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The Function of the Anterior Cingulate Cortex (ACC) in the Insightful Solving of Puzzles: The ACC Is Activated Less When the Structure of the Puzzle Is Known

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It has been observed in recent neuroimaging studies that the anterior cingulate cortex (ACC) is involved in the insightful solving of puzzles. Yet, the exact function of the ACC in insight is not clear. In this event-related fMRI study, we compared the neural correlates of the solving of two kinds of puzzles. In Condition A, the subjects solved a list of puzzles that were constructed by different principles; whereas in Condition B, all of the puzzles were constructed by the same principle. Thus, it was possible for the solvers to allocate some task-general strategy to solve the puzzles in Condition B. For Condition A, such top-down control was relatively difficult to achieve. The results showed that, relative to the resting baseline, both conditions evoked comparable activities in the left lateral prefrontal cortex, but that Condition A evoked more ACC activities than

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Condition B. This result implied that the function of ACC in the insightful solving of puzzles was not to serve as the regular top-down attentive control, but rather as an "early warning system" when the top-down control has failed

Insights are sporadic, unpredictable, short-lived moments of exceptional thinking, during which implicit assumptions about the relevance of common knowledge to a problem must be discarded before a solution can be revealed. These assumptions define the boundaries of a mental set that constrains a subject's search for a solution. Discarding these assumptions is generally regarded as the breaking of one's mental impasse; hence, the figurative description of ìthinking outside the box.î The concept of mental impasse emerged from early research on classic problem-solving tasks, such as Maier's "nine-dots problem" and "two strings problem," Duncker's "candle problem," and Luchins' "water-jug problem." Typically, achieving the desired goal requires using an object in a way that differs from its common, intended function. For example, in Duncker's "candle problem," the subjects are given a candle and a box of nails, and the goal is to attach a candle to a wall so that the wax does not melt onto the floor. Naturally, the subjects assume that the role of the box is to contain the nails, and that the role of the nails is to attach the candle to the wall. But, these assumptions do not afford a solution. Instead, the solution requires treating the box as a container for the candle and using a nail to attach the box to the wall. Studies showed that subjects failed to solve the problems because they could not break out of their fixation on the natural roles of objects.

The nature of insight makes a neurological study paradoxical: In addition to the obvious physical constraints, recording generally requires a precise timing of repeatable behavior. But once insight has been attained on a problem, subsequent exposure to it or to a closely related problem is no longer regarded as likely to lead to insights. For example, changing the basis of classification between a few well-known dimensions (e.g., color, shape, etc.) in the Wisconsin Card Sorting Task (WCST) is regarded as shifting one's mental set, not breaking it (Monchi, Petrides, Petre, Worsley, & Daghe, 2001). Conversely, if the relevant dimensions are well hidden, the time involved in coming to a solution can vary beyond the constraints of the data acquisition method. To resolve this issue, we provided a trigger to catalyze the puzzle-solving process. This allowed us to record neural activity correlated with breaking one's mental set within a time-limited window for a large variety of puzzles that the subjects previously regarded as unsolved.

By using traditional riddles as materials, our previous neuroimaging study showed that a wide region of the cerebral cortex was involved in the insightful solving of problems (Luo & Niki, 2003). In particular, it was proposed that the activities of the medial prefrontal cortex and anterior cingulate cortex (ACC) are related to the process of breaking through a mental impasse when gaining an insight (Luo, Niki, & Phillips, 2004; Mai, Luo, Wu, & Luo, 2004), because this area is known to be involved in the monitoring of cognitive conflicts (see Botvinick, Braver, Barch, Carter, & Cohen, 2001, for a review). In contrast to the general point of view that the ACC is the mechanism that detects the co-occurrence of competing motor responses in incongruent trials of Stroop and Flanker tasks (Botvinick et al., 2001), our observation implied that the function of the ACC could be less specific. The ACC could also participate in the insightful solving of puzzles where cognitive conflicts are created by a competition between the correct way of thinking and the incorrect but prepotent and more readily accessible way of thinking. This hypothesis was consistent with the results of previous neuroimaging studies that proved that the ACC also participates in higher-level cognitive conflicts such as semantic processing and metacognition processing. In the task of generating verbs, for example, there is greater activation of the ACC when a person is generating a verb for a noun that has many associated verbs than for a noun that has a single dominant verb (Barch, Braver, Sabb, & Noll, 2000). The ACC was also found to be activated in the tip of the tongue (TOT) state, which involved a conflict between the metacognitive level — a person's confidence in the existence of knowledge — and the cognitive level — his or her actual inability to retrieve the target knowledge (Maril, Wagner, & Schacter, 2001).

Yet the critical characteristics of ACC in the generation of insights are not clear. Generally speaking, the ACC appears to be involved in a wide range of activities that have been collectively termed the "executive function" (Vogt, Finch, & Olson, 1992). For example, the ACC is known to reflect the detection of input conflicts in Stroop tasks and in the detection of output (response) errors and/or conflicts in tasks such as the Eriksson flanker task and the Continuous Performance Test (AX-CPT) (e.g., Carter et al., 1998). Early studies showed the ACC to be involved in various kinds of high-level cognitive tasks such as language comprehension, problem solving, and cued-recall; and it was generally considered that this area serves in the role of attentive control. In contrast to this general hypothesis, recent neuroimaging studies have revealed that the function of the ACC could be more specific. For example, it has been suggested that the ACC's function was not to implement top-down attentional control or strategic processes. Rather, the ACC functions as an early warning system when strategic processes are less engaged or have failed (Botvinick et al., 2001; Carter et al., 2000; Milham, Banich, Claus, & Cohen, 2003). It was proposed that the ACC is engaged when task-irrelevant information is relatively automatic and top-down control fails to abolish the activation evoked by that information (Milham et al., 2003). Carter et al. (2000) changed the ratio of incongruent versus congruent trials in different blocks of the Stroop task. In this way, they manipulated the strategic processes engaged in processing. Their results showed that the response-related increase in ACC activity was present when strategic processes were less engaged and when conflict was high, but not when strategic processes were engaged and conflict was reduced. This observation implies that the function of the ACC is somewhat "compensation-like" — it participates in processing only when the regular top-down control fails. In other words, the ACC serves as an "early warning system" to deal with the unusual situation in which no suitable strategic process has been prepared in advance or where the tendency to follow the wrong direction in information processing is relatively automatic. A similar framework to understanding the function of the ACC was proposed by Smith and Jonides (1999). According to their theory, the ACC mediates the inhibition of "preprogrammed responses." For example, in the Stroop task, the tendency to name a color word according to its semantic meanings (e.g., to name "RED" in blue ink as "red") is a kind of "preprogrammed response" that was highly skilled and automatic. To inhibit this tendency requires the involvement of the ACC. The difference between the regular top-down control and the control allocated by the ACC might be like that between the "software" and the preprogrammed "firmware," whose codes were less easily rewritable (i.e., the difference between changing a WinWord document and modifying the WinWord software itself).

Based on these hypotheses on the function of ACC, we hypothesize that the role of the ACC in generating insights is not that of the regular top-down attentional control; rather, the ACC serves as "early warning system" — breaking the mental impasse when top-down control fails. In insight, the top-down control may fail for two reasons. One is that the solution/keyword to the puzzle was unexpected and no suitable strategic processes could be prepared in advance. The other is that the switchover of thinking directions occurred within a very short period, and the tendency to follow the wrong direction of thinking was relatively automatic. For these two reasons, the regular top-down control, which might be mediated by the left prefrontal cortex, failed in insightful problem solving, and the ACC was needed to engage in processing.

There are two pieces of evidence that support such a hypothesis. The first is that, in the WCST, which also involves cognitive set shifting, no ACC activation is observed (Monchi et al., 2001). The WCST asks the subject to match test cards to reference cards according to the color, shape, or number of stimuli on the cards. Feedback is provided after each match, enabling the subject to acquire the correct rule of classification. After a fixed number of correct matches, the rule is changed without notice, and the subject must shift to a new way of classification. Thus, the WCST measures cognitive flexibility, which is the ability to alter a behavioral response mode in the face of changing contingencies (set-shifting). Neuroimaging studies have shown that, although relative to the baseline, there was ACC activation in the WCST, this activation could not survive the contrasts of ìreceiving negative feedback minus receiving positive feedbackî that critically signaled the need for a mental shift to a new response set (the area that is sensitive to set-shifting is the left lateral prefrontal cortex) (Monchi et al., 2001). Why has no ACC activation been observed in the WCST? It is possible that in the WCST the basis of card sorting is repeatedly switched among several well-known dimensions (e.g., color, shape, or number). Thus, the subjects always know what to do next when they receive negative feedback. In other words, the subjects are able to implement some task-general strategy or top-down control in the WCST. However, the situation for insights is different. It has been shown that insightful problem solving is beyond the monitoring of metacognitive processes. For example, the subjects usually know, by their feeling-of-knowing (FOK) judgments, when they are on the verge of solving analytical problems (such as those found in standardized tests). However, the subjects had little ability to rate their closeness to solutions to problems of insight. This supports the hypothesis that the insight is beyond the monitoring of metacognition (Metcalfe, 1986a, 1986b; Metcalfe & Weibe, 1987). It is for this reason that ACC activities are observed in insightful problem solving but not in WCST — although both tasks require the solver to change his/her information processing set.

The second piece of evidence consistent with the hypothesis that the

ACC functions as an “early warning system” in breaking of a mental impasse when the top-down control fails is that the activation of the ACC decreased when the subjects became familiar with the insightful solving of puzzles and developed some task-general strategy. In our recent studies (Luo, Niki, & Phillips, 2004), we examined the involvement of the ACC across the first, second and third blocks in the whole experimental session. The results showed that, relative to the resting state, all of the three blocks were associated with activities in both the ACC and left lateral PFC; however, greater ACC activity was observed for the first block than for the second and third ones, with the ratios of Aha/insight events comparable in the three blocks. This result is consistent with Milham et al.’s (2003) observation that the practice-related decreases in ACC activity were more rapid and more pronounced than those in the lateral PFC. Milham et al. proposed that the ACC engaged in response-related processes when top-down control, which might be mediated by the lateral PFC, failed to abolish the activation evoked by task-irrelevant information. Therefore, the involvement of the ACC declined when the implementation of attentional control became more effective with practice. Accordingly, in “Aha! Reaction,” the reliance on the function of the ACC might be reduced when some task-general strategy to control the situation was developed with practice.

The above-mentioned consideration implies an interesting hypothesis that the involvement of the ACC will decrease once the subjects grasp the structure of the puzzle and are able to allocate some top-down control. In this study, we compared the neural correlates in the solving of two kinds of puzzles. In Condition A, the subjects solved a list of puzzles that were constructed by different principles; whereas in Condition B, all of the puzzles were constructed by the same principle. We proposed that it was possible for the subjects to allocate some task-general strategy to solve the puzzles in Condition B; but that for Condition A, it was relatively difficult for them to do so. The so-called “cerebral gymnastics” puzzles, which contain descriptions designed to divert attention from the solution, were taken as materials for Condition A. Different “cerebral gymnastics” puzzles were constructed in different ways. For example, to the puzzle “For many reasons the newspapers do not report the facts as reliably and honesty as they should. However, there is one thing that you can always believe in. What’s that?” The answer is the “date of press.” In this puzzle, the puzzle solver’s attention was misled to the contents of the newspapers, and he/she might search for the answer from among different kinds of news (political news, medical news, scientific news, etc.). The "date of press" evoked an insightful solution because the date is also printed in the newspaper, but is usually not considered part of the contents. Another example is: "There are 13 oranges to be given equally to nine persons, how do you do that?" (Make juice). The person trying to solve the puzzle might be aware that 13 cannot be divided exactly by 9, and think about ways to divide the oranges by a knife. However, this way of thinking could not result in a perfect answer. The orange juice is liquid that can be exactly measured and divided. In Condition B, the "homophone puzzles" were used. The "homophone puzzle" is a type of Japanese puzzle that conceals a solution that is orthographically, but not semantically, related to the elements of the puzzle. For example, "What is the animal that can win three times?" The answer is "salamander." In Japanese, "salamander" is read as "*san*-*shou*-*uo*," with "*san*" having the same pronunciation as "three" and "*shou*" the same pronunciation as "win." To the puzzle "What is the food that a male eats and then dies?", the answer is *Osu*-*si* (*Osu*-*si* is a type of food; but "*osu*" also means "male" and "*si*" means "died"). To the puzzle "What is the place where one will become old if one goes there?", the answer is corridors (corridors is read as "*rou*-*ka*" in Japanese; but "*rou*" also means "old" and "*ka*" means "to become"). Thus, in Condition B, all of the puzzles are generated from the same principle and the solver can be aware that they should search for a word whose pronunciation is consistent with the meaning of the puzzle, but inconsistent with the meaning of the word.

In both conditions, the list of puzzles for each subject was selected through a pre-scan test, so that the subjects understood these puzzles and dwelled on unsuitable approaches, but did not yet know the answers. During scanning, we provided a trigger (the solution) to catalyze the puzzle-solving process. This allowed us to record neural activity correlated with insight within a time-limited window. The pre-scan testing procedure ensured that each puzzle was sufficiently pondered over and that the unsuitable approaches were thoroughly considered. This procedure also enabled us to get sufficient a number of trials needed for imaging. The procedure of providing the answers to the subjects guaranteed that the event of puzzle-solving occurred within a time-limited window — this procedure was necessary, given that the time to a solution could vary beyond the constraints of the data acquisition method (usually less than 20–30 minutes). Recognizing a presented solution might differ from finally coming up with a solution to a problem after having dwelled on unsuitable approaches in several aspects, such as the “feeling of achievement” and the sufficiency of the “incubation” process. However, this procedure maintained the essential component of insight. First, this procedure led to “Aha! Reaction,” in which the impasse was suddenly broken and transformation from “not knowing” to “knowing” was rapidly attained. Second, the solution was uncovered to the subjects when they were in the “impasse” states, in which (a) the information to solve the problem were adequate, (b) the methods to solve the problem were well within the competence of the problem solver, and (c) the correct solutions were still unknown after the problem had been sufficiently pondered over and the unsuitable approaches had been thoroughly thought about.

In sum, in this study, a list of “cerebral gymnastics” puzzles (Condition A) and a list of “homophone” puzzles (Condition B) were solved by two groups of subjects respectively. Both conditions contained the puzzles that were selected from the rich resources of the Internet, and were evaluated as highly reasonable and interesting by another group of subjects who did not participate in the formal experiment. Also, in both conditions, the list of puzzles was “subject-specific”: The list of puzzles for each subject was selected through a pre-scan test so that these puzzles were sufficiently thought about but the solutions were still unknown. The only difference between these two conditions were that the puzzles in Condition B share a common structure and that it was possible for the solver to allocate some task-general strategies; whereas in Condition A, such top-down control was relatively difficult to achieve because the structures of the puzzles were different from one puzzle to another. If, as was proposed earlier, the ACC serves as an “early warning system” in breaking of mental impasses rather than the regular top-down control mechanism, then the ACC will be activated more in Condition A than in B. On the contrary, if the role of the ACC in insightful problem solving is the regular top-down attentive control, then its level of activity in both conditions will be comparable.

Method

Participants

Twenty-one healthy, right-handed volunteers (6 females and 16 males), between the ages of 21 to 35, participated in the experiments. There were 11 participants (3 females and 8 males) in Condition A, and 10 (3 females and 7 males) in Condition B. The participants were interviewed one or two days before they attended the fMRI experiment and gave their informed consent to their participation, following an explanation of the experiment by the MRI ethics committee of the Neuroscience Research Institute of the AIST. We excluded any individuals from participating if he/she had a medical, neurological, or psychiatric illness, or if he/she did not feel well while in the MRI machine.

Procedures

In the pre-scan test, the participants were provided with a list of "cerebral gymnastics" puzzles (Condition A) or a list of "homophone" puzzles (Condition B) and asked to solve them. For each puzzle, the subjects were asked to select one of the following three possibilities: (a) I can understand this puzzle very well and also know the solution to it (they were also required to write down the solution in this situation); (b) I can understand this puzzle very well, but I do not know the solution; or (c) I cannot understand this puzzle and do not know the solution. The subjects were given a maximum of three minutes to work on each puzzle. All of the "b" type items were selected as materials for formal testing, and all of the "c" type items were abandoned. An "a" type item was selected only when the solution the subject thought about was different from the standard solution. In this way, we selected a list of 17 puzzles for each subject in Condition A and 20 for each subject in Condition B as the formal experimental list. The subjects understood the puzzle in the selected puzzles very well, but did not know the correct solution.

About one hour after the pre-scan test, the formal puzzle-solving task with the MRI scanning started. The selected puzzles and the corresponding solutions were presented in a randomized order relative to the pre-scan test. In Condition A, each puzzle or question was presented for 10 seconds. The subjects were required to press the left or right key of the response box that was attached on their right leg by their index or middle finger to indicate whether or not they could understand what the sentence meant (left key: yes, I can; right key: no, I cannot). They were required to do so before the end of the sentence presentation phase, after which time they were asked to cease thinking about the sentence. After a 6-second cross-viewing delay, the answer was uncovered (the puzzle-solving or the question-answering phase); the answer was presented for 5 seconds, followed by a 10-second cross-viewing delay. The subjects were required to press a key as early as possible to indicate whether or not they understood the solution (left key: yes, I can; right key: no, I cannot). The subjects were asked to cease thinking about the problem after they had made their judgment. (We explicitly told the subjects that “the main aim of this study is to detect your brain activity in the insightful puzzle solving that was evoked by the keyword, and, your brain activity during the cross-viewing delay will be taken as the ‘baseline’ for reference. For this reason, it is important to not think about the puzzle any longer after you have made your judgment. During this resting stage, please clear your mind to wait for the keyword or next puzzle.”) The procedures for Condition B were the same, except that the durations between the presentation of the stimuli were shorter. In Condition B, each puzzle was presented for 5 seconds; then, after a 6-second unfilled delay, the solution was presented for 5 seconds, followed by a 4-second unfilled delay. We thought that the differences in the two conditions in terms of the duration during which the stimulus was presented did not effect the results of this study because (a) the event-related analysis of the SPM software enabled us to detect the momentary response in just the moment when insightful problem solving occurred; (b) the durations in both conditions were long enough for one’s mind to return to the resting state; and (c) we did not do a between-subjects contrast in this study; rather the processes of insightful problem solving was only contrasted against the implicit baseline within that condition. To familiarize the subjects with the procedures and pace of the task, they were trained with another set of similar materials in the same procedure before the formal experiment. Besides the puzzle-solving task, another task was also included in Conditions A and B, but that task was unrelated to the major topic of this paper and is not reported here.

FMRI Data Acquisition

All scanning was performed on a 3.0-Tesla MRI Scanner (GE 3T Signa) equipped with EPI capability. Eighteen axial slices (5.3 mm thick, interleaved) were prescribed to cover the whole brain (there were gaps between the slices, and the standard thickness of the gap was 1.0 mm). A T2* weighted gradient echo EPI was employed. The imaging parameters were TR = 2 sec, TE = 30 ms, FA = 70 degrees, FOV = 20 × 20 cm (64 × 64 mesh). To avoid head movements, participants wore a neck brace and were asked not to talk or move during scanning. Motion correction was also performed in a standard realignment process in SPM99.

FMRI Data Analysis

The image data were analyzed by SPM99. The data of the 11 subjects in Condition A (or that of the 10 subjects in Condition B) were individually pre-processed (timeslice adjusted, realigned, normalized, and smoothed). The data were then estimated to establish a random-effects model in which five types of trials were defined, including the presentation of questions, the answer presentation that evoked successful solutions, and the answer presentation that failed to evoke successful solutions (the subjects judged those answers to be "incomprehensible"). We also modeled two other kinds of trials that were unrelated to the main goal of this paper and are therefore not reported here. The presentation of puzzles or questions was modeled using a boxcar function convolved with the canonical hemodynamic response function. The presentation of solutions or answers was time-locked at the beginning of the presentation of the solution and modeled with the canonical hemodynamic response function. The threshold was set at $p < .001$ (uncorrected) and at 10 or more contiguous voxels (the size of each voxel is 2 mm^3). The locations reported by the SPM were converted into Talairach coordinates (Talairach & Tournoux, 1988) by the transform specified in the mni2tal.m program (Brett, 2002). These coordinates were used to determine the nearest gray matter (region and corresponding Brodmann area) using the Talairach Daemon program version 1.1 (Lancaster et al., 2000) with a maximum range of 11 mm.

Results

The participants' online judgment indicated that, with the help of the presented answers, they successfully solved 91% of the "cerebral gymnastics" puzzles in Condition A and 95% of the "homophone" puzzles in Condition B. The averaged response times to the puzzles and solutions are shown in Table 1. To extract and define the neural networks underlying the processes of puzzle solving, the answer presentation events that evoked

Table 1. Response Time in Two Conditions

	To puzzle		To solution	
	Condition A	Condition B	Condition A	Condition B
Response time	4.78	3.68	2.70	2.13
SD	0.84	1.55	0.45	0.42

successful solutions in Conditions A and B were analyzed against the implicit baseline. Contrasted with the resting baseline, the solving of "cerebral gymnastics" puzzles in Condition A was associated with activity in the anterior cingulate gyrus (BA 24 and 32) and the medial frontal gyrus (BA 8), the bilateral inferior frontal gyrus (BA 9, 47, 44, and 45), the right precentral gyrus (BA 44) and the left postcentral gyrus (BA 3), the right superior and inferior temporal gyrus (BA 38 and 37), the left middle temporal gyrus (BA 37 and 39), the left inferior parietal lobule (BA 7), the left thalamus, the left red nucleus, the right medial globus pallidus, the left angular gyrus (BA 39), and the left precuneus (BA 19) (Table 2). Contrasted with the resting baseline, the solving of "homophone" puzzles in Condition B was associated activities in the bilateral inferior frontal gyrus (BA 47 and 44) and the bilateral insula (BA 13), the left anterior

Table 2. Significant Voxels of Activity for the Solving of Puzzles Minus Resting in Condition A

Number of voxels	T	Talairach Coordinates x	y	z	Area
912	12.29	4	4	37	R. Cingulate Gyrus, BA 24
	6.95	4	19	38	R. Cingulate Gyrus, BA 32
	6.05	2	25	43	R. Medial Frontal Gyrus, BA 8
313	10.56	40	15	–14	R. Inferior Frontal Gyrus, BA 47
	5.66	34	5	–12	R. Superior Temporal Gyrus, BA 38
1,262	8.59	–50	16	10	L. Inferior Frontal Gyrus, BA 44
	8.02	–46	9	22	L. Inferior Frontal Gyrus, BA 9
	7.55	–36	17	–11	L. Inferior Frontal Gyrus, BA 47
377	7.64	–6	–19	1	L. Thalamus
	7.22	0	–26	–12	L. Red Nucleus
230	7	–51	–56	1	L. Middle Temporal Gyrus, BA 37
	4.86	–48	–67	11	L. Middle Temporal Gyrus, BA 39
214	6.75	48	11	23	R. Inferior Frontal Gyrus, BA 9
25	6.57	61	–55	–4	R. Inferior Temporal Gyrus, BA 37
20	6.53	16	–2	0	R. Medial Globus Pallidus
110	6.44	–40	–29	51	L. Postcentral Gyrus, BA 3
109	5.77	–30	–60	38	L. Angular Gyrus, BA 39
	5.27	–32	–58	47	L. Inferior Parietal Lobule, BA 7
	4.35	–24	–72	31	L. Precuneus, BA 19
13	5.57	46	6	9	R. Precentral Gyrus, BA 44
40	4.63	53	16	5	R. Inferior Frontal Gyrus, BA 45

Note. L.: left; R.: right; BA: Brodmann area.

cingulate gyrus (BA 32 and 33), the left inferior parietal lobule (BA 40), the left supramarginal gyrus (BA 40), the left angular gyrus (BA 39), the left and right red nucleus, and the left precuneus (BA 19) (Table 3). Critically, the volume of activation in the left ventrolateral prefrontal cortex was similar for the two conditions (1,262 voxels in Condition A and 1,072 voxels in Condition B, with the random effect analysis at the same threshold of $p < .001$, uncorrected), but the volume of activation in the ACC was much more for Condition A than for Condition B (912 voxels in Condition A, 24 and 19 voxels in Condition B, with the random effect analysis at the threshold of $p < .001$, uncorrected) (Figure 1). This observation showed that the level of activity of the ACC was higher in Condition A than in B.

Discussion and Conclusion

In this study, we compared the solving of two types of puzzles, the "cerebral gymnastics" puzzles (Condition A) and the "homophone"

Table 3. Significant Voxels of Activity for the Solving of Puzzles Minus Resting in Condition B

Number of voxels	T	Talairach Coordinates x	y	z	Area
1,072	11.1	–36	21	–6	L. Inferior Frontal Gyrus, BA 47
	10.41	–40	4	11	L. Insula, BA 13
	6.88	–36	24	–20	L. Inferior Frontal Gyrus, BA 47
186	9.41	–46	–43	32	L. Supramarginal Gyrus, BA 40
	5.25	–42	–55	34	L. Inferior Parietal Lobule, BA 40
	5.12	–42	–33	40	L. Inferior Parietal Lobule, BA 40
69	6.64	34	14	–1	R. Insula, BA 13
	6.25	40	10	7	R. Insula, BA 13
25	6.43	4	–22	–6	R. Red Nucleus
33	5.93	50	5	13	R. Inferior Frontal Gyrus, BA 44
178	5.66	–30	–60	36	L. Angular Gyrus, BA 39
	5.06	–26	–72	37	L. Precuneus, BA 19
24	5.62	–2	11	23	L. Anterior Cingulate, BA 33
19	5.36	–4	21	32	L. Cingulate Gyrus, BA 32
27	4.97	–6	–21	–2	L. Red Nucleus
12	4.48	30	7	–14	R. Inferior Frontal Gyrus, BA 47

Note. L.: left; R.: right; BA: Brodmann area.

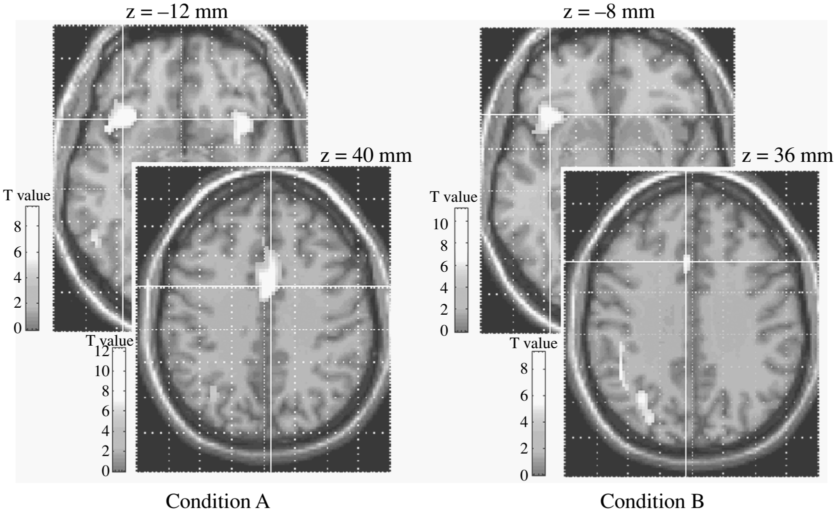

Figure 1. The Ventrolateral Prefrontal Cortex and the ACC Activities Shown in the Uncovering of the Criterion Solution to the Unresolved Puzzles in Conditions A (left) and B (right).

puzzles. The key difference between these types of puzzles was that the “cerebral gymnastics” puzzles were generated by a wider range of principles than the “homophone” puzzles. The subjects in Condition B reported that they knew that they should find a word whose pronunciation is consistent with the meaning of the puzzle, but inconsistent with the meaning of the word, even though they did not know what that word was when they solved the puzzle by themselves. However, in Condition A, although the subjects sometimes said “I know there is certain trick hidden in the descriptions of the puzzle,” they did not know exactly what kind of direction of thinking they should follow. Thus, an extra “early warning system” was needed to control one’s primary direction of thinking in processing the answers in Condition A. But in Condition B, such an “early warning system” was less needed because the answers were within one’s general information processing prediction. Consistent with these underlying cognitive processes, extensive ACC activity was observed to be associated with the solving of “cerebral gymnastics” puzzles in Condition A, but less ACC activity was associated with the solving of “homophone” puzzles in Condition B. This observation supported the hypothesis that the function of the ACC was not the routine top-down control; rather, the ACC served as an "early warning system" when top-down control failed.

It was not plausible that the differences between Condition A and B was caused by the fact that subjects solved more puzzles (prior to the appearance of the answer) in Condition B than in A. This is because, before the formal experimental session, both conditions included a pre-scan test that required the subjects to solve a long list of puzzles. Only these puzzles for which subjects failed to get the correct answer were selected as materials for the formal "question-answer" presentation session. In the formal "question-answer" presentation session, we also asked the subjects to make a judgment as to whether they could solve each question (puzzle) the puzzle before seeing the correct answer (the subjects might be able to solve some of the puzzles when they saw them again). Our records of the subjects' on-line responses showed they could not solve any of the selected puzzles by themselves. Therefore, in our experimental procedure, it was not possible that the answers to some of the puzzles in Condition A and B were known in advance, before the correct answer was uncovered.

Similar to the difference in the ACC, the right lateral prefrontal cortex also activated more in Condition A than in Condition B (see Figure 1, Table 2, and Table 3). This observation was consistent with the view of Garavan and his colleagues that proposed the right lateral prefrontal cortex could also participate in the processing of information (in addition to the left side) when the task was complicated and difficult (Garavan, Ross, & Stein, 1999).

In contrast to the activity in ACC and in right lateral prefrontal cortex, both conditions evoked comparable activity in the left lateral prefrontal cortex. This area was frequently reported in semantic tasks; it has been hypothesized that the left lateral prefrontal cortex subserves semantic retrieval (Buckner et al., 1995; Demb et al., 1995; Demonet et al., 1992; Kapur et al., 1994). However, later research showed that it was semantic selection, rather than semantic retrieval, that led to the activation of the left lateral prefrontal cortex (Thompson-Schill, D'Esposito, Auirre, & Farah, 1997). Besides semantic processing, the function of the left lateral prefrontal cortex was also proposed as the mechanism to hold cognitive goals in working memory and to allocate attention to the appropriate processing systems to meet those goals. Recent neuroimaging studies that temporally separated the preparatory attention from the response selection in attentional control showed that left lateral prefrontal cortex was responsible for establishing attentional sets and switching to new attentional sets (Luks, Simpson, Feiwell, & Miller, 2002; MacDonald III, Cohen, Stenger, & Carter, 2000). In particular, the left lateral prefrontal cortex was observed in the “negative versus positive feedback” contrast of the WCST that signaled the need for a mental shift to a new responseset (Monchi et al., 2001). These observations suggest that the function of the left lateral prefrontal cortex in the solving of puzzles might be related to top-down control. It was this area that mediated the shifting of cognitive sets in the solving of puzzles. The fact that the left lateral prefrontal cortex was equally activated in Conditions A and B implied these two conditions involved comparable components of semantic processing and top-down control.

The basic framework on insightful problem solving proposes that there is an “early” stage and a “late” stage to insights. The “early” stage (or the “illumination” phase) occurs when a penetrating flash of insight about an appropriately satisfying resolution to the original problematic situation appeared. This “early” stage is followed by the “late” stage (or “verification” phase), wherein the subjects apply the breakthrough to the whole context and work out the details of the resolution. Based on this view, and on the recent cognitive neuroscience observation showing that the detection of errors or conflicts is associated with the ACC and that the resolution of conflicts is associated with the lateral prefrontal cortex, it was reasonable for us to propose that the ACC might participate in the “early” or “illumination” stage of insightful problem solving, while the lateral prefrontal cortex might subserve the “late” or “verification” stage. However, we still cannot directly examine this point of view in this study because the temporal resolution of fMRI is not high enough (Logothetis, Paul, Augath, Trinath, & Oeltermann, 2001). Through using the event-related potentials (ERP) that were excellent in temporal resolution, we observed a difference wave, which peaked at around 380 ms (N380) after the presentation of the answers, which we associated with the activity of insightful puzzle solving. A dipole source analysis suggested that the generator of N380 was around the ACC (Mai et al., 2004). This result was highly consistent with our fMRI studies. Given that it took about 2000–3000 ms (this was the mean reaction time for insightful puzzle solving) for the whole process to be accomplished, the difference wave that peaked at 380 ms and had the generator around the ACC implied that this area might activate at the “early” or “illumination” stage of insightful problem solving. That is, the ACC might serve as an “early warning system” to pretreat unusual situations, to make possible the more concentrated processing that is allocated by the top-down control.

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扣帶前回在頓悟性謎語解決過程的作用：如果知道謎語的結構，扣帶前回的參與程度就降低

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摘 要

新近的腦成像研究表明，扣帶前回 (ACC) 參與謎語類問題的頓悟性解決過程。但是，這個區域在頓悟中的確切功能還有待進一步的研究。在這項事件相關功能性磁共振成像 (event-related fMRI) 研究中，研究者比較了參與兩類不同謎語的破解過程的大腦機制。A條件下的各項謎語是由不同的謎語構成規則形成的，而B條件下的各項謎語則由相同的規則構成。因此，在B條件下，問題解決者有可能採取一些一般性的問題解決策略，而在A條件下，這樣的一般性策略就難以奏效。研究結果表明，相對於靜息狀態而言，A、B兩種條件下的謎語破解過程激活了程度相當的左側額葉的活動，但在A條件下，ACC的活動明顯比B條件下的更多。這一結果說明：ACC在頓悟中的功能並不是一般性的自上而下的注意性信息加工，ACC是在當一般性的自上而下的信息加工不能起作用時作為「早期預警系統」而參與頓悟的。