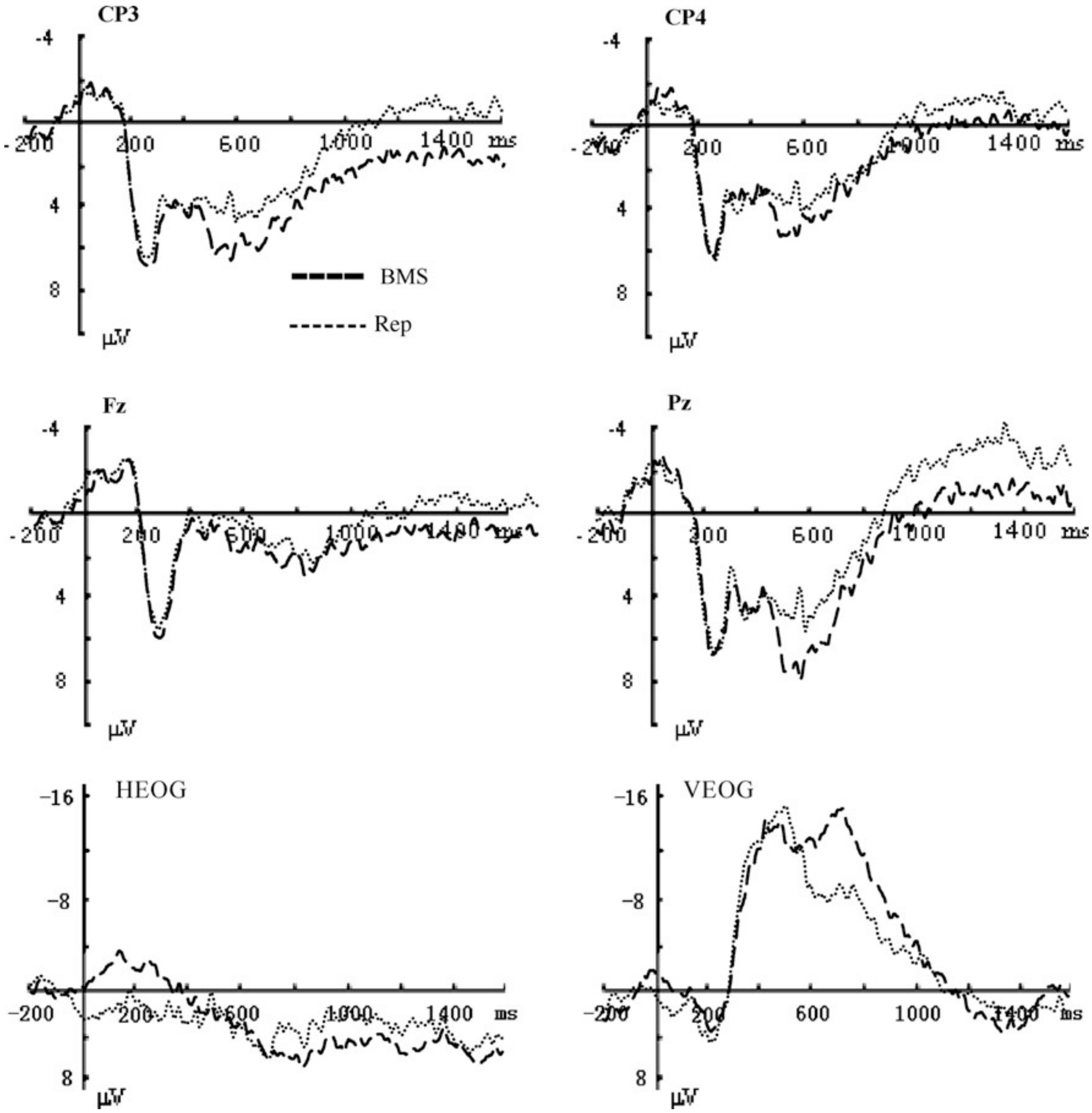
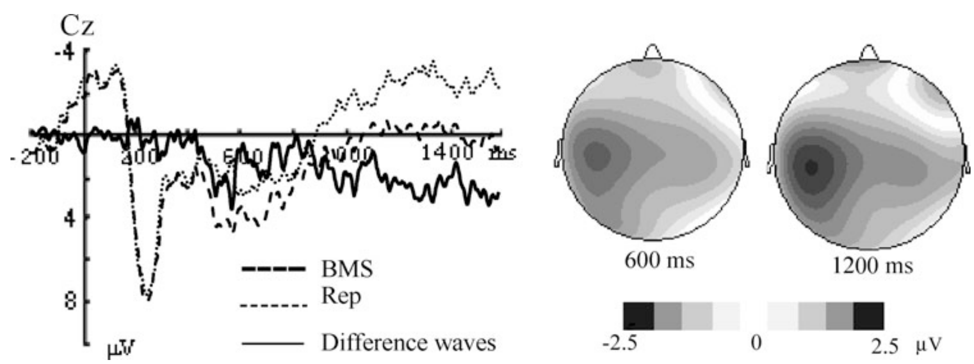


Fig. 2 Grand-average ERPs at CP3, CP4, Fz, Pz, HEOG and VEOG for the breaking mental set condition (BMS) and the repetition condition (Rep)

Fig. 3 Grand-average waveforms at Cz and topographic maps of the difference wave (BMS minus Rep) in the 600 and 1,200 ms



sites), the results of the ANOVAs revealed a main effect of task type between 500 and 700 ms, $F(1,12) = 5.29$, $P < 0.05$. BMS elicited a more positive ERP deflection (P500-700) than did Rep. Furthermore, the main effect of task type was also significant between 900 and 1,300 ms over the centro-parietal scalp regions, $F(1,12) = 4.51$,

$P < 0.05$. The mean amplitude was more positive (P900-1300) for BMS than for Rep. The main effect of electrode site and the interaction between task type and electrode site were not significant in both time windows. Nor were there significant differences between the BMS and Rep conditions in the time windows of 500–700 and 900–1,300 ms over the frontal scalp regions (10 electrode sites), $F(1,12) = 0.84$, $P > 0.05$; $F(1,12) = 0.66$, $P > 0.05$.

Discussion

In the present study, we used a learning–testing experimental paradigm to examine the electrophysiological correlates of breaking mental set. Scalp ERP data showed that BMS elicited a more positive ERP deflection (P500-700) than did Rep between 500 and 700 ms. Then, BMS also elicited a more positive ERP deflection (P900-1300) than did Rep between 900 and 1,300 ms. Below, we discuss the implication of these findings in the character-generation task.

Between 500 and 700 ms after onset of the second test stimuli, subjects likely generated a new character in a fixed way based on previous solutions to similar problems. That is, they had learned a stereotype or mental set, supported by the subjects' report of tendency to generate characters the same way that had worked in the past. However, subjects were likely conscious of the strategy that normally worked well but did not provide an effective solution to the present problem under the BMS condition. In fact, our behavioral data showed that the Chinese character-generation task yielded a robust breaking mental set effect, with longer RTs for the BMS than Rep condition. This likely reflects three factors related to BMS: the tendency to solve a problem in a fixed way, unsuccessfully solving a problem using methods suggested by prior experience, and realizing that the solution requires different methods. The ERP data also showed that BMS elicited a more positive ERP deflection (P500-700) than did Rep after onset of the second testing stimuli. Observing the ERPs grand-averaged waveforms, we found that the P500-700 possibly might be the third positive component in the waveform, and it therefore might be a late P300 component (e.g., Donchin and Coles 1988; Kutas et al. 1977). In general, P300 amplitude reflects the amount of attentional resources employed in a given task (Donchin and Coles 1988). Previous studies have indicated that the P300s are often linked to memory updating, encoding, or retrieval, given their appearance in tasks making demands on stimulus evaluation and memory updating resources (Donchin and Coles 1988; Kutas et al. 1977). In a study of insight problem study, using a similar learning–testing paradigm as the present research, Qiu et al. (2008) found that "successfully" guessed logogriphs elicited a more positive ERP deflection than did "unsuccessfully" guessed logogriphs in the time window from 200 to 600, which was thought to reflect the forming of rich associations. Recently, Wang et al. (2009) found that insight problems elicited a more positive ERP deflection (P300-800) than did routine problems over the parieto-occipital scalp regions. However, Wang et al. (2009) also found that insight problems elicited a more negative ERP deflection (N300-800) than did routine problems over the fronto-central scalp regions. In the present study, we presume that subjects need to realize their own mental sets and then get rid of the unsuitable "fixation"; then, they try to find an effective method and form rich associations in order to generate a new character. Thus, we speculate that the positive component (P500-700) might reflect the successful breaking of mental set and the forming of new associations.

Subsequently, BMS still elicited a more positive ERP deflection (P900-1300) than did Rep between 900 and 1,300 ms. Previous studies indicated that slow waves in the ERP are correlated with rehearsal/retention operations in working memory (e.g., Ruchkin et al. 1992; Mecklinger and Pfeifer 1996). Moreover, Berti et al. (2000) found that the larger the processing demands to keep object information in working memory, the larger the slow wave activity (see also e.g., Ruchkin et al. 1992; King and Kutas 1995; Mecklinger and Pfeifer 1996). Thus, we assume that subjects might spend more mental resources to generate a new character under BMS compared to Rep condition after breaking mental set. That is to say, the P900-1300 might reflect searching and generating a new character after breaking the mental set in our study.

In conclusion, this work may be the first ERP study to investigate the spatiotemporal patterns of brain activation associated with "breaking mental set" using the Chinese character-generation task. Scalp ERP data revealed the neurophysiological substrate of the breaking of mental set effect: BMS elicited a more positive ERP deflection (P500-700) than did Rep between 500 and 700 ms and a more positive ERP deflection (P900-1300) than did Rep between 900 and 1,300 ms after onset of the test stimuli. In our study, by using a simpler and easier task, we attempted to examine the complex process of insight, which is relatively rare and difficult to elicit in the laboratory. Although the basic elements related to breaking mental set are similar, some differences may exist between our paradigm and that of others, such as the extent of the mental set. In the future, to elicit stronger mental sets, the percentage of BMS trials could be decreased, while those used in the test phase using the learning rule could be increased.

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