



The neural basis of analogical reasoning: An event-related potential study

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ABSTRACT

The spatiotemporal analysis of brain activation during the execution of easy analogy (EA) and difficult analogy (DA) tasks was investigated using high-density event-related brain potentials (ERPs). Results showed that reasoning tasks (schema induction) elicited a more negative ERP deflection (N500–1000) than did the baseline task (BS) between 500 and 1000 ms. Dipole source analysis of difference waves (EA-BS and DA-BS) indicated that the negative components were both localized near the left thalamus, possibly associated with the retrieval of alphabetical information. Furthermore, DA elicited a more positive ERP component (P600–1000) than did EA in the same time window. Two generators of P600–1000 were located in the medial prefrontal cortex (BA10) and the left frontal cortex (BA6) which was possibly involved in integrating information in schema abstraction. In the stage of analogy mapping, a greater negativity (N400–600) in the reasoning tasks as compared to BS was found over fronto-central scalp regions. A generator of this effect was located in the left fusiform gyrus and was possibly related to associative memory and activation of schema. Then, a greater negativity in the reasoning tasks, in comparison to BS task, developed between 900–1200 ms (LNC1) and 2000–2500 ms (LNC2). Dipole source analysis (EA-BS) localized the generator of LNC1 in the left prefrontal cortex (BA 10) which was possibly related to mapping the schema to the target problem, and the generator of LNC2 in the left prefrontal cortex (BA 9) which was possibly related to deciding whether a conclusion correctly follows from the schema.

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1. Introduction

Analogical reasoning, or the ability to find correspondences between the structures of distinct mental representations is essential for learning and abstract thinking (e.g., Hummel & Holyoak, 1997; Green, Fugelsang, Kraemer, Shamosh, & Dunbar, 2006). Like all forms of reasoning, analogical reasoning can be broken into a number of component processes (e.g., Gentner, 1989; Gick & Holyoak, 1983). It is known that a structure (base analog) has two components, elements and relations. This means that a structural representation must include relations (Gick & Holyoak, 1983). In the abstraction of a schema for an analogy (schema induction), two processes are central, i.e., manipulation of component terms in working memory and integration of relations (Holyoak, 2005; Green et al., 2006). In addition, analogy also includes mapping relations between a base and a target (Gentner, 1983; Gick & Holyoak, 1983; Holyoak & Thagard, 1989). The success of an analogical reasoning requires accessing a useful analog to a target problem, mapping the analog to the problem, and transferring the analog's

solution to the problem (Gentner, 1983; Holyoak & Thagard, 1989).

Recently 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., analogical reasoning). For example, neuropsychological investigations of reasoning in clinical populations have found that specific deficits in relational integration of terms are associated with damage to prefrontal cortex (e.g., Boroojerdi et al., 2001; Morrison et al., 2004; Waltz et al., 1999). Previous neuroimaging researches, using visuo-spatial stimuli, have specifically implicated left anterior prefrontal cortex in tasks involving relational reasoning (e.g., Christoff et al., 2001; Wharton et al., 2000; Kroger et al., 2002). Luo et al. (2003) using different types of analogy tasks found that the bilateral activation in the prefrontal regions (right BA 11\BA 47 and left BA 45), the fusiform gyrus, the left postero-superior temporal area, and the hippocampal region might be involved integrating different forms of information. Recently, Bunge, Wendelken, Badre, and Wagner (2005) used four-word analogies to investigate the neural substrates of analogical thinking. They found that anterior left inferior PFC (aLIPC) was modulated by associative strength, but that left frontopolar cortex was more sensitive to integration demands than was aLIPC. Using fMRI, Green et al. (2006) strongly suggests that frontopolar cortex (BA 9/10) mediates abstract relational integra-

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tion in complex reasoning while parieto-frontal regions mediates working memory processes, including manipulation of terms for the purpose of categorical alignment, and the facilitation of integration.

Compared to fMRI and PET, event-related potential (ERP) can provide a more precise picture of the time course of the process of analogical reasoning. Moreover, fMRI studies examined the brain activation during the whole reasoning process after the onset of a base and target stimuli synchronously in a blocked fashion and could not distinguish reasoning-related processes during different stages of problem processing. Therefore, the purpose of the present study is to investigate the spatiotemporal pattern of brain activation in performing the analogical reasoning tasks and one baseline task (memory retrieval) by using high-density (64 channels) ERP recording and dipole source analysis (BESA software). To investigate the temporal course of the brain processes underlying analogical reasoning, we selected the fluid letter string analogy task (Copycat) as materials that were used in previous studies (e.g., Hofstadter, 1995; Burns, 1996; Geake & Hansen, 2005). For example, Geake and Hansen (2005) investigated the neural correlates of intelligence associated with undertaking fluid letter string analogy tasks, and found that the regions of activation associated with undertaking fluid letter string analogies such as inferior and superior lateral prefrontal areas were similar to those associated with convergent analogizing using simple analogies (e.g., black is to white as high is to ?) or the Raven Progressive Matrices (Christoff et al., 2001; Kroger et al., 2002; Luo et al., 2003; Wharton et al., 2000).

Both in research and clinical practice, the P300 component is a useful tool for investigating the nature of cognitive processing. 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). Thus, the P300 component can provide considerable insight into analogy reasoning (e.g., scheme induction) because it provides independent measures of stimulus evaluation time and attentional requirements (Ilan & Polich, 1999). In addition, previous studies indicate 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) found that the relative increase in negative slow wave activity at the mid-frontal electrodes might reflect increasing load in the object memory task. In our study, participants need keep the schema in working memory temporarily in order to make a rapid analogy mapping and retrieve alphabetical information during analogy reasoning. Therefore, we hypothesize that these different ERP components (e.g., P300 and slow waves) are involved in analogical reasoning, especially, in association with the different cognitive processes (e.g., schema induction and analogy mapping). Moreover, we predict that P300 amplitude would increase as analogy reasoning task difficulty increased during schema induction, and the amplitude of the negative slow wave recorded over midline frontal electrodes would be larger in the analogy reasoning task than in the baseline task. In addition, the neural mechanism might be different between the analogy reasoning task (including schema induction and analogy mapping) and the baseline task. This assumption is based on findings from previous fMRI studies (e.g., Luo et al., 2003; Geake & Hansen, 2005; Green et al., 2006) that showed that there might be different neural networks (e.g., the left prefrontal cortex and the fusiform gyrus, the left postero-superior temporal gyrus and the hippocampal region) involved in human analogical reasoning, compared to some baseline tasks (e.g., semantic judgment). We might be able to characterize the functional roles of specific brain areas in the processes of analogical reasoning

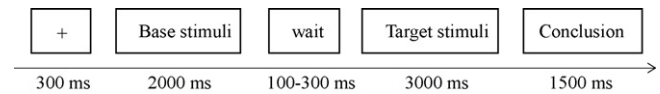


Fig. 1. Timeline of stimuli. Base stimuli and target stimuli were the target events to which three different tasks ERP data were time-locked, respectively.

by bringing together the previously found anatomic specificity of fMRI mapping and the time resolution of ERP recordings.

2. Materials and methods

2.1. Participants

Twelve healthy Chinese young students at Southwest University in China (mean age 22.7; range 20–25, six men, six women) participated in this study. All participants were right-handed, had normal or corrected-to-normal vision, received over 15 years of education, and had no history of neurological or psychiatric illness.

2.2. Stimuli

The analogical reasoning stimuli consisted of 140 fluid letter string items (Copycat, see e.g., Hofstadter, 1995) of two different degrees of complexity (easy and difficult analogy tasks), presented visually in a random order. The task was to complete the second part of an analogy, given the first transformation pair. As an easy analogy task (EA) example, abc:abd (base stimuli) as ijk:?(target stimuli). Most people can correctly respond “ijl” (advance the last letter by one alphabetical step). The difficult analogy tasks (DA) were like abc:abe, ijk:?. People should respond “ijm” (increase the last letter by two steps). That is to say, in an easy analogy task, the two last letters are adjacent in the alphabetic sequence, but in a difficult analogy task, there is an alphabetical interval between the last letters. Participants were instructed to produce the letter in the target pair according to the relation between the letter strings in the base pair. We selected 70 letter strings of baseline tasks (BS) for the simplest matching of letter string analogies [e.g., abc:abc, ijk:?(ijk)] (see, Geake & Hansen, 2005).

2.3. Procedure

A given reasoning item was presented in the following way (see Fig. 1). The beginning of the trial was signaled by a “+” in the center of screen (300 ms) followed by the appearance of the base stimuli (e.g., abc:abd; 2.8° (horizontal) × 0.9° (vertical)) on the screen for 2000 ms. Then, the target stimuli (e.g., ijk:?. 1.9° (horizontal) × 0.9° (vertical)) was presented for 3000 ms after a 100–300 ms interval when the base stimuli disappeared. Finally, the conclusion which was a possible correct answer (e.g., ijl or ijm; 1.4° (horizontal) × 0.9° (vertical)) appeared for 1500 ms. Participants were asked to make a decision whether the given conclusion was right or wrong according to their inference. The ratio of correct to incorrect answers presented was 1:1. They pressed “1” key by using their right index finger if the conclusion was right and “2” by using their right middle finger if it was wrong.

The total experiment was divided into a practice phase and a test phase. The practice part consisted of 15 trials to familiarize the participants with the procedure of this task and the pressing of the response buttons. The test stage was composed of five blocks and every block had 39 trials (each task including 13 trials). The stimuli appeared at random. Participants could take a rest after finishing one block. They were seated in a semi-dark room facing a monitor placed at 60 cm distance from the eyes. They were instructed to avoid blinking or moving their eyes and to keep their eyes fixated on the monitor during task performance and respond as fast and accurately as possible by pressing the corresponding keys on the keyboard. The formal test lasted about an hour.

2.4. ERP recording and analysis

Brain electrical activity was recorded at 64 scalp sites using tin electrodes mounted in an elastic cap (Brain Product), with the reference electrodes on the left and right mastoids. The horizontal electrooculogram (HEOG) was recorded with electrodes placed outside of eyes. The vertical electrooculogram (VEOG) 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 0.05–100 Hz bandpass and continuously sampled at 500 Hz for off-line analysis. Eye movement artifacts (blinks and eye movements) were rejected offline and 16 Hz low pass filter was used. Trials with EOG artifacts (mean 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 percentage of the rejected trials for each condition was very low (<8%) so that we can get enough trials to be overlapped and averaged.

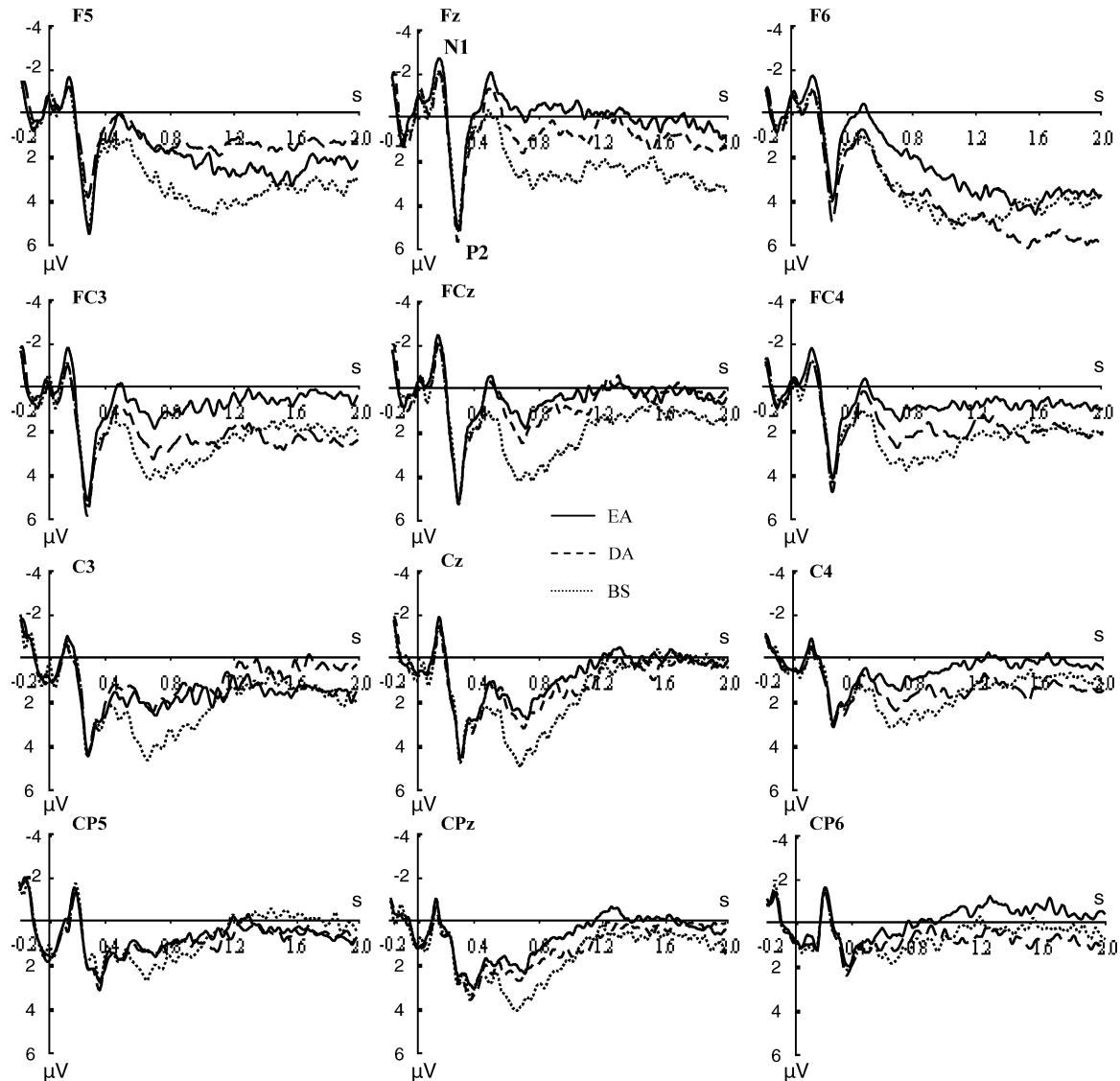


Fig. 2. Grand average ERPs at Fz, F5, F6, FCz, FC3, FC4, Cz, C3, C4, CPz, CP5 and CP6 for three tasks after onset of the base stimulus, including the easy analogy task (EA), the difficult analogy task (DA) and the baseline task (BS).

The ERP waveforms were time-locked to the onset of the base and target stimuli. The averaged epoch for the base stimuli's ERP, including a 200-ms pre-stimulus baseline, was 2200 ms. In addition, the averaged epoch for ERP should be 3200 ms including a 200 ms pre-target stimuli. However, we found that there were similar late negative ERP components among different conditions after 2500 ms. Thus, we analyzed the averaged epoch for the target stimuli's ERP was only 2700 ms. The ERP waves under each condition were obtained after the ERPs elicited by different trials with correct answers (EA, DA and BS) were overlapped and averaged, respectively. As observed in the grand averaged waveforms (see Figs. 2 and 3), the ERPs elicited by the reasoning tasks and the baseline task conditions clearly differed from each other. The difference waves were obtained by subtracting the averaged ERP of the baseline task from the averaged ERP of the reasoning tasks, and these differences were prominent over the fronto-central scalp regions. On the basis of the ERPs grand averaged waveforms (see Figs. 2 and 3), the following 17 electrode sites mainly localized in fronto-central scalp regions were chosen for statistical analysis: AF7, AF8, F5, F6, Fz, FC3, FC4, FCz, C3, C4, Cz, CP5, CP6, CPz, P3, P4 and Pz. Mean amplitudes in each time window were analyzed using two-way repeated-measures analyses of variance (ANOVA). The ANOVA factors were task types (three levels: EA, DA and BS), and electrode site. For all analyses, *P*-values were corrected for deviations according to Greenhouse Geisser.

2.5. Dipole source analysis

Brain Electrical Source Analysis program (BESA, Version, 5.0, Software) was used to perform dipole source analysis. For dipole source analysis, the four-shell ellip-

soidal head model was used. In order to focus on the scalp electrical activity related to the processing of analogical reasoning, including schema induction and analogy mapping, the averaged ERPs evoked by the BS was subtracted from the ERPs evoked by the reasoning tasks. Because dipole source localization was quite sensitive to noise, so in our study, the grand average ERP was used to get the maximal signal-noise ratios for dipole modeling. When the dipole points were determined, software would automatically determine the dipoles location. The relevant residual variance criterion was used. It is the percentage of the variance in the data not explained by the model.

3. Results

3.1. Behavioral data

In EA, DA and BS conditions, the percentage of the correct judgment of conclusions were 87.1 ± 12.2 , 74.1 ± 14.9 and 96.0 ± 2.0 , respectively, and the average response times (RTs) were 717 ± 38 , 736 ± 26 and 711 ± 29 ms, respectively. Repeated-measures analyses of variance (ANOVA) for the percentage of correct judgment showed that the effect of task type was significant ($F(2, 22) = 24.2$, $P < 0.001$). Post hoc tests showed that DA task was more difficult than EA ($P < 0.01$) or BS ($P < 0.01$) task, and EA was more difficult

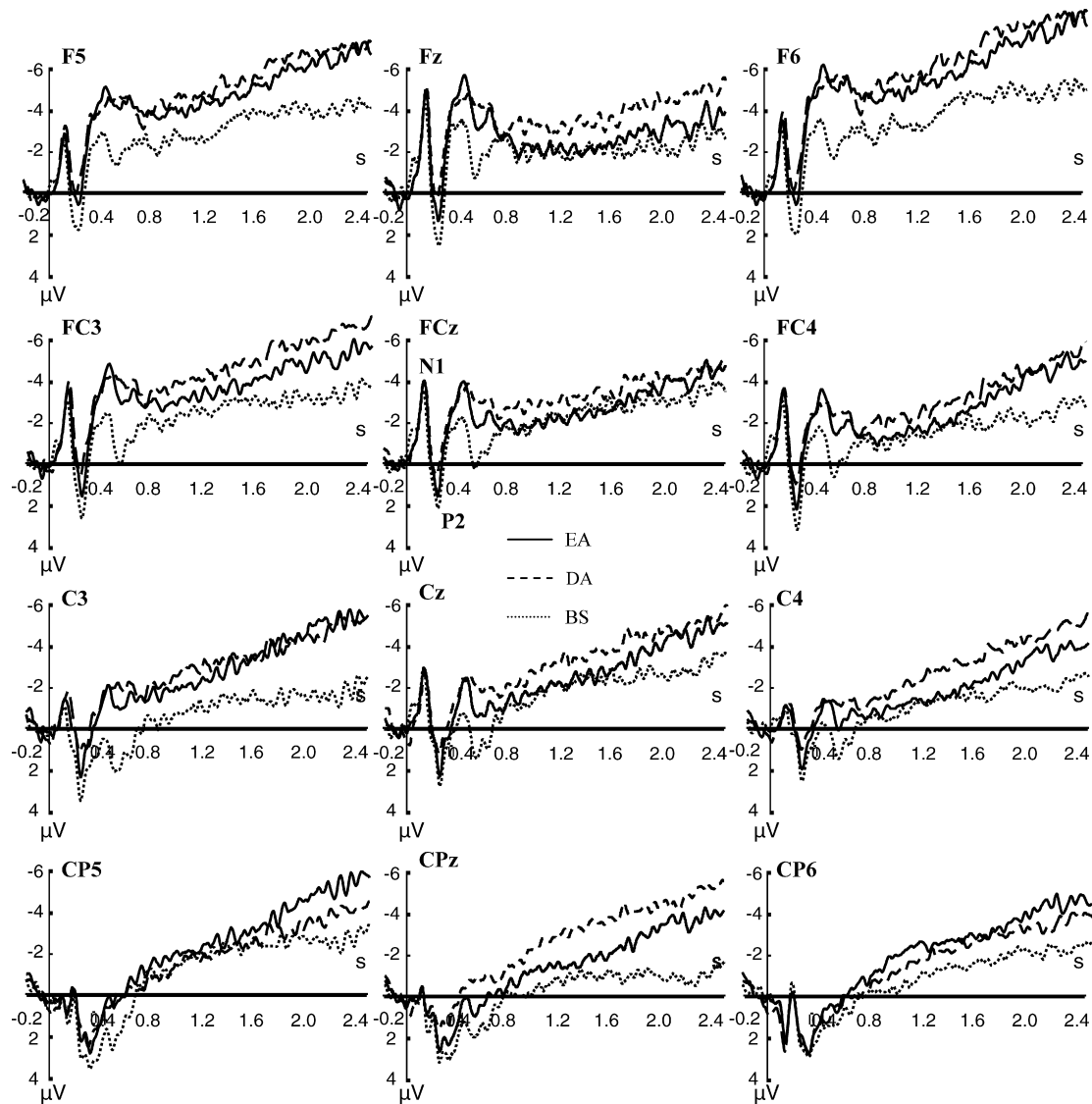


Fig. 3. Grand average ERPs at Fz, F5, F6, FCz, FC3, FC4, Cz, C3, C4, CPz, CP5 and CP6 for three tasks after onset of the target stimulus, including the easy analogy task (EA), the difficult analogy task (DA) and the baseline task (BS).

than BS task ($P < 0.05$). This result indicated that there was indeed a linear trend of task difficulty for BS, EA and DA task. In addition, the average reaction time (RT) of the three tasks was not significant, $F(2, 22) = 1.08$, $P > 0.05$. This result indicated that participants indeed made a judgment as fast as possible by pressing the corresponding key on the keyboard according to their previous conjecture whether the task was EA, DA, or BS (easy or difficult). That is to say, they had deduced a conclusion when the answer was presented.

3.2. Electrophysiological scalp data

3.2.1. Electrophysiological scalp data in the stage of base stimuli (schema induction)

ERP waveforms evoked by the EA, DA and BS tasks after the onset of base stimuli are shown in Fig. 2. The N1 and P1 were elicited by all the three conditions. The main effect of task type was not significant. From ERP waveforms, we found EA and DA both elicited a more negative ERP deflection than did BS in the time interval between 600 and 1000 ms. Mean amplitudes in the time window of 600–1000 ms (500–600, 600–700, 700–800, 800–1000 ms) were analyzed using two-way repeated-measures ANOVAs.

There were significant main effects of task type in the time windows of 500–600, 600–700, 700–800 and 800–1000 ms, $F(2, 22) = 4.05$, $P < 0.05$; $F(2, 22) = 7.87$, $P < 0.001$; $F(2, 22) = 6.06$, $P < 0.05$; $F(2, 22) = 6.75$, $P < 0.01$. Post hoc tests showed that the mean amplitude was more positive for the BS than for the EA ($P < 0.01$) and DA ($P < 0.05$), and the difference between EA and DA was also significant ($P < 0.05$). It showed a greater negativity (N500–1000) of EA and DA as compared to BS, and a greater positivity (P600–1000) of DA as compared to EA. However, results of the ANOVAs showed that there were no main effects of electrode site in the time windows of 600–700, 700–800 and 800–1000 ms, $F(16, 176) = 1.24$, $P > 0.05$; $F(16, 176) = 1.94$, $P > 0.05$; $F(16, 176) = 2.85$, $P > 0.05$. In addition, the interaction task type and electrode site was significant in these time windows, $F(32, 352) = 2.51$, $P < 0.05$; $F(32, 352) = 2.81$, $P < 0.05$; $F(32, 352) = 2.18$, $P = 0.07$.

3.2.2. Electrophysiological scalp data in the stage of target stimuli (analogy mapping)

ERP waveforms evoked by the EA, DA and BS tasks after the onset of target stimuli are shown in Fig. 3. After the onset of the stimuli, three tasks elicited some obvious early components,

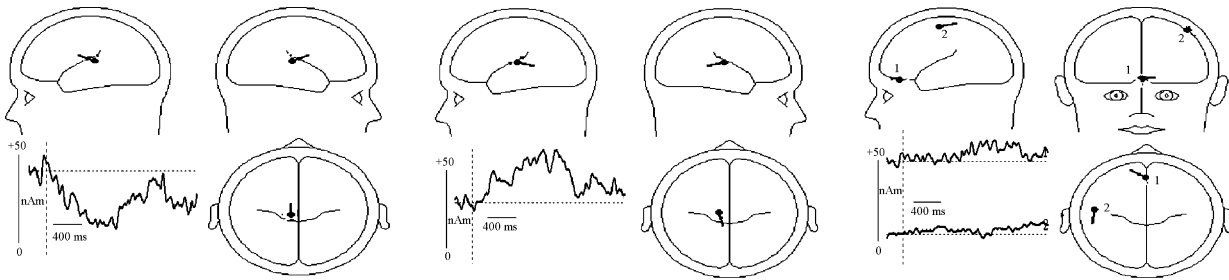


Fig. 4. Results of the dipole source analysis of the difference wave (EA vs. BS; DA vs. BS; DA vs. EA) in the time range of 600–1000 ms. The left-bottom of each figure shows the source activity waveforms, whereas the other displays the mean locations of the dipole. (Left) The dipole of the difference wave (EA vs. BS) is located approximately in the left thalamus ($x = -8.3$, $y = -23.8$, $z = 13.5$). (Middle) The dipole of the difference wave (DA vs. BS) is located in near the left thalamus ($x = -11.1$, $y = -18.1$, $z = 13.8$). (Right) The first dipole of the difference wave (DA vs. EA) is located in near the prefrontal cortex ($x = -1.4$, $y = 43.4$, $z = -8.1$), and the second dipole near the dorsolateral prefrontal cortex ($x = 50.6$, $y = -14.6$, $z = 55.4$).

for example, N1 and P2. In the present study, we hypothesized that these early ERP components might be similar among different reasoning tasks. Between 400 and 600 ms, a greater negativity (N400–600) in EA and DA as compared to BS was both found over midline fronto-central scalp regions. In addition, all of them elicited a late negative component after 900 ms. Amplitudes and latencies of these early components (N1 and P2) and mean amplitudes in the time window of 400–600 ms (400–500, 500–600), 900–1200, 1200–1500, 1500–2000 and 2000–2500 ms were analyzed using two-way repeated-measures ANOVAs.

There was no significant difference among different task types for the amplitude and latency of N1, $F(2, 22) = 1.75$, $P > 0.05$; $F(2, 22) = 1.07$, $P > 0.05$. The results of the ANOVAs showed that there was a main effect of task type for the amplitude of P2, $F(2, 22) = 4.32$, $P < 0.05$. Post hoc tests showed that amplitude for P2 was more positive for BS than for EA ($P < 0.001$) and DA ($P < 0.05$), but there was no significant difference between EA and DA. We did not find a significant main effect of task type for the latency of P2, $F(2, 22) = 0.37$, $P > 0.05$. There were main effects of task type in the time windows of 400–500 and 500–600 ms, $F(2, 22) = 4.54$, $P < 0.05$; $F(2, 22) = 6.67$, $P < 0.05$. Post hoc tests showed that mean amplitude was more positive for BS than for EA ($P < 0.05$) and DA ($P < 0.05$), but the difference between EA and DA was not significant ($P > 0.05$). In addition, the main effect of electrode site was significant in these time windows, $F(16, 176) = 12.21$, $P < 0.001$; $F(16, 176) = 6.80$, $P < 0.01$. After 900 ms, a late more negative component ERP was elicited by the analogy reasoning tasks than the baseline task. The results of the ANOVAs showed that the main effect of task type was significant in 900–1200 ms (LNC1) and 2000–2500 ms (LNC2), $F(2, 22) = 3.63$, $P < 0.05$; $F(2, 22) = 5.87$, $P < 0.05$. Post hoc tests showed that mean amplitude was more negative for EA ($P < 0.05$) and DA ($P < 0.05$) than for BS, but the difference between EA and DA was not significant ($P > 0.05$). The main effect of electrode site was also significant in these time windows, $F(16, 176) = 2.91$, $P < 0.05$; $F(16, 176) = 3.31$, $P < 0.05$. However, the interaction task type and electrode site was not significant in 900–1200 ms and 2000–2500 ms, $F(32, 352) = 0.52$, $P > 0.05$; $F(32, 352) = 0.70$, $P > 0.05$.

3.3. Dipole source analysis

3.3.1. Schema induction

To gain further information about the scalp electrical activity related to the process of schema induction, the source analysis using BESA software was performed on the ERP difference waves including EA-BS, DA-BS and DA-EA in the 600–1000 time windows (see Fig. 4). As for the ERP difference wave of EA-BS, PCA indicated that one principal component was needed to explain 92.4% of the variance in 600–1000 ms. Therefore, one dipole was fitted with no restriction to the direction and location of dipole.

The result indicated that this dipole was located approximately in the left thalamus (location according Talairach coordinates: $x = -8.3$, $y = -23.8$, $z = 13.5$) and revealed maximal dipole moment strength at about 640 ms. This model explained the data best and accounted for most of the variance with a residual variance (RV) of 6.8% at the peak activity of this dipole. As for the ERP difference wave of DA-BS, PCA indicated that one principal component was needed to explain 94.6% of the variance in the data. The result indicated that this dipole was also located approximately in the left thalamus ($x = -11.1$, $y = -18.1$, $z = 13.8$) and revealed maximal dipole moment strength at about 690 ms. This model explained the data best and accounted for most of the variance with a residual variance (RV) of 7.5% at the peak activity of this dipole. As for the ERP difference wave of DA-EA, PCA indicated that two components were needed to explain 77.4% and 11.7% of the variance in the data. Therefore, two dipoles were fitted with no restriction to the direction and location of dipole. The result indicated that one dipole was located near the prefrontal cortex (BA 10) ($x = -1.4$, $y = 43.4$, $z = -8.1$) and the other dipole located near the left frontal cortex (BA 6) ($x = -50.6$, $y = -14.6$, $z = 55.4$). This model explained the data best and accounted for most of the variance with a residual variance (RV) of 19.2% and revealed maximal dipole moment strength at about 850 ms.

3.3.2. Analogy mapping

To gain further information about the scalp electrical activity related to the process of analogical mapping, the source analysis was performed on the ERP difference wave of EA and BS (see Fig. 5) because the ERP components elicited by the analogy reasoning tasks were similar to each other. Based on the statistical results and the topography of the difference waves, principal component analyses (PCA) were employed in the three time windows (400–600, 900–1200 and 2000–2500 ms) in which the main effect of task type was significant. PCA indicated that one component was needed to explain 90.9% of the variance in the data in the 400–600 ms time window. Therefore, one dipole was fitted with no restriction to the direction and location of dipole. The result indicated that this dipole was located approximately in the left fusiform gyrus ($x = -33.6$, $y = -50.1$, $z = 9.3$) and revealed maximal dipole moment strength at about 520 ms. This model explained the data best and accounted for most of the variance with a residual variance (RV) of 5.3% at the peak activity of this dipole. In 900–1200 ms, PCA indicated that one component was needed to explain 93.6% of the variance in the data. The result indicated that the dipole was located near the prefrontal cortex (BA 10) ($x = -8.9$, $y = 61.9$, $z = 13.7$) and explained the data best and accounted for most of the variance with a residual variance (RV) of 15.2% and revealed maximal dipole moment strength at about 1020 ms. In 2000–2500 ms, PCA indicated that one component was needed to explain 90.5% of the variance in the data, the result indicated that the dipole was located near the left prefrontal

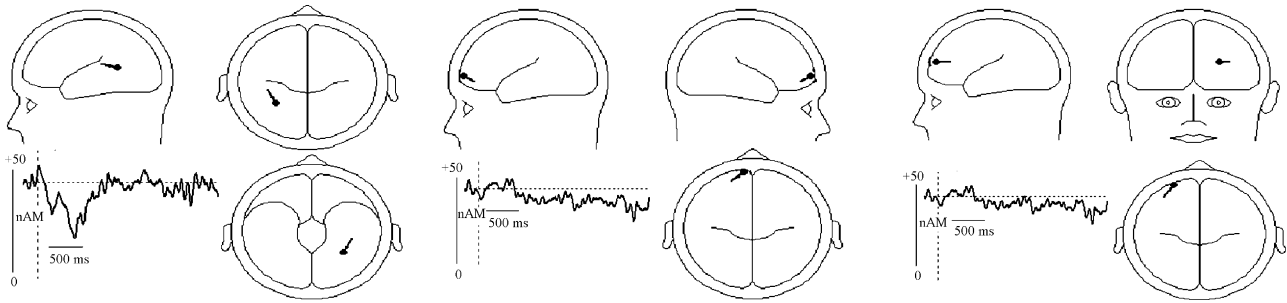


Fig. 5. Results of the dipole source analysis of the difference wave (EA vs. BS) in the time range of 400–600, 900–1200 and 2000–2500 ms. The left-bottom of each figure shows the source activity waveforms, whereas the other displays the mean locations of the dipole. (Left) In the time range of 400–600 ms, the dipole is located approximately in the left fusiform gyrus ($x = -33.6, y = -50.1, z = 19.3$). (Middle) In the time range of 900–1200 ms, the dipole is located in near the prefrontal cortex ($x = -8.9, y = 61.9, z = 13.7$). (Right) In the time range of 2000–2500 ms, the dipole is located in near the left prefrontal cortex ($x = -28.1, y = 54.2, z = 26.4$).

cortex (BA9) ($x = -28.1, y = 54.2, z = 26.4$) and explained the data best and accounted for most of the variance with a residual variance (RV) of 18.4% and revealed maximal dipole moment strength at about 2310 ms.

The validities of these models were tested through the following steps. First, the display of the residual maps in the time windows 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, participants had to induce the relationship of the first transformation pair (the base stimuli) and complete the second (the target stimuli) in an analogous way in the analogy reasoning tasks. In this process they must keep the schema in working memory temporarily in order to make a rapid analogy mapping and information retrieving. Obviously, from observing the grand average map and dipole source analysis performed on the difference wave (reasoning tasks minus baseline task), the activation of brain areas related to analogy reasoning processing could be presumed.

Firstly, our results showed that after the base stimuli was presented, reasoning tasks (e.g., abc:abd) elicited a more negative ERP deflection (N500–1000) than did BS (e.g., abc:abc) in the time window of 500–1000 ms. In the stage of schema induction, participants should abstract a schema on the basis of integration relationship of the first transformation pair letter strings after completing the early perceptual processing. When the first transformation pair letter strings (base stimuli) are the same, they only remember it without retrieving the alphabetical knowledge and judging the relation of letter strings. Otherwise, participants have to retrieve information about the sequence of alphabet from the long-term memory and judge the relation of letter strings. In the present study, EA and DA compared with BS are more difficult so that participants should process the base stimuli deeply in order to complete schema induction. Therefore, N500–1000 probably reflects internal alphabetical knowledge retrieval during the processing of the letter strings. Dipole source analysis of difference waves (EA-BS and DA-BS) indicated that the negative components were both localized near the left thalamus, which was possibly related to alphabetical knowledge retrieval. For example, many previous studies indicated that the thalamus was involved in various higher brain functions such as memory and learning (e.g., Karussis, Leker, & Abramsky, 2000; Nagaratnam, McNeil, & Gilhotra, 1999; Radanovic & Scaff, 2003), and might be related to the regulation and/or facilitation of the ongoing cortical processing of memory and language (Baker, Frith, & Dolan, 1997; Ojemann et al., 1998; Warburton et al., 1996).

Furthermore, DA elicited a more positive ERP component (P600–1000) than did EA in the time window of 600–1000 ms, and the generator of P600–1000 was mainly located in the medial prefrontal cortex (BA10) which was involved in integrating information in order to abstract a schema. As explained above, participants need to retrieve alphabet information to judge the relation of letter strings in EA and DA tasks. However, in the present study, the last letters are in immediate succession in sequence in EA tasks, but there is an alphabetical gap between the last letter and the preceding letter in DA task. It indicates that participants spend more cognitive resource to retrieve alphabet information to complete the schema induction in DA task than in EA task. The P600–1000 was actually the third positive component in the waveform, and it therefore may be a P300 component, similar to that found in other studies (Donchin & Coles, 1988; Kutas, McCarthy, & Donchin, 1977). 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 et al., 1977). We therefore thought that the P600–1000 might reflect the processing of relational integration (schema induction) on the basis of alphabet information retrieval. Our results also supported the view that P300 amplitude increased as task difficulty increased (e.g., Hagen, Gatherwright, Lopez, & Polich, 2006). Many previous studies clearly indicated that prefrontal cortex, specifically left anterior prefrontal cortex, was involved in relational integration that underlies reasoning (e.g., Baker et al., 1996; Green et al., 2006; Osherson et al., 1998). However, it is not clear whether the involvement of the frontal regions represents schema induction of the base stimuli or analogy mapping to the target stimuli (Holyoak, 2005; Holyoak & Thagard, 1989). In Geake and Hansen's (2005) study, significant activations were found in the left superior frontal gyrus, adding support to the claim that this region is used to retrieve rule-based knowledge, in this case, the knowledge of the alphabetical order and ordinality. Taken together, our results indicate that the brain activation of medial prefrontal cortex is mainly related to abstracting a schema by manipulating component terms in the working memory and integrating relations in the processing of the base stimuli.

Secondly, our results showed that after the onset of the target stimuli, three tasks elicited an obvious P2 component. From ERP waveforms, we found that the reasoning tasks (structure mapping) elicited a smaller P2 than did BS around 200–300 ms following the onset of the target stimulus. It indicated that P2 might reflect stimulus identification and attention resource distribution in the early time of analogy mapping. Hillyard and Kutas (1983) found that the P170 (P2) component might be related to the initial stimulus identification and evaluation. In the recent studies, many experiments using ERP (e.g., Gao, Wei, & Peng, 2003; Luo & Parasuraman, 2001) showed that the effect of P2 might reflect the cortical mechanisms

of visual spatial attention level in “the quantity” which meant that participants might spend different cognitive mental efforts (the different quantity) in processing these different visual tasks. Liu, Dong, and Zhao (2006) compared and investigated the features of event-related potential waveforms elicited by three lists of single Chinese character stimulus (related, non-related, pseudo-words). The results showed that the component P2 was “V” shape in related semantic stimulus and was “W” shape in non-related and pseudo-word stimulus. That is to say, component P2 was also involved in the early identification and classification of the target stimulus and the process of attention. Recently, in Kim and Kim (2006), left-dominant positivity at the frontal region, P2, was also observed in the time window from 250 to 280 ms, and they suggested that the P2 appeared to reflect semantic processing and early stages of decision. In the present study, the P2 might reflect a property of the experimental design, namely, that participants had to select and apply the schema for analogy reasoning while holding in mind the overall goals of the task.

Between 400 and 600 ms, a greater negativity (N400–600) in the analogy reasoning tasks as compared to BS was found over fronto-central scalp regions. In the present study, after the target stimuli appeared, participants should firstly retrieve letter information that has a close relation with ‘ijk’, just like ‘klmn’ and so on for transferring and adapting the base analog’s solution to the target problem. Dipole source analysis of difference waves (EA-BS) indicated that the negative components were localized near the left fusiform gyrus. Now it is widely agreed that the left fusiform gyrus is responsible for the processing of such physical features as word/letter shape and early semantic processing (e.g., Curran, Tucker, & Kutas, 1993; Kim & Kim, 2006; McCandliss, Cohen, & Dehaene, 2003). Luo et al. (2003) found that activation of bilateral fusiforms occurred during participants’ performing a verbal analogy task and suggested that this area might be activated by a visual mental imagery process involved in analogical reasoning. Therefore, we suggest that participants mainly retrieve letter sequence information and maintain the results in the visual mental imagery between 400 and 600 ms.

After 600 ms, three tasks elicited a late negative component (LNC1). However, a greater negativity in the reasoning tasks, in comparison to BS task, developed between 900 and 1200 ms (LNC1). Dipole source analysis (EA-BS) localized the generator of LNC1 in the left prefrontal cortex (BA 10) which was possibly related to mapping the schema to the target problem and completing it analogically. In the present study, participants would automatically activate the schema and map it between the base and the target letter strings after letter information retrieval in the time window of 900–1200 ms. Xue, Chen, Jin, and Dong (2006) had said that “This process, known as analogical mapping, requires more than simply identifying conventionalized semantic relations within each item/situation, and involves an alignment process whereby the component elements of one item/situation are aligned one-to-one with corresponding elements of the other item/situation (Gentner, 1983; Holyoak & Thagard, 1989)”. Previous work indicates that the left hemisphere executes the function of formal logic manipulation, whereas the right hemisphere focuses on activating the relevant knowledge and experience with reasoning tasks (Deglin & Kinsbourne, 1996; Wharton & Grafman, 1998). The activity in the left prefrontal cortex found in the present study was in agreement with the findings of other studies on reasoning that found the same activation in this area (Christoff et al., 2001; Ruff, Knauff, Fangmeier, & Spreer, 2003) or similar frontopolar cortex (Bunge et al., 2005; Goel, Gold, Kapur, & Houle, 1997; Green et al., 2006). We thought that the brain activation of left prefrontal cortex is mainly related to mapping the schema to the target problem (analogy mapping) in the processing of the target stimuli, similar

to executing the function of formal logic manipulation in deductive reasoning.

Lastly, our results showed that reasoning tasks (EA and DA) elicited a more negative ERP component (LNC2) than did BS in the time window of 2000–2500 ms. Previous studies had 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 et al., 1992). Moreover, Berti, Geissler, Lachmann, and Mecklinger (2000) examined the ERP waveforms in a delayed matching task to examine the effects of stimulus complexity, and suggested that the larger the processing demands to keep object information in working memory, the larger the negative slow wave activity (see e.g., King & Kutas, 1995; Mecklinger & Pfeifer, 1996; Ruchkin et al., 1992). Therefore, the LNC2 might be related to monitor and inspect the putative conclusion in participants’ working memory. We also found that the generator of LNC2 in the left prefrontal cortex (BA 9). Previous work indicates that the activity in portions of the middle frontal gyrus, corresponding to BA 9, might reflect that reasoning involves the active manipulation and inspection of information in working memory (Knauff, Mulack, & Greenlee, 2002; Petrides, 2000). This result possibly supports that participants would be intent to validate whether their putative conclusions are right or wrong during analogy mapping.

In a word, this study used ERP to investigate the neurophysiological correlates of analogy reasoning. The results suggest that the ERP components elicited by the BS task were different from the analogy reasoning tasks. Moreover, the ERP results implicate that schema induction mainly activated the left thalamus (memory), and then the left frontal cortex (relation integration) in the processing of base stimuli, and that structural mapping mainly activated the left fusiform gyrus (alphabetical knowledge retrieval) and the left prefrontal cortex (schema analogy and conclusion validation) in the processing of target stimuli. Of course, it should be stressed that dipole source analysis is an inverse problem and has no unique solution. Due to the inherent limitations of source localization, the brain areas implicated by source localization are only tentative. Regarding the involvement of brain regions in analogical reasoning, the current results provide only a model rather than empirical data.

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