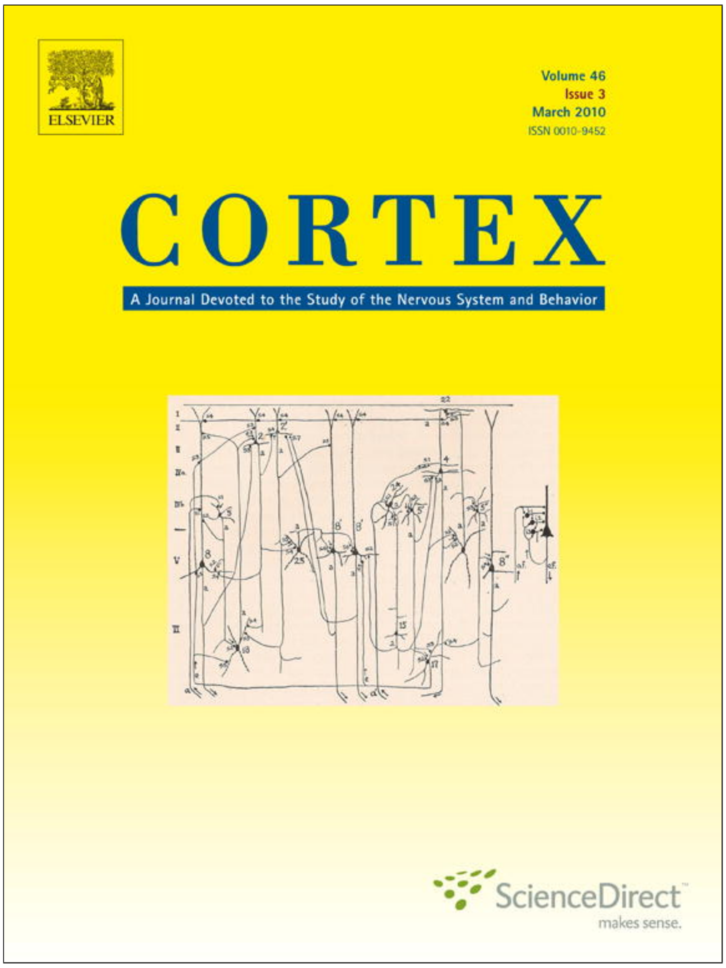
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Note

Neural correlates of the "Aha" experiences: Evidence from an fMRI study of insight problem solving

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ABSTRACT

In the present study, we used learning–testing paradigm to examine brain activation of "Aha" effects with event-related functional magnetic resonance imaging (fMRI) during solving Chinese logographs. Blood oxygenation level-dependent fMRI contrasts between Aha and No-aha conditions were measured. Increased activities in the precuneus (BA 19/7), the left inferior/middle frontal gyrus (BA 9/6), the inferior occipital gyrus (BA 18), and the cerebellum were specifically associated with the "Aha" effects. The results indicate that (1) the precuneus might be involved in successful prototype events retrieval, (2) the left inferior frontal/middle frontal gyrus might be involved in forming novel association and breaking mental sets, (3) the inferior occipital gyrus and the cerebellum might be involved in re-arrangement of visual stimulus and deployment of attentional resources.

1. Introduction

The early Gestalt psychologists thought that insightful problem solving resulted from reconstructing the whole problem. The occurrence of an "Aha" experience means rethinking about some basic assumptions about the problem content and realizing a new solution, which happens in a relatively sudden and unpredictable manner (Kohler, 1925). During the last century, cognitive psychologists studied the processes of insight with respect to problem solving skills, using human and animal subjects (e.g., Kohler, 1925; Kaplan and Simon, 1990; MacGregor et al., 2001). However, the cognitive mechanisms of insight remain largely unknown.

Brain-imaging techniques such as functional magnetic resonance imaging (fMRI) have made it possible for us to record precisely the brain activation associated with insightful problem solving. For example, Luo and Niki (2003) and Luo et al. (2004) recorded neural activities using fMRI and correlated activities associated with cognitive insight by providing a trigger (the solution) to catalyze insightful riddle solving processes, and found that insightful riddle

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solving was associated with activities 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) and fMRI, Jung-Beeman et al. (2004) and Bowden et al. (2005) revealed an increased signal in the right anterior superior temporal gyrus for the ''Aha'' effects.

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 (e.g., Luo and Niki, 2003; Qiu et al., 2006). However, it was not an insight in the strict sense but an apperception when subjects understand the solution after being told it (e.g., Metcalfe, 1986; Smith and Kounios, 1996). Research demonstrated that the cognitive processes in insight problem solving through participants' actively solving the problem versus passively understanding the answer are different. In the case of getting an answer, there might be a lack of problem restructuring or impasse experience which was typical of insightful problem solving (Luo and Knoblich, 2007).

Therefore, in the present study, a novel model using learning–testing experimental paradigm (for details see the Procedure) was adopted to explore the brain mechanisms of insightful problem solving. In this study, subjects had to find a solution on their own initiative rather than receive answers passively. We believe that one needs to retrieve a prior experience with a similar problem to form a new relation between the problem elements in order to solve an analogous insightful problem. Based on the previous work (e.g., Luo and Niki, 2003; Bowden and Jung-Beeman, 2003; Bowden et al., 2005), we predicted that ''Aha'' effects will activate regions in the medial frontal/ACC (breaking mental set), the anterior temporal gyrus (forming novel association), the medial parietal association cortex or precuneus (successfully retrieving heuristic information).

2. Materials and methods

2.1. Subjects

Sixteen junior undergraduates (8 women, 8 men) aged 19–25 years (mean age, 22.6 years) from Beijing Normal University in China participated in the experiment as paid volunteers. All subjects were healthy, right-handed, and had normal or corrected to normal vision. Informed written consent was obtained from each subject after procedures were fully explained.

2.2. Task

A word riddle about a Chinese character may be a phrase, a Chinese proverb and a saying, or a sentence in a poem. The answer to a word riddle is a Chinese character. Chinese characters are formed with radicals, and some complex characters are composed of simple characters. One attains an ''Aha'' experience when one successfully guesses the answer of the riddle. In a preparatory experiment, we required a group of subjects to rate their understanding on a scale of 1 (extremely boring/old) to 5 (extremely interesting/novel) for each of the 150 logographs. We selected 60 logographs which were evaluated to be interesting (mean scores > 3.5) as target logographs and 36 simple logographs (mean scores < 1.5) as baseline logographs. In order to determine the level of the Aha experience for these Chinese logographs, we had another group of subjects (total 12) solve these logographs and rate their Aha experience on a scale of 1 (No-aha feeling) to 3 (strongest Aha feeling) for each logograph. Our results showed that there was a significant difference [$F(1, 11) = 29.30$, $p < .001$] between the mean score for the target logographs (mean score = 1.8, stronger Aha feeling) and that of the baseline logographs (mean score = 1.1, No-aha feeling).

For each of the 60 target logographs, a heuristic logograph was made for subjects to learn. For example, ''you kou nan yan'' (有口难言) was the heuristic logograph for the target logograph ''you yan nan jian'' (有眼难见). Subjects first learned the heuristic logograph and received heuristic information for solving the matching target logograph. The heuristic logograph, ''you kou nan yan'' (''having a mouth but being unable to speak'') refers to the Chinese character ''yǎ'' (哑) (meaning mute). In Chinese, ''yǎ'' is composed of two simpler characters, ''kou'' (口) (meaning mouth which is the semantic-code radical signifying that the word concerns mouth) and ''yà'' (亚) (denoting the sound or pronunciation of the word). In other words, when the simpler character ''kou'' (mouth) is combined with ''yà'', the combined, emergent character is ''yǎ'' (mute). The riddle is ''having a mouth but being unable to speak'', and when ''kou'' (mouth) is combined with ''yà'', the character produced (yǎ) is mute. Therefore, the answer to this riddle is ''yà''. The crucial process in solving the riddle is first thoroughly understanding the surface meaning of the riddle and then obtaining the answer by analyzing the Chinese character into component radicals (i.e., component, simpler characters). When the target logograph appeared, subjects could easily guess the answer to the logograph ''you yan nan jian'' (''having eyes but being unable to see'') because the target logograph resembled the heuristic logograph in a key aspect. The superficial meaning, ''you yan nan jian'' is ''having eyes but being unable to see''. The answer to this riddle's is a Chinese character ''mang'' (盲, meaning blind). In Chinese, ''mang'' is composed of two simpler characters, ''wang'' (亡, is a phonetic radical, and pronounced ''mang'' in old Chinese) and ''mu'' (目, is a semantic radical signifying that the word concerns eyes). By understanding the surface meaning of the riddle and isolating the Chinese character ''mu'' from the character ''mang'' in which ''mu'' is embedded, the answer ''mang'' can be obtained.

In addition, we used a baseline logogoriph (No-aha condition), so that the activation caused by general problem processing could be differentiated from the activation caused by processes associated with insightful problem solving. For these baseline logographs, there was no paradoxial misleading information given in the riddle. For instance, the riddle ''shi tou cheng dui'' (石头成堆) means ''a pile of stones'' and refers to the Chinese character ''磊'' (as can be seen, three ''shi's'' are stacked up). In Chinese, ''石'' means a stone, and '' a pile of stones'' or stacking up three Chinese characters (石) in a pile forms the Chinese character (磊).

2.3. Procedure

To familiarize subjects with the procedure and pace of this task, we trained them with a set of similar materials in the same procedure before they entered the scanner. In the formal experiment, 96 test logogriphs (60 target and 36 baseline logogriphs) were presented in an event-related design in four separate blocks with 24 logogriphs per block. There was not any repetition of stimuli in the formal test. Most logogriphs were between 2 and 6 characters in length, while all the answers were a single character. The words that appeared in both the questions and answers were of high frequency. They were presented in the center of the screen in size 16 Song Ti font.

The flow of the learning–testing procedure is shown in Fig. 1. First, 5 heuristic logogriphs (including answers) were presented in the center of the screen one at a time for 8 sec each during the learning stage. The 5 heuristic logogriphs were presented in a random order for each subject and sub-block. Subjects were instructed to understand the logogriph and its answer. After they had seen 5 heuristic logogriphs, the testing stage began. The test stage began with a 2-sec ready signal (“Ready?”) followed by a plus sign for 1 sec which was followed by a test logogriph (either a baseline or a target logogriph randomly selected from the 8 logogriphs) displayed for 6 sec. Subjects were required to guess at the answers during the 6 sec period. They pressed “1” key if they believed they guessed the answer but made no response if they thought they did not guess the answer. The display of the logogriph was followed by a 1 sec interval of a + sign, and finally the correct answer was presented for 2 sec. At this time, subjects judged whether the guess they made was the same as the correct answer. They pressed “1” key if their guessed answer was the same as the correct answer, but made no response otherwise. Between two blocks, they could take a short rest.

In order to determine whether there was a significant difference between the rating on target and baseline logogriphs, we had another group of subjects (total 12) solve these logogriphs with a procedure similar to that used for our fMRI study. When subjects solved the test logogriph, they were required to rate their Aha experience on a scale of 1 (No-aha feeling) to 3 (strongest Aha feeling) for each test logogriph.

2.4. Scanning procedures and image acquisition

Images were acquired from a 3 T Siemens TRIO MRI scanner (repetition time – TR = 2000 msec, echo time – TE = 30 msec, 30 axial slices with 4 mm thick each, .8 mm gap, field of view 200 × 200 mm, acquisition matrix was 64 × 64, flip angle 90°, in-plane resolution = 3.0 × 3.0 mm^2). For each subject, we acquired whole-brain T1-weighted anatomical scans and gradient echo T2*-weighted echo planar images (EPI) with blood oxygen level dependent (BOLD) contrast.

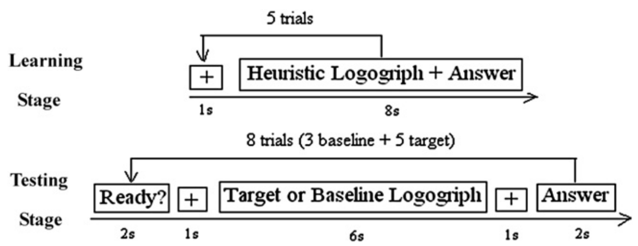

Fig. 1 – The flow of learning and testing logogriphs in each learning–testing repetition.

2.5. Imaging data analysis

Data analysis was performed with statistical parametric mapping (SPM2) from the Wellcome Department of Cognitive Neurology, London. Scans were first realigned, normalized (using the functional EPI template provided in SPM2), smoothed (a Gaussian kernel with a full width at the full width at half maximum – FWHM of 8 mm), and filtered (high-pass filter set at 128 sec, low-pass filter achieved by convolution with hemodynamic response function). The resulting images had cubic voxels of 3 × 3 × 3 mm. Two types of events were defined in the analysis based on subjects' responses: (1) presentation of the target logogriphs to which participants guessed the answer correctly (Aha condition, this event was time-locked to the beginning of target logogriph presentation with a duration of 2 sec); (2) presentation of the baseline logogriphs to which participants guessed the answer correctly (No-aha condition, this event was also time-locked to the beginning of baseline task presentation with a duration of 2 sec).

For each participant, an event-related analysis contrasted fMRI signal for Aha condition with that for No-aha condition. Aha condition versus No-aha condition difference-scores from each participant were combined in a group-level random effects analysis to identify differences consistent across participants. These contrasts used an uncorrected voxelwise threshold of $p < .0001$ with a corrected $p < .05$ for cluster extent of thirty contiguous voxels. This combination threshold yields very low false-positive rates in simulations.

3. Results

3.1. Behavioral data

Behavioral data showed that, the average number of target logogriphs that subjects guessed correctly (Aha condition) was 37 (standard deviation – SD = 9), and the mean reaction time (RT) was 2745 msec (SD = 341). The average number of baseline tasks that subjects also guessed correctly (No-aha condition) was 28 (SD = 4), and the mean RT was 2251 msec (SD = 320). Repeated-measures analyses of variance (ANOVA) for correct ratio and RTs showed that the effects of task type was significant [$F(1, 15) = 53.8$, $p < .001$; $F(1, 15) = 37.5$, $p < .001$], which indicated that these target logogriphs were indeed more difficult for subjects to solve than the baseline logogriphs even when subjects learned the specific heuristic logogriphs.

In addition, according to the 12 subjects' average ratings on target and baseline logogriphs, we found that there was a significant difference [$F(1, 11) = 13.22$, $p < .01$] between the mean score for the target logogriphs (mean score = 1.5, stronger aha feeling) and that of the baseline logogriphs (mean score = 1.3, No-aha feeling). That is to say, we thought that it might be effective to compare the fMRI signal for Aha condition (solved target logographs) to that for No-aha condition (solved baseline logographs).

3.2. Imaging data

Contrasts were set up between Aha condition and No-aha condition. The main contrast of Aha condition–No-aha condition using a random effects analysis resulted in activation in the precuneus (BA 19/7), the left inferior/middle frontal cortex (BA 9/6), and the inferior occipital gyrus (BA 18), and the cerebellum. A reverse analysis (No-aha condition–Aha condition) revealed mainly significant effects in the superior temporal gyrus (BA 22), the medial frontal/ACC (BA 9/32), the right postcentral gyrus (BA 40) and the right posterior cingulate gyrus (BA 31). These results are summarized in Table 1 and in Fig. 2.

4. Discussion

In the present study, our results showed that "Aha" effects can be localized in three main areas in the brain: (1) the precuneus which is involved in successful episodic memory retrieval, (2) the left inferior frontal gyrus (IFG) and middle frontal gyrus (MFG) which is involved in forming novel association and breaking a mental set, (3) the inferior occipital gyrus and the cerebellum which are involved in the rearrangement of visual stimuli leading to a representational change. We would discuss the role of these areas in insightful problem solving.

4.1. Precuneus

Many recent fMRI studies suggest that the precuneus might be related to episodic memory retrieval success (e.g., Dobbins et al., 2003). This kind of memory entails the recollection of heuristic information that is related to an individual's previous learning experiences (e.g., Tulving, 2002). Our study found that activation of the heuristic information (prototype event) is associated with reconstructing the problem representation in solving the target logograph. That is, episodic memory is employed for storage and recall of previously experienced events (i.e., prototype events subjects learned earlier the experiment). In addition, previous work indicated that the precuneus is sensitive to the quality or amount of information retrieved (e.g., Nyberg et al., 2000; Rugg et al., 1998). Based on these findings, we speculated that the precuneus might be involved in retrieval of heuristic information.

4.2. Left inferior/middle frontal cortex

Recently, many fMRI studies have found that understanding metaphoric sentences elicits greater activation than does literal sentences in the left IFG (e.g., Rapp et al., 2004; Eviatar and Just, 2006; Mashal et al., 2007). This finding indicated that the left IFG is more activated when subjects processed novel metaphorical meaning compared with literal meaning of an expression. Moreover, Mashal et al. (2007) suggested that the cooperation of left (IFG and MFG) and right (posterior superior temporal sulcus – PSTS and IFG) brain regions is required for attributing novel, creative, meanings to two word expressions. In addition, the left MFG plays a role in manipulation of information being actively maintained in working memory, as required for high-level planning (e.g., Cairo et al., 2004; Woodward et al., 2006). Previous work also proposed that the ventromedial PFC might be involved in quick intuitive "feeling of rightness" responses (Gilboa, 2004; King et al., 2005). In our study, subjects needed to understand the potential significations of these logographs in order to guess it correctly, a process similar to comprehending "novel metaphorical meaning" of a metaphoric sentence or an ambiguous idiom. Thus, we suggest that activation of the left IFG/MFG clusters might be involved in breaking a mental set and forming novel associations under Aha condition compared with No-aha condition.

4.3. Inferior occipital gyrus and cerebellum

We found that increased activation of the inferior occipital cortex was also involved in the "Aha" effects during solving the target logographs. Blackwood et al. (2004) indicated that the activation observed in occipital cortex might represent a greater degree of use of visual imagery when comparing two competing probabilistic hypotheses relative to two uncertain events. In a similar study, Luo et al. (2006) found that the left inferior occipital was activated in chunk decomposition of a Chinese character. To some extent, our results support their demonstration that visual processes can provide the crucial information for representational change during insightful problem solving (Luo et al., 2006). In addition, accumulated evidence indicates that the cerebellum engages in online amplification and refinement of behaviors or thoughts as they are occurring, which provides an error correction mechanism for performing the task (e.g., Houk, 2005; Ravizza et al., 2006). Based on these suggestions, we believe that the cerebellum might be involved in the rapid deployment of attentional resources in a highly attentive condition (Aha condition).

4.4. Implications

In a word, our results are different from previously reported results in CRAs problems (e.g., Bowden and Jung-Beeman, 2003; Bowden et al., 2005) where the right anterior temporal activation has been found to be associated with making connections across distantly related information during comprehension. In addition, Reverberi et al. (2005) found that patients with focal damage to the lateral frontal cortex should perform better than a group of healthy participants on the rather difficult matchstick insight problems (Reverberi et al., 2005). Goel and Vartanian (2005) also investigated the neural basis of insight problem solving (Match Problems: a classic divergent thinking task), and found that a comparison of Match Problems versus baseline trials revealed activation in right ventral lateral PFC (BA 47) and left dorsal lateral PFC (BA 46). In a recent fMRI study, Aziz-Zadeh et al. (2009) used English anagram solving to compare the neural correlates of insight with search solutions, and their findings were different from previous studies. Specifically, they found that verbal insight solutions activated a distributed neural network that included bilateral activation in the insula, the right PFC, and the ACC. Thus, we thought that different kind of problems

Table 1 – Brain regions showing significant differences by comparisons between Aha and No-aha conditons (voxelwise threshold of $p < .0001$, with a corrected $p < .05$ for cluster extent, $n = 16$, KE > 30).

Gyrus/structure	BA	Cluster		Voxel				Talairach coordinates		
		p (cor)	KE	*p* (FDR-cor)	T	Z	*p*(unc)	x	y	z
Aha > No-aha										
Right precuneus	19	.000	304	.000	11.21	5.72	.000	33	−69	36
Right superior parietal lobule	7			.000	10.22	5.50	.000	30	−69	45
Right superior parietal lobule	7			.000	10.09	5.47	.000	30	−60	45
Left precuneus	19	.000	399	.000	8.88	5.17	.000	−30	−69	33
Left superior parietal lobule	7			.000	8.25	4.99	.000	−30	−60	42
Left precuneus	7			.001	8.01	4.92	.000	−18	−72	48
Right inferior occipital gyrus	17	.000	176	.000	9.32	5.29	.000	21	−93	−3
Right inferior occipital gyrus	18			.000	8.65	5.11	.000	33	−93	−12
Right middle occipital gyrus	18			.001	6.22	4.31	.000	36	−93	3
Left inferior occipital gyrus	18	.000	279	.001	7.69	4.82	.000	−30	−93	−6
Left inferior occipital gyrus	18			.001	7.56	4.79	.000	−21	−96	−6
Left gyrus fusiformis	37			.001	7.17	4.66	.000	−45	−66	−15
Left inferior frontal gyrus	9	.000	98	.001	6.89	4.56	.000	−45	6	30
Left middle frontal gyrus	9			.001	6.17	4.29	.000	−51	15	33
Left middle frontal gyrus	6	.000	56	.001	7.07	4.62	.000	−33	0	54
Right cerebellum		.000	45	.001	7.41	4.74	.000	39	−69	−27
Right cerebellum				.001	6.89	4.56	.000	27	−63	−30
Left cerebellum		.000	30	.001	7.35	4.72	.000	−3	−81	−30
Right cerebellum				.001	7.09	4.63	.000	9	−78	−24
No-aha > Aha										
Right superior frontal gyrus	9	.000	530	.002	8.54	5.08	.000	3	51	27
Medial frontal gyrus	9			.002	8.38	5.03	.000	0	57	18
Left anterior cingulate	32			.002	7.29	4.70	.000	−12	36	9
Right postcentral gyrus	40	.000	221	.002	8.74	5.13	.000	63	−21	21
Right precentral gyrus	13			.002	7.04	4.61	.000	48	−12	9
Right postcentral gyrus	40			.002	7.02	4.60	.000	54	−24	21
Left superior temporal gyrus	22	.000	89	.002	7.36	4.72	.000	−51	−12	3
Left superior temporal gyrus	22			.002	6.62	4.46	.000	−54	−3	3
Left superior temporal gyrus	22			.003	6.30	4.34	.000	−39	−3	−6
Right superior temporal gyrus	13	.000	80	.002	6.92	4.57	.000	39	0	−3
Right superior temporal gyrus	38			.002	6.86	4.55	.000	30	3	−12
Right cingulate gyrus	31	.000	91	.003	6.07	4.25	.000	6	−24	39
Right paracentralis gyrus	5			.003	6.00	4.22	.000	12	−36	48
Right cingulate gyrus	31			.003	5.52	4.02	.000	18	−30	39

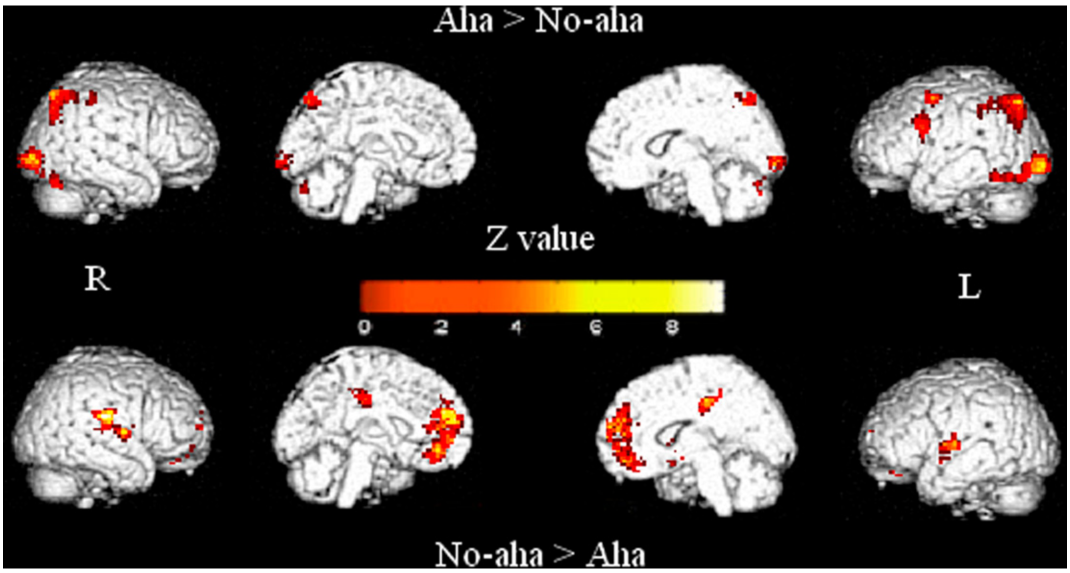

Fig. 2 – Brain regions with significant activity for the comparison between Aha and No-aha conditions (voxelwise threshold of $p < .0001$, with a corrected $p < .05$ for cluster extent).

might result in different brain activation of the "Aha" effects. Therefore, the brain activation pattern associated with insightful solution in our study may be also different from theirs.

4.5. *Limitations and future directions*

In the present study, we used learning–testing paradigm to examine brain activation of "Aha" effects with event-related fMRI during solving the Chinese word riddles. Although we selected interesting and novel Chinese logographs as materials, we did not have independent measures of whether and when the "Aha" experience actually occurred in a given trial. In addition, although subjects could solve the target logographs quickly due to learning the corresponding heuristic logographs, some key cognitive processes of insight problem solving, such as representation change, restructuring and breaking mental set, might be weakened. Therefore, in the future, we would use the method (subjective reports of the solving experience; Bowden and Jung-Beeman, 2003; Bowden et al., 2005) to identify whether a problem has been solved with an insight.

In our study, behavioural data showed that the RTs (correct ratio) from our baseline task were much faster (ratio higher) than those in the insight condition. These results suggested that subtracting the activation found in No-aha condition (baseline logographs) from the activation found in Aha condition (target logographs) might not be a completely reasonable thing to do, because the differences between the conditions might be confounded with unequal difficulties of the problems in the two conditions. In future studies, we should pay much more attention to this problem. Our experimental paradigm should be improved and more efficient materials should be developed. Nevertheless, Brain-imaging techniques like ERP and fMRI can be effectively applied to high-level cognitive processes to reveal human's brain mechanisms in creative thinking and problem solving.

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