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The neural basis of insight problem solving: An event-related potential study

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ABSTRACT

The electrophysiological correlates of successful insight problem solving (Chinese logographs) were studied in 18 healthy subjects using high-density event-related potentials (ERPs). A new experimental paradigm (learning-testing model) was adopted in order to make subjects find a solution on their own initiative rather than receive an answer passively. Results showed that Successful guessed logographs elicited a more positive ERP deflection (P200–600) than did Unsuccessful guessed logographs in the time window from 200 to 600 ms after onset of the stimuli. Subsequently Successful logographs elicited a more negative ERP deflection than did Unsuccessful logographs in the time windows of 1500–2000 ms (N1500–2000) and 2000–2500 ms (N2000–2500). Maps of the P200–600 showed strong activity in the midline parieto-occipital scalp regions. Dipole analysis localized the generator of P200–600 in the left superior temporal gyrus and parietotemporo-occipital cortex areas. The N1500–2000 and N2000–2500 had a distinct activation over left frontal scalp regions. Dipole analysis localized the generator of the N1500–2000 in the anterior cingulate cortex (ACC) and the N2000–2500 in the posterior cingulate cortex (PCC). This result indicates that the parietotemporo-occipital cortex areas might be involved in forming rich associations in the early stage of successful logograph solving. Then, the ACC might play an important role in the breaking mental set and the forming of novel associations. At last, “Aha” feeling might activate the PCC.

1. Introduction

The early Gestalt psychologists thought that insight problem-solving was a process of reconstructing the whole situation as an “Aha” experience. The occurrence of “Aha” experience means rethinking some basic assumptions about the problem content, which happens in a relatively sudden and unpredictable manner (Kohler, 1925; Scheerer, 1963). During the last century, cognitive psychologists have studied the processes of insight with respect to problem solving skills, on human and animal subjects (e.g., Kaplan & Simon, 1990; Kohler, 1925; MacGregor, Ormerod, & Chronicle, 2001; Scheerer, 1963). However, the neural basis of insight remains unknown, and there are different theories 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). Differently, the Progress Monitoring theory (MacGregor et al., 2001; Ormerod, MacGregor, & Chronicle, 2002) attempted to explain the cognitive progress of insight in the framework of means-ends analysis heuristics.

Developed brain imaging techniques such as functional magnetic resonance imaging (fMRI) and positron emission tomography (PET) have made it possible for us to record precisely the brain activity associated with many high-level cognitive processes (e.g., insight problem resolving). For example, Luo et al. recorded neural activity using fMRI and correlated activity with cognitive insight by providing a trigger (the solution) to catalyze insightful riddle solving processes (Luo & Niki, 2003; Luo, Niki, & Phillips, 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 non-insight solutions and scalp EEG recordings revealed a sudden burst of high-frequency (gamma-band) neural activity in the same region just before insight, but not non-insight, solutions (Bowden, Jung-Beeman, Fleck, & Kounios, 2005; Bowden & Jung-Beeman, 2003).

Subsequently, Mai, Luo, Wu, and Luo (2004) applied ERPs to examine the electrophysiological correlates of insight problem solving when the answers provided by using 120 interesting Chinese logographs. The ERP difference wave (Aha minus No-aha answer) showed the maximum amplitude over the central site (Cz)

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with a peak latency period of 380 ms (N380). The dipole analysis localized the N380 generator to the ACC. Thus, they thought that the N380 likely reflected an "Aha" effect, and that the ACC generator may be involved in the breaking of mental set. However, Qiu, Li, Luo, Chen, et al. (2006) used traditional Chinese logographs as test materials, and found that relative to No-aha answer, Aha and Uncomprehended answer both elicited a more negative ERP deflection in 320 ms. The dipole analysis localized the generator of the difference wave with a peak latency period of 320 ms (N320) (Aha minus No-aha answer) to the ACC. Therefore, it might reflect the cognitive conflict center between familiar and new ways of solving the logographs.

In a word, previous studies (Luo & Niki, 2003; Mai et al., 2004; Qiu et al., 2006) designed a puzzle task and catalyzed the progress of insight by presenting the answers. It is undoubtedly an innovation to adopt riddles as experimental materials and to catalyze insight by presenting the correct answers so as to reveal the activity of the brain. But to reveal the epoch change of insight within brain in ERP research, this paradigm seemed imperfect. As Fu (2004) pointed out that subjects could understand the correct answer after being told it, but it was not insight in the strict sense, but apperception. In the research of Metcalfe (1986), participants judged well for the perception of known or unknown when solving routine problems, but could not be aware of the vicinity of answers in solving insight problems, which indicated that it was an all-or-none progress. Smith and Kounios (1996) found the information in the insight problem solving was not gradually accumulated and the problem could be solved suddenly if the special information appeared. That is to say, in the process of insight problem solving, the initially purposeful thinking is followed by an impasse, a state of mind in which the problem solvers become stuck and have no idea of what to do next after all options have been explored. A new idea or option will, in some cases, suddenly and unexpectedly comes to mind after continued concentration on the problem (Metcalfe, 1986; Smith & Kounios, 1996). Obviously, all the researches proved that the cognitive process of insight problem solving through participants' active thinking was different from that of producing an Aha experience by means of understanding the answers. As for now, investigators (e.g., Bowden & Jung-Beeman, 2003; Bowden et al., 2005; Luo & Niki, 2003; Mai et al., 2004) tried their best to adopt the advanced brain-imaging techniques to discuss its neural mechanism. However, as Luo said that "the difficulties still lie in: (1) it is hard to find appropriate and enough tasks for the systematic study of insight because classical insight problems are very few, such as the 'nine-dot problem' and the 'two string problem'; (2) for these insight problems the time to solution is well beyond the constraints of the data acquisition method (it can take hours, days, or even weeks to solve a difficult insight problem) "(see Luo & Knoblich, 2007).

In the present study, a novel model using a learning-testing experimental paradigm was adopted to explore the brain mechanism of insight problem solving. The model is designed to make subjects find a solution on their own initiative rather than receive answers passively. Our study adopted riddles (Chinese logographs), which are traditionally classified as "insight problems". Riddles about a Chinese character might be phrases, Chinese proverbs and sayings, or sentences in a poem, and the answer to the riddles is a Chinese character. We know that Chinese characters are formed by strokes and some complex characters are composed of some other simple characters. To solve Chinese logographs, the subjects are expected to read between the lines and discover the deep meanings of the riddles, and they may get the answer either by splitting or removing certain components of the Chinese characters in the riddles and recombining the components of the characters to make new ones or by catching the implicit meanings the riddles intend. First, subjects learned a base logograph with the answer offered (learning stage), and then they were asked to solve a homotypical logograph (target logograph) where the base logograph learned beforehand would provide heuristic information for finding a solution (testing stage). Luo and Knoblich (2007) said that "one needs to detach oneself from one's prior experience with similar problems and to see the problem in a new way, or one needs to establish a new relation between the problem elements in order to solve insight problems. Especially, restructuring can involve a perceptual reinterpretation of the problem, directing attention to the critical problem elements, a re-combination of elements that gives the problem a new meaning, or a change in the goal of problem solving". Thus, we thought that there were two key cognitive processes including heuristic information activation and restructuring during target logograph solving. We hypothesized that there might be different ERP components (e.g., P300 and slow waves) that are involved in insight problem solving (e.g., heuristic information activation and restructuring). By recording and analyzing high-density ERPs elicited by target logographs guessed or not, ERP data therefore allow for more precise examinations of the time course of activation for different stages of successful insight problem solving and provide more valuable results for determining cognitive mechanism of insight.

2. Experimental procedures

2.1. Subjects

As paid volunteers, 18 junior undergraduates which were all native Chinese speakers (9 women, 9 men) aged 19–26 years (mean age, 22.3 years) from certain University in China participated in the experiment. All subjects were healthy, right-handed, and had normal or corrected to normal vision.

2.2. Experimental stimuli

Previous studies (Luo & Niki, 2003; Luo et al., 2004; Mai et al., 2004; Qiu et al., 2006) had shown that you would attain an "Aha" experience once you guess the answer of riddle successfully. The Chinese logograph we adopted has the characteristic of traditional insight problem: first, these logographs are difficult because they always contain some misleading information; second, people without special knowledge and skills could solve the logograph; finally, the base logograph learned beforehand would provide heuristic information for solving the target logograph, and the target problem could be solved in a few seconds once the heuristic information is activated successfully, and then "Aha" experience would be produced in our experiment. In our preparatory experiment, we required another group of subjects to rate their understanding on a scale of 1 (extremely boring/old) to 5 (extremely interesting/novel) for each logograph. According to their results, we selected these logographs which were evaluated to be interesting (Mean scores >3.5) as experimental materials (totally 150 target logographs). That is to say, subjects would experience an "Aha" sensation of surprise when they guess or understand the answers of these interesting logographs. Most logographs were between 2 and 6 characters in length, while all answers were a single character. The words that appeared in both the questions and answers were of high frequency, and were presented in the center of the screen. The characters were presented in the Song Ti font, at size No. 16. According to the learning-testing model, we divided the 150 logographs into two groups, true- and false-matching logographs.

2.2.1. True-matching logographs

For each of the 75 target logographs, a real heuristic logograph (a base logograph) was made for subjects to learn. For example, "you kou nan yan" (有口难言 base logograph) vs. "you yan nan jian"

(有眼难见target logogriph). Subjects first learn the base logogriph and get heuristic information for solving the target logogriph. Based on its literal meaning, "you kou nan yan" (literally meaning being unable to speak even with a mouth) will first be associated with a Chinese character "yǎ (哑 literally means mute)". In the Chinese language, "yǎ" is composed of two other characters, "kou" (口 literally meaning mouth) and "yà" (亚 literally meaning second). In other words, when the character "kou" (mouth) is added to "yà", the newly formed character is "yǎ" (mute). Because the meaning of the riddle is being unable to speak even with a mouth, when "kou" (mouth) is added to "yà", the meaning of the character formed (yǎ) is mute. Therefore the answer to the riddle is "yà". The key point in solving the riddle is first through understanding the surface meaning of the riddle and then obtaining the answer by recombining, splitting and removing certain components of the Chinese characters. When the target logogriph appeared, subjects could easily guess the answer of logogriph ("you yan nan jian") because the target logogriph resembled the base logogriph. Based on the superficial meaning, "you yan nan jian" (literally meaning being unable to see even with eyes) will first be associated with a Chinese character "mang (盲, literally means blind)". In Chinese language, "mang" is composed of two other characters, "wang"(亡, literally means death) and "mu"(目, literally means eyes). Therefore understanding the surface meaning of the riddle and removing certain components of the Chinese character ("mu"), the answer ("wang") would be obtained. In addition, we found a similar example of English counterparts: "It has an egg in it, but when you have it. You can eat no egg." [Base Riddle (answer): Eggplant]; "It has an apple in it, but when you have it. You can eat no apple." [Target Riddle (answer): pineapple].

2.2.2. False-matching logogriphs

For each of the remaining 75 target logogriphs, a non-heuristic logogriph was made for subjects to learn. Contrary to true-matching logogriphs, base logogriphs and target logogriphs in this group had no connection at all. Therefore, subjects could not get useful heuristic information from the base logogriphs to help guess the target logogriphs. It was often difficult to find the correct answer in time and subjects seldom had an "Aha" experience. In our design, the first logogriphs in both of the true-matching and false-matching trials were equally easy to be comprehended and transferred to the second logogriph.

2.3. Experimental design

The flow of learning and testing logogriphs in each trial is shown in Fig. 1. Firstly the learning logogriphs (including logogriphs and answers) were presented in the center of the screen for 8 s. Subjects were instructed to try to understand the logogriphs and answers fast and make the corresponding response by pressing keys. If subjects understood the logogriphs and answers, they were asked to press "1" key quickly and press no key if did not understand them all along. After a 1 s' interval, the test logogriph was then presented in the center of the screen for 4 s. Subjects were required to guess the answers quickly according to the information they gained in the learning stage. Subjects were required to press "1" key quickly once they guessed the answers and press no key if they did not guess the answers. In the end, after a 1 s' interval, the correct answer was presented in the center of the screen for 2 s. At this time, subjects were asked to judge whether the guess they made themselves was consistent to the correct answers and hereby make the corresponding response by pressing keys. Press "1" key if their own guesses were consistent to the correct answers, press "2" key if they did not guess the riddles but could understand the correct answers and pressing no key if they neither guessed the riddles nor understood the correct answers.

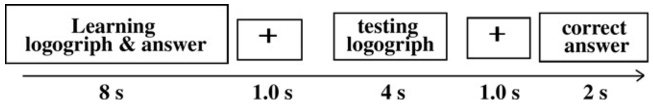

Fig. 1. The flow of learning and testing logogriphs in each trial.

The whole test was divided into two parts. First, to familiarize the subjects with the procedure and pace of this task, subjects were trained with 10 logogriphs (5 truly-matching logogriphs and 5 falsely-matching logogriphs) in the same procedure before the formal ERP experiment. Then, 140 logogriphs (70 truly-matching logogriphs and 70 falsely-matching logogriphs) were divided into five blocks which had 28 logogriphs in each block in the formal ERP experiment. There was no any repetition of stimuli in the formal test, and they were randomly selected and presented. Between the blocks, subjects could take the appropriate rest. Subjects were seated in a quiet room facing a screen placed at 60 cm distance from the eyes and were instructed to respond as fast and accurately as possible by pressing the corresponding button of the keyboard. Subjects were asked to try to make few movement and little eye-blink.

2.4. 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 (EOG) was recorded with electrodes placed above and below 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. High frequency noise was removed by applying a low-pass filter set at 16 Hz. Trials contaminated by blinks, eye-movements, and excessive muscle activity, were rejected offline (voltage exceeded ±80 μV in any channel) before averaging. During averaging, all scalp-recorded activity was digitally re-referenced to an average of the left and right mastoids.

In the present study, we mainly analyzed ERP elicited by target logogriphs and epoch change after the onset of logogriphs within 2500 ms with the baseline pre-stimulus 200 ms. According to results of guessing logogriphs, EEG of different response types were separately overlapped. As observed in the grand average waveforms and topographical maps (see Fig. 2), the ERPs elicited by Successful guessed logogriphs and Unsuccessful guessed logogriphs conditions clearly differed from each other. The difference waves were obtained by subtracting the averaged ERP of Unsuccessful logogriphs from the averaged ERP of Successful logogriphs, and these differences were prominent over the fronto-central and parieto-occipital scalp regions. Thus, the following 23 electrode points were chosen for two-way repeated measures analyses of variance. The ANOVA factors were response type (Successful; Unsuccessful logogriphs solving), and electrode site (foreside: FPz, Fz, Cz, AF3, AF4, F1, F2, F5, F6, C3, C4, FT7 and FT8; rearward: Pz, Oz, P1, P2, P5, P6, O1, O2, TP7 and TP8). *P*-value of analyses of variance was corrected for deviations according to Greenhouse–Geisser method.

2.5. ERP source analysis

Brain Electrical Source Analysis program (BESA, Version, 5.0, Software) was used to perform dipole source analysis. For dipole source analysis, a four-shell spherical head model (brain, skull, cerebrospinal fluid and scalp) was used as an approximation for dipole fitting. Scalp and skull thickness were set to 6 and 7 mm, respectively. In order to explore the brain mechanism of insight

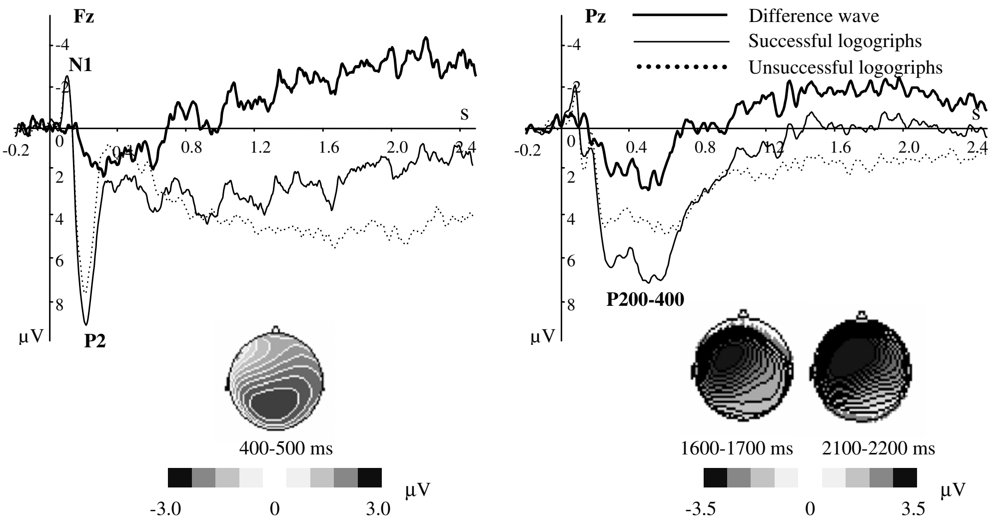

Fig. 2. *Top:* Grand average ERPs at Fz and Pz for Successful logogriphs (thin solid lines), Unsuccessful logogriphs (dotted lines) and the difference wave (Successful minus Unsuccessful) (think solid lines). *Bottom left:* Topographical maps of the voltage amplitudes for the Successful vs. Unsuccessful condition difference wave in the 400–500 ms. *Bottom right:* Topographical maps of the voltage amplitudes for the Successful vs. Unsuccessful condition difference wave in the 1600–1700 and 2100–2200 ms.

problem solving and increase the precision of source location, principal component analysis (PCA) was employed in the ERPs difference wave evoked by the Successful logogriphs and Unsuccessful logogriphs. When the dipole points are determined, software will automatically determine the dipoles location. Source locations are described in Talairach–Tournoux coordinates. To evaluate the solutions, the residual variance (RV), which provides an estimate of the amount of ERP power not explained by the seeded dipoles, was calculated by comparing the squared total error to the squared data (data power).

3. Results

3.1. Behavioral performance

The average number of solved logogriphs (Successful logogriphs) was 43 ± 10 (61.4 ± 14.2%), and the mean reaction times (RTs) were 2285 ms under the true-matching condition. Under the false-matching condition, within the time allowed (4 s), the average number of unsolved logogriphs (Unsuccessful logogriphs with no response) was 48 ± 11 (68.5 ± 15.7%). The results indicated that the heuristic information helped subjects get the correct answers and "Aha" experience occurred. However, it was hard for subject to get the answer if the base logogriph did not match the target logogriph. We also used the subjective reports on the solving experience, that is to say, each subject told us their solving experience when they finished the experimental tasks. Results showed that they generally reported a pleasant feeling of surprise and the solution came all at once when they solved the logogriphs successfully. In contrast, non-insight solutions (Unsuccessful logogriphs) were characterized as difficult by solvers who felt that they tried their best to solve the task but could not get the satisfied answers until the stimuli disappeared.

3.2. Electrophysiological scalp data

As the grand average waveforms and difference wave map shown (see Fig. 2), the anterior N1 and P2 were elicited in the early time by Successful logogriphs and Unsuccessful logogriphs. There was no main effect of the response type. From ERP waveforms, we found Successful logogriphs elicited a more positive ERP deflection (P200–600) than did Unsuccessful logogriphs between 200 and 600 ms and mainly activated in the midline parieto-occipital scalp regions. After the positive component, Successful logogriphs elicited a more negative ERP deflection than did Unsuccessful logogriphs within 600–2500 ms and mainly activated in the left frontal scalp regions. Mean amplitudes in the time windows of 200–600 ms and 600–2500 were chosen for statistical analysis.

Two-factors repeated measures ANOVA showed that the main effect between 200 and 600 ms of the response type was significant, $F(1,17) = 6.82$, $P < 0.05$. Successful logogriphs elicited a more positive ERP deflection (P200–600) than did Unsuccessful logogriphs. The interaction between response type and electrode site, $F(22,374) = 2.52$, $P < 0.05$, reached significance. As shown in Table 1, we found that the main effect of the response type between 600 and 1500 ms was not significant. But the main effect of the response type in the time windows of 1500–2000 ms (N1500–2000) and 2000–2500 ms (N2000–2500) were significant. Successful logogriphs elicited a more late negative ERP deflection than did Unsuccessful logogriphs. In addition, there was a main effect of the electrode site. The interaction between response type and electrode site did not reach significance.

The dipole source analysis based on a three-shell spherical head model was carried out using the BESA software (BESA, Version, 5.0, Software) on the grand average difference wave between Successful logogriphs and Unsuccessful logogriphs (See Fig. 3). According to the statistical result, PCA were employed in three time windows (200–600, 1500–2000, 2000–2500) in which the main effect of response type was significant. We determined the number of dipoles on the basis of results of PCA and our own scientific hypotheses. Then, double click on head schemes to create a new dipole, then start fit button to fit a dipole. The relevant residual variance criterion was used to evaluate whether this model explained the data best and accounted for most of the variance.

Table 1
Summary of results for the ANOVAS in the 600–1000, 1000–1500, 1500–2000, and 2000–2500 ms time windows

Time (ms)	Task		Electrode site		Task × Electrode site	
	F	*P*	*F*	*P*	*F*	*P*
600–1000	0.02	ns	4.94	0.001	1.09	ns
1000–1500	0.83	ns	8.27	0.000	1.78	ns
1500–2000	8.37	0.01	13.14	0.000	1.94	ns
2000–2500	7.06	0.02	9.41	0.000	1.23	ns

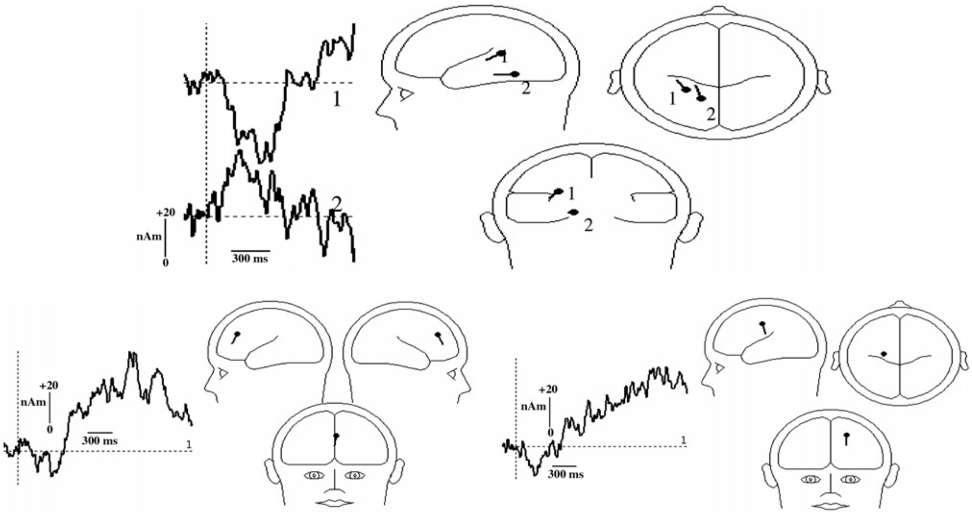

Fig. 3. Results of the dipole source analysis of the difference wave (Successful vs. Unsuccessful logographs) in the time range of 200–600, 1500–2000 and 2000–2500 ms. *Top:* The left-bottom shows the source activity waveforms, whereas the right figure displays the mean locations of the dipole. In the time range of 200–600 ms, the first dipole is located approximately in left superior temporal gyrus ($x = -34.3$, $y = -46.2$, $z = 18.6$) and the second near the left parietotemporo-occipital cortex ($x = -15.4$, $y = -50.5$, $z = -13.1$). *Bottom left:* In the time range of 1500–2000 ms, the dipole is located approximately in the anterior cingulate cortex ($x = -2.3$, $y = 30.7$, $z = 38.7$). *Bottom right:* In the time range of 2000–2500 ms, the dipole is located near the posterior cingulate cortex ($x = -22.7$, $y = -16.5$, $z = 44.6$).

Two principal components were needed to explain 92.6% (separately 76.6% and 16.0%) of the variance in the data from 200 to 600 ms. Therefore, these two dipoles were fitted with no restriction to the direction and location of dipole. The first dipole is located approximately in the left superior temporal gyrus (location according Talairach coordinates: $x, y, z = -34.3, -46.2, 18.6$; orientation fixed: x-ori, y-ori, z-ori $= -0.4, 0.8, -0.5$) and the second near the left parietotemporo-occipital cortex (x, y, $z = -15.4$, -50.5, -13.1; orientation fixed: x-ori, y-ori, z-ori $= -0.2$, 1.0, 0.1). This model explained the data best and accounted for most of the variance with a residual variance (RV) of 13.7% at the peak activity (480 ms) of these dipoles. In the 1500–2000 ms time window, PCA indicated that one principal component was required to account for 91.7% of the variance in the data. The result indicated that this dipole was located in the ACC (x, y, $z = -2.3$, 30.7, 38.7; orientation fixed: x-ori, y-ori, z-ori $= 0.1$, 0.5, -0.9). This model explained the data best and accounted for most of the variance with a residual variance (RV) of 11.9% at the peak activity (1680 ms) of this dipole. At last, PCA indicated that one principal component was required to account for 91.7% of the variance in the data 2000–2500 ms. The result indicated that this dipole was located approximately in the posterior cingulate cortex (PCC) (x, y, $z = -22.7$, -16.5, 44.6; orientation fixed: x-ori, y-ori, z-ori $= -0.0$, -0.2, -1.0). This model explained the data best and accounted for most of the variance with a residual variance (RV) of 21.7% at the peak activity (2200 ms) of this dipole.

The validities of these models were tested through the following steps. First, the display of the residual maps in the time windows (200–600, 1500–2000 and 2000–2500 ms) showed no further dipolar activity; second, no other dipoles could be fitted in the investigated time windows by comparing the solution with other plausible alternatives (e.g., bilaterally symmetric dipoles). These tests suggest that the models explained the data in the best manner for the time windows.

4. Discussion

In the present study, we introduced a learning-testing experimental paradigm and used the traditional Chinese logographs as the experimental materials to examine the electrophysiologic correlates of insight problem solving. We found that there was no significant difference between early components in the Successful logographs and Unsuccessful logographs, such as N1 and P2. This showed N1 and P2 were associated with the early stage of visual processing. Most presented logographs were between 2 and 6 characters in length, so that the degree of visual processing was almost consistent under two conditions. But the higher cognitive processing of logographs happened later. Results showed that Successful logographs elicited a more positive ERP deflection than did Unsuccessful logographs in the time window within 200–600 ms, and a more negative ERP deflection than did Unsuccessful logographs in the time window of 1500–2500 ms after onset of the target logographs.

Between 200 and 600 ms after onset of the target logograph, subjects need identify and understand the superficial meaning of the lines firstly. Obviously, they should inhibit the superficial meaning and discover its deep meaning in order to guess the logograph. Our results showed that Successful logographs elicited a more positive ERP deflection (P200–600) than did Unsuccessful logographs, and dipole analysis localized the generator of P200–600 in the left superior temporal gyrus and the parietotemporo-occipital cortex. We thought that the P200–600 might be an obvious P300 component. In general, P300 latency is thought to represent the relative duration of multiprocess stimulus evaluation/classification operations, and P300 amplitude reflects the amount of attentional resources employed in a given task (Donchin & Coles, 1988). Previous studies have indicated that the P300 are often linked to memory updating, encoding, or retrieval, given their appearance in tasks making demands on stimulus evaluation and memory updating resources (Donchin & Coles, 1988; Kutas, McCarthy, & Donchin, 1977). We therefore thought that the P200–600 might reflect forming novel and rich associations (schema induction) on the basis of heuristic information retrieval under the true-matching condition, compared to the false-matching condition.

In addition, the main function of the left superior temporal gyrus and parietotemporo-occipital cortex areas was to form comprehensive associations (e.g., Geschwind, 1965; Luo, Perry, Peng, Jin, et al., 2003; Wilkins & Wakefield, 1995). In Luo's (2003) study, they also found that the stronger activation of the postero-superior temporal area when subjects performed a verbal analogy task (e.g., soldier is to army as drummer is to band) compared to perform a semantic judgment task. They (Luo et al., 2003) suggested that "its activation might have been due to subjects' efforts to compare, _integrate and map different attributes of words and relationships between concepts that often do not bear surface similarities". Recently, Kounios et al. (Kounios et al., 2006) hypothesized that a distinct type of mental preparation, manifested in a distinct brain state, would facilitate insight problem solving. In fact, they found greater neural activity for insight than for non-insight preparation in bilateral temporal cortex. They proposed that this temporal lobe activity reflects readiness to engage semantic activation, particularly guided by top-down processes (Kounios et al., 2006). Thus, in our study, we speculated that the left superior temporal gyrus and parietotemporo-occipital cortex might be related to forming rich associations and activating heuristic information in order to find the useful information to be extracted from the superficial logogriph representations in the early stage of successful logogriph solving.

Compared to Unsuccessful logogriphs, Successful logogriphs elicited a more negative ERP deflection in the time window of 1500–2000 ms and led to the strong activation of ACC. Previous studies indicated that negative slow waves in the ERP are correlated with rehearsal/retention operations in working memory (e.g., King & Kutas, 1995; Mecklinger & Pfeifer, 1996; Ruchkin, Johnson, Grafman, Canoune, & Ritter, 1992). For example, Mecklinger and Pfeifer (1996) suggested that the relative increase in negative slow wave activity at the mid-frontal electrodes might reflect increasing load in the object memory task. In the present study, subjects need break mental set and form novel associations in working memory temporarily in order to get the answer. Moreover, Berti, Geissler, Lachmann, and Mecklinger (2000) found that the larger the processing demands to keep object information in working memory, the larger the negative slow wave activity (see also e.g., King & Kutas, 1995; Mecklinger & Pfeifer, 1996; Ruchkin et al., 1992). Therefore, the N1500–2000 might be related to breaking mental set and forming novel associations in working memory.

Moreover, the ACC is usually thought of as playing an important role in implementing the processes underlying adjustments of performance control (e.g., Botvinick, Braver, & Barch, 2001; Carter et al., 1998; VanVeen & Carter, 2002). Botvinick, Cohen, and Carter (2004) suggested that ACC activation can be explained by the single function of the detection of conflict and puts forth the hypothesis that conflict might serve as an index of the demand for mental effort. In addition, some researchers (e.g., Kroger et al., 2002; Ruff, Knauff, & Spreer, 2003) indicated that the medial frontal gyrus activation during reasoning might reflect information integration from various sources and irrelevant information inhibition in working memory. In Liston, Matalon, Hare, Davidson, and Casey (2006), the implementation of cognitive control associated with task switching engaged a network of structures including dorsolateral prefrontal cortex, ACC and posterior parietal cortex. Kounios et al. (2006) also found that mental preparation leading to insight involves heightened activity in the ACC associated with cognitive control (e.g., suppress extraneous thoughts). In the present study, subjects often encountered impasses due to the superficial meaning of the logogriph. However, they could solve it by using a new or novel way of thinking under the true-matching condition. Thus, together with the prior findings, we thought that activation of the ACC might be involved in the breaking of mental set successfully and the forming of novel associations in insight.

At last, dipole source analysis of the ERP difference wave (Successful minus Unsuccessful logogriphs) localized the generator of N2000–2500 in the PCC. In the present study, subjects made a motor response (press a button) when they guessed the answer of the logogriph, but not when they did not solve it. It might induce the ERP difference between Successful and Unsuccessful logogriphs. However, many fMRI studies had found that the primary motor cortex (BA 4) works in association with pre-motor areas (BA 6) to plan and execute movements (e.g., Haggard & Whitford, 2004; Lee & Quessy, 2003). Some researches (e.g., Maddock, 1999; Maddock, Garrett, & Buonocore, 2002) indicated that the PCC might be associated with cognitive processing of emotion. When subjects guessed the answers, they had "Aha" experience mostly. Csikszentmihalyi and Sawyer (1995) also suggested that "Aha" experience was mainly a feeling of excitement in finding correct answers. In our study, the N2000–2500 therefore might reflect the excited emotion effect.

5. Limitations and future directions

In the present study, ERP data allow for more precise examinations of the time course of "Aha" experience during insight problem solving. However, there were still some shortcomings in our study. For example, previous studies (Luo & Niki, 2003; Luo et al., 2004) had shown that different classes of riddles can reliably produce insight-like experiences, and we also selected interesting and novel Chinese logogriphs as materials. However, there were no independent measures of whether and when the "Aha" experience actually occurs in a given trial. Recently, in Bowden's (2003, 2005) studies, subjective reports of the solving experience was used to identify whether a problem has been solved with insight. "The reports are subjective, but they are yoked to each solution, indicating what solving processes were engaged on a trial-by-trial basis" (see Bowden & Jung-Beeman, 2007), they said. This method would be used in our future studies.

In addition, previous studies (e.g., Metcalfe, 1986; Smith & Kounios, 1996) proved that the cognitive process of insight problem solving was different from that of routine problem solving. Therefore, we did not devise non-insight problems as baseline tasks in our study. On the contrary, we compared the ERP waveforms elicited by successful and unsuccessful insight problem solving. However, subjects were required to make a decision and press "1" key under successful guessed logogriph, but not under unsuccessful guessed logogriph. Therefore, the differences between conditions might be confounded with the presence vs. absence of insight. As Luo and Knoblich (2007) said that "it is relatively difficult to come up with good reference states in studies of insight problem solving, because insight includes a set of highly integrated processes that are released in one moment". In the future studies, we should pay much more attention to this problem.

The method of dipole source localization was used to explore the brain mechanism of insight problem solving in the present study. However, it should be stressed that dipole source analysis is an inverse problem because there is no unique solution. Due to inherent limitations of source localization, the brain areas implicated by source localization are only tentative. The results of dipole source analysis, therefore, should be considered with caution, as the difference wave (Successful logogriphs minus Unsuccessful logogriphs) may embody complex brain processes accomplished by multiple areas and their interactions. In the future, our experimental paradigm should be improved and more efficient materials should be adopted. Brain-imaging techniques like ERP and fMRI should be effectively applied to high-level cognitive process so as to reveal human's brain mechanism of creative thinking.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.bandc.2008.03.004.

References

Berti, S., Geissler, H. G., Lachmann, T., & Mecklinger, A. (2000). Event-related brain potentials dissociate visual working memory processes under categorial and identical comparison conditions. *Cognitive Brain Research, 9*, 147–155.

Botvinick, M. M., Braver, T. S., & Barch, D. M. (2001). Conflict monitoring and cognitive control. *Psychological Review, 108*, 624–652.

Botvinick, M. M., Cohen, J. D., & Carter, C. S. (2004). Conflict monitoring and anterior cingulate cortex: An update. *Trends in Cognitive Sciences, 12*, 539–546.

Bowden, E. M., Juang-Beeman, M., Fleck, J., & Kounios, J. (2005). New approaches to demystifying insight. *Trends in Cognitive Sciences, 9*, 322–328.

Bowden, E. M., & Jung-Beeman, M. (2003). Aha! Insight experience correlates with solution activation in the right hemisphere. *Psychonomic Bulletin & Review, 10*, 730–737.

Bowden, E. M., & Jung-Beeman, M. (2007). Methods for investigating the neural components of insight. *Methods, 42*, 87–99.

Carter, C. S., Braver, T. S., Barch, D. M., Botvinick, M. M., Noll, D., & Cohen, J. D. (1998). Anterior cingulated cortex, error detection, and the online monitoring of performance. *Science, 280*, 747–749.

Csikszentmihalyi, M., & Sawyer, K. (1995). Creative insight: The social dimension of a solitary moment. In R. J. Sternberg & J. E. Davidson (Eds.). *The nature of insight* (pp. 329–364). Cambridge, MA: MIT press.

Donchin, E., & Coles, M. G. H. (1988). Is the P300 component a manifestation of context updating? *Behavioural Brain Science, 11*, 355–372.

Fu, X. L. (2004). Mental process and brain mechanism of insight: Comments on Luo's neural correlates of insight. *Acta Psychologica Sinica, 36*, 234–237.

Geschwind, N. (1965). Disconnection syndromes in animals and man. *Brain, 88*, 237–294. 585–644.

Haggard, P., & Whitford, B. (2004). Supplementary motor area provides an efferent signal for sensory suppression. *Cognitive Brain Research, 19*, 52–58.

Kaplan, C. A., & Simon, H. A. (1990). In search of insight. *Cognitive Psychology, 22*, 374–419.

King, J. W., & Kutas, M. (1995). Who did what and when? Using word and clause-level ERPs to monitor working memory usage in reading. *Journal of Cognitive Neuroscience, 7*, 376–395.

Kohler, W. (1925). *The mentality of apes*. London: Routledge.

Kounios, J., Frymiare, J. L., Bowden, E. M., Fleck, J. I., Subramaniam, K., Parrish, T. B., et al. (2006). The prepared mind: Neural activity prior to problem presentation predicts subsequent solution by sudden insight. *Psychological Science, 17*(10), 882–890.

Kroger, J. K., Saab, F. W., Fales, C. L., Bookheimer, S. Y., Cohen, M. S., & Holyoak, K. J. (2002). Recruitment of anterior dorsolateral prefrontal cortex in human reasoning: A parametric study of relational complexity. *Cerebral Cortex, 12*, 477–485.

Kutas, M., McCarthy, G., & Donchin, E. (1977). Augmenting mental chronometry. The P300 as a measure of stimulus evaluation time. *Science, 197*, 792–795.

Lee, D., & Quessy, S. (2003). Activity in the supplementary motor area related to learning and performance during a sequential visuomotor task. *Journal of Neurophysiology, 89*, 1039–1056.

Liston, C., Matalon, S., Hare, T. A., Davidson, M. C., & Casey, B. J. (2006). Anterior cingulate and posterior parietal cortices are sensitive to dissociable forms of conflict in a task-switching paradigm. *Neuron, 50*, 643–653.

Luo, J., & Niki, K. (2003). The function of hippocampus in 'insight' of problem solving. *Hippocampus, 13*, 274–281.

Luo, J., Niki, K., & Phillips, S. (2004). Neural correlates of the 'Aha! Reaction'. *NeuroReport, 15*, 2013–2017.

Luo, J., & Knoblich, G. (2007). Studying insight problem solving with neuroscientific methods. *Methods, 42*, 77–86.

Luo, Q., Perry, C., Peng, D. L., Jin, Z., et al. (2003). The neural substrate of analogical reasoning: An fMRI study. *Cognitive Brain Research, 17*, 527–534.

MacGregor, J. N., Ormerod, T. C., & Chronicle, E. P. (2001). Information processing and insight: A process model of performance on the nine-dot and related problems. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 27*, 176–201.

Maddock, R. J., Garrett, A. S., & Buonocore, M. H. (2002). Posterior cingulate cortex activation by emotional words: fMRI evidence from a valence decision task. *Human Brain Mapping, 18*, 30–41.

Maddock, R. J. (1999). The retrosplenial cortex and emotion: New insights from functional neuroimaging of the human brain. *Trends in Neuroscience, 22*, 310–316.

Mai, X. Q., Luo, J., Wu, J. H., & Luo, Y. J. (2004). 'Aha!' effects in guessing riddle task: An ERP study. *Human Brain Mapping, 22*, 261–270.

Mecklinger, A., & Pfeifer, E. (1996). Event-related potentials reveal topographical and temporal distinct neuronal activation patterns for spatial and object working memory. *Cognitive Brain Research, 4*, 211–224.

Metcalfe, J. (1986). Feeling of knowing in memory and problem solving. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 12*, 288–294.

Ormerod, T. C., MacGregor, J. N., & Chronicle, E. P. (2002). Dynamics and constraints in insight problem solving. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 28*, 791–799.

Qiu, J., Li, H., Luo, Y. J., Chen, A. T., et al. (2006). Brain mechanism of cognitive conflict in a guessing Chinese logogriph task. *NeuroReport, 17*, 679–682.

Ruchkin, D. S., Johnson, R., Jr., Grafman, J., Canoune, H., & Ritter, W. (1992). Distinctions and similarities among working memory processes: An event-related potential study. *Cognitive Brain Research, 1*, 53–66.

Ruff, C., Knauff, M., & Spreer, J. (2003). Reasoning and working memory: Common and distinct neuronal processes. *Neuropsychologia, 41*, 1241–1253.

Scheerer, M. (1963). Problem solving. *Scientific American, 208*, 118–128.

Smith, R. W., & Kounios, J. (1996). Sudden insight: All-or-none processing revealed by speed–accuracy decomposition. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 22*, 1443–1462.

VanVeen, V., & Carter, C. S. (2002). The timing of action monitoring processes in the anterior cingulate cortex. *Journal of Cognitive Neuroscience, 14*, 593–602.

Wilkins, W. K., & Wakefield, J. (1995). Brain evolution and neurolinguistic preconditions. *Behavior Brain Science, 18*, 161–226.