

Neural correlates of the 'Aha! reaction'

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Received 21 May 2004; accepted 12 July 2004

An 'Aha! reaction' is a brief moment of exceptional thinking where an unexpected change in one's mental perspective reveals the solution to an otherwise intractable problem. In this event-related fMRI study, subjects read incomprehensible sentences followed by solution cues that were used to evoke such a reaction by triggering an alternative interpretation of the critical concepts. For 73% of the trials, subjects attributed their failure in the initial stage of

sentence presentation to "having thought about it in another direction". This behavior implies that the breaking of mental impasse is a critical component of the Aha! reaction phenomenon. During the Aha! reaction we observed anterior cingulate and left lateral prefrontal cortical activation, which are two areas known to mediate cognitive conflict. *NeuroReport* 15:2013–2017 © 2004 Lippincott Williams & Wilkins.

Key words: Aha! reaction; Anterior cingulate cortex (ACC); Event-related fMRI; Left lateral prefrontal cortex (PFC)

INTRODUCTION

The 'Aha! reaction' is the familiar abrupt change in mental perspective that leads one to the solution of an otherwise intractable problem. Auble and colleagues were first to introduce a sentence comprehension task as a way of evoking such a reaction in the laboratory [1]. In their experiment, subjects read ambiguous sentences followed by a solution cue. In the difficult-to-comprehend condition, two aspects of the sentence appeared incomprehensible without the solution cue. For example, in the sentence 'The haystack was important because the cloth ripped', the link between haystack and cloth is not obvious, because subjects usually suppose that cloth refers to something wearable. This assumption is so dominating that it is difficult if not impossible for a subject to interpret the word in any other way. An Aha! reaction is evoked with the solution cue parachute, which triggers the alternative interpretation that cloth refers to canopy and therefore the role of the haystack is to cushion a fall. By contrast, in the easy-to-comprehend condition, the two aspects of the sentence were highly correlated in daily life, so that subjects understood the situation without seeing the solution cue (e.g. 'The office was cool because the windows were closed' – 'air-conditioner'). Therefore, the solution cue in the easy-to-comprehend condition does not elicit an Aha! reaction.

A component process of an Aha! reaction is breaking mental impasse. This process differs from semantic integration, which underlies N400, in several ways [2]. First, an Aha! reaction involves an impasse–insight sequence [3], whereas semantic integration does not. Second, in an Aha! reaction, the solution cue fits well within the context of the ambiguous sentence, whereas with semantic integration the final word does not typically fit within the context of sentence. Third, an Aha! reaction arises from dramatic

representational change by reforming the relationships between the essential components into new scripts. In semantic integration, modifications are made within the frame of the original script. Breaking mental impasse also differs from cognitive set shifting in the Wisconsin Card Sorting Task (WCST). In the WCST, subjects are able to implement some general principles because the basis of card sorting is repeatedly switched among several dimensions (e.g., color, shape, or number), whereas in breaking mental impasse, this kind of task-general strategy is not possible.

To break a mental impasse, subjects need to detect and resolve cognitive conflict. Conflict detection in the parachute example is realizing one's error in interpreting cloth as something wearable and detecting the conflicts between different scripts to interpret the sentence (i.e. parachute jumping script *vs* other daily life scripts). Conflict resolution is selecting an alternative for which the causal relation becomes apparent—the parachuted ripped, so the haystack became important for breaking the fall. Previous studies have shown that anterior cingulate cortex (ACC) implements conflict detection. Although ACC was typically activated by the co-occurrence of competing motor responses on incongruent trials of the Stroop and Flanker tasks [4], it was also activated in the verb-generation task when the production of verbs that were weak associates, rather than, strong associates of particular nouns [5]. ACC was also activated in the tip of the tongue (TOT) state that involved a conflict between the metacognitive level and the cognitive level [6]. Therefore, it is possible that ACC is involved in an Aha! reaction when there is a conflict between the prepotent response and a logical, meaningful resolution to the problem. An Aha! reaction may also involve lateral prefrontal cortex (PFC), as this region has also been linked to conflict resolution in working memory

[7], semantic selection [8], and cognitive set shifting in the WCST [9]. We predict that lateral PFC participates in the Aha! reaction and subserves the process of semantic selection and attentional set regulation.

MATERIALS AND METHODS

Subjects: Fifteen healthy, right-handed volunteers (five female), aged 20–43 (mean 26.7) years, participated in this experiment. The data for two subjects were not used because they indicated they could not understand the solution cue to most of the ambiguous sentences. Subjects were given informed consent in accordance with the MRI ethics committee guidelines of the Neuroscience Research Institute, AIST.

Materials: The 42 pairs of ambiguous sentences and their solution cues used in this study were mostly taken from Auble *et al.*'s study [1]. Some sentences were modified due to cultural differences, and additional sentences were also constructed. All sentences and their solution cues were evaluated as highly reasonable and interesting by another group of subjects who did not attend the fMRI experiment. The classification of items into those that evoked an Aha! reaction was determined by the subject's on-line response during scanning and subsequent evaluation of post-scan questionnaires. To control the ratio of Aha *vs* non-Aha trials, about half of the 42 ambiguity sentences were difficult-to-comprehend (and so the presentation of the solution cues tended to evoke the Aha! reaction) and the other half were easy-to-comprehend. This partitioning was also evaluated by the experimenters and another group of subjects. Examples of difficult-to-comprehend sentences were: 'His position went up because his partner's position went down (See-saw)'. 'Her eyebrows fell below her eyes because her muscles tensed (Handstand)'. 'You could not tell who it was, because a professional took the photo of that old man (X-rays)'. Examples of easy-to-comprehend sentences were: 'He burned the paper because the sunlight was well focused (Magnifying glass)'. 'The coffee was sweet because the powder was added (Sugar)'.

Procedure: In the sentence presentation phase, each ambiguous sentence was presented for 8 s. Within this period, subjects pressed a key to indicate whether or not they could understand the sentence (left key/index finger of right hand: yes; right key/middle finger of right hand: no). After pressing a key, they were requested to cease thinking about the sentence. After sentence presentation there was a 7 s unfilled delay, followed by presentation of the solution cue for 2 s, followed by a 4 ± 1 s unfilled delay. Subjects were required to press a key as early as possible to indicate whether they understood the solution cue or not. 42 items were randomly assigned to three blocks with 14 items in each block. There was 30 s rest between blocks.

After subjects left the MRI machine (2–5 min after the puzzle solving stage), they were required to answer a questionnaire on how they comprehended each sentence. They were asked to indicate whether or not they understood the ambiguous sentence before seeing the solution cue; whether or not they understood the solution cue; and if so how easy/difficult it was to understand; subjects were also

required to report the reason for their failure in the initial stage of ambiguous sentence presentation.

An Aha event was defined when the presentation of the solution cue evoked a sudden understanding about the sentence, after subject had failed in the initial stage. If during the initial stage the subject had obtained an understanding that was consistent with the solution cue, then a non-Aha event was defined. If the solution cue differed from the subject's understanding in a way that triggered better comprehension on the sentence, then it was also regarded as an Aha event. To simplify the underlying processes involved in the Aha! reaction, such an event was defined only when the meaning of the solution cue was judged as obvious to understand. Cases judged as understandable, but fairly hard, were regarded as difficult solution events, but not Aha events. In the present study, we focused primarily on brain activity during the processing of solution cues. Critically, we contrasted the processing of solution cues that evoked the Aha! reaction with the processing of solutions that did not.

All classifications of events were done according to the subject's on-line responses with fMRI scanning and their post-scan evaluations. If there was an inconsistency between on-line response and post-scan evaluation, the judgment was based on the former. To familiarize the subjects with the procedure and pace of the task, they were trained with another set of similar materials in the same procedure (but without the post-scan questionnaire) before the formal experiment.

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

fMRI data analysis: The imaging data of the 13 subjects were analyzed by SPM99. The data of each subject were individually pre-processed (timeslice adjusted, realigned, normalized and smoothed). The spatially pre-processed data were then estimated to establish a random-effects model. Six event types were defined as presentation of (1) incomprehensible ambiguous sentences; (2) comprehensible ambiguous sentences; presentation of solution cues that were defined as (3) Aha events (see above); (4) non-Aha events; (5) difficult solution events; and (6) not understandable events. Ambiguous sentence presentation events (1) and (2) were modeled with a boxcar convolved with the canonical hemodynamic response function (HRF). The period of the boxcar coincided with the duration of the sentence presentation phase. Solution cue presentation events (3–6) were modeled with the canonical HRF time-locked to the onset of solution cue presentation. We did not consider the results of difficult solution or not understandable events, because there were insufficient trials (<10). Both Aha and non-Aha events comprised >10 trials in each subject and the number of trials in these two events were comparable (mean number of trials for Aha event was

Table 1. Significant voxels of activity for Aha vs non-Aha event.

K _E	Talairach coordinates				Area
	T	x	Y	z	
Aha > No-Aha					
467	6.39	0	17	38	L. Cingulate gyrus, BA 32
	6.09	10	4	48	R. Cingulate gyrus, BA 24
	5.52	8	14	38	R. Cingulate gyrus, BA 32
536	6.26	-40	16	7	L. Insula, BA 13
	4.67	-44	5	13	L. Insula, BA 13
	4.59	-42	7	24	L. Inferior frontal gyrus, BA 9
88	6.05	-42	4	40	L. Middle frontal gyrus, BA 6
	4.58	-36	12	42	L. Middle frontal gyrus, BA 6
10	5.17	-55	-58	-2	L. Inferior temporal gyrus, BA 37
12	5.01	-22	3	51	L. Sub-Gyral, BA 6
32	4.68	-26	-68	40	L. Precuneus, BA 7
15	4.50	-18	16	45	L. Superior frontal gyrus, BA 8
No-Aha > Aha					
27	7.41	10	50	-14	R. Superior frontal gyrus, BA 11
166	7.32	28	-86	23	R. Cuneus, BA 19
546	6.57	-14	-77	11	L. Cuneus, BA 17
	6.19	8	-65	18	R. Posterior cingulate, BA 31
27	6.12	0	-69	9	L. Cuneus, BA 30
	6.14	34	-70	-2	R. Lingual gyrus, BA 18
	4.71	36	-80	-1	R. Inferior occipital gyrus, BA 18
14	5.35	-10	-44	17	L. Posterior cingulate, BA 29
18	5.29	-6	46	-6	L. Anterior cingulate, BA 32
13	4.44	38	-7	-28	R. Middle temporal gyrus, BA 21

K_E: Number of Voxels; L.: left; R.: right; BA: Brodmann area. Threshold was set at $p < 0.001$ (uncorrected for multiple comparisons) and ten or more contiguous voxels. Voxel size: $2.0 \times 2.0 \times 2.0$ mm.

16.67 (SD=3.80) and for non-Aha event 14.50 (SD=3.18)). The relatively low numbers of trials in each event were sufficient to detect the neural correlates of Aha! reaction, because the effect was strong at individual and in group-level analyses. The threshold was set at $p < 0.001$ (uncorrected) and ≥ 10 contiguous voxels. Locations reported by SPM99 were converted into Talairach coordinates [10] by the transform specified in the mni2tal.m program [11]. These coordinates were used to determine the nearest gray matter (region and corresponding Brodmann area) using the Talairach Daemon program version 1.1 [12] with the maximum range of 11 mm.

RESULTS

The mean reaction time for Aha events was 1.87 (SD=0.52)s and for non-Aha events was 1.09 (SD=0.17)s ($t(11)=5.98$, $p < 0.001$). One subject's reaction time was not available due to a recording failure. For 75.7 (SD=0.15)% of the Aha trials, subjects thought the sentence and its solution cue fitted very well. For 72.9 (SD=0.26)% of the Aha trials, subjects attributed their failure in the initial stage of sentence presentation to having thought about it in another direction. Relative to the Non-Aha event, the Aha event was associated with activities in ACC, left lateral PFC, and other areas (Table 1; Fig. 1).

We also examined the effect of solution difficulty (as indicated by time-on-task), contrasting the Aha event with the difficult solution event, which subjects evaluated as understandable, but fairly hard. The image data of the six subjects who provided sufficient difficult solution trials (> 10) were analyzed. The mean reaction time for difficult solution trials of 2.68 s was significantly longer than that for Aha event trials (2.14 s; $t(5)=3.82$, $p < 0.05$). Conjunction

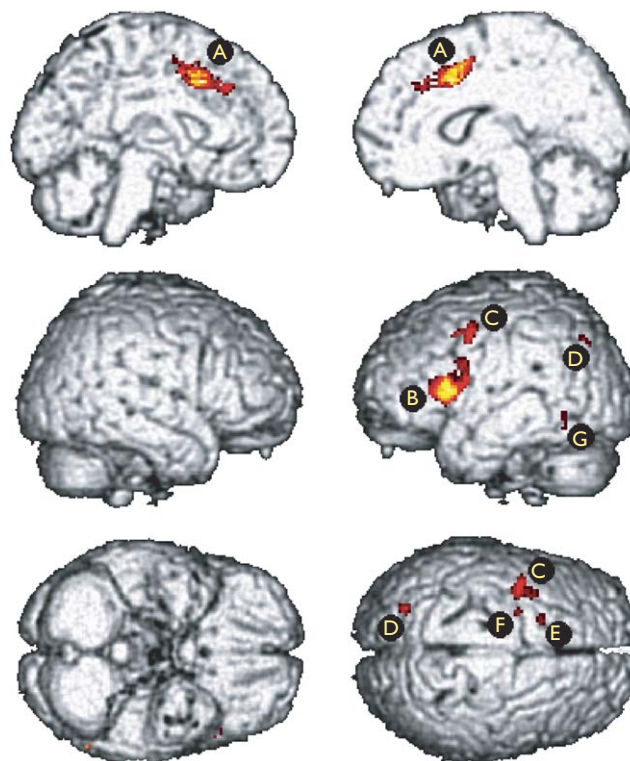


Fig. 1. Activity associated with the Aha! reaction. This is result of random effect analysis of 13 subjects thresholded at $p < 0.001$ (uncorrected) with ten or more contiguous voxels. (A) Bilateral cingulate gyrus (BA 24 and 32); (B) left insula (BA 13) and inferior frontal gyrus (BA 9); (C) left middle frontal gyrus (BA 6); (D) left precuneus (BA 7); (E) left superior frontal gyrus (BA 8); (F) left sub-gyral (BA 6); (G) left inferior temporal gyrus (BA 37).

analysis, which is used to make inferences about a population from a small number of subjects [13], showed greater activity for difficult solution events relative to non-Aha events in both left lateral PFC (BA47: $-51, 17, -4$; $T=5.23$; number of voxels [K_E]: 119) and ACC (BA32: $-10, 10, 42$; $T=4.85$; K_E : 123). However, relative to the Aha event, the difficult solution showed activation in only left lateral PFC (BA47; $-34, 27, -13$; $T=3.92$; K_E : 124) but not in ACC. This result implied that left lateral PFC was sensitive to task difficulty whereas ACC was not.

In summary, two major areas, ACC and left lateral PFC, were associated with the Aha! reaction. In the ACC, activation was significantly greater for difficult solutions and Aha events than for non-Aha events, but activation for Aha events and difficult solutions did not significantly differ. In contrast, in left lateral PFC, activation was lowest for non-Aha events, significantly higher for Aha events, and greater still for difficult solution events.

DISCUSSION

We have identified the neural correlates of the Aha! reaction, which included activity in ACC, lateral PFC, and several additional brain areas. For the majority of Aha trials (72.9%), subjects attributed their initial failure to having thought about it in another direction. This implies that the Aha! reaction involves breaking mental impasse. That is, upon seeing the solution cue subjects discarded their previous assumptions and changed their mental perspective in a way that led to a solution.

The contribution of ACC to breaking mental impasse was related to conflict detection. Recent studies have suggested that ACC implements an early warning system [4,14,15] and is engaged when top-down control fails to block automatic processing of task-irrelevant information [14]. For example, in the Stroop task, Carter *et al.* [15] observed ACC activity when strategic processes were less engaged and conflict was high, but not when strategic processes were more engaged and conflict reduced. Similarly, in breaking of mental impasse, the strategic processes may also fail to block the activation of task-irrelevant automatic processes because inappropriate chunks were decomposed into component features during this process [16], therefore, ACC participation was required. In contrast to recent theories that associate ACC with response-related processing [17,18], our results suggest that ACC may function more generally as the mechanism for conflict detection between different ways of thinking [19,20].

The function of left lateral PFC in breaking mental impasse may be related to conflict resolution. This area is known to mediate active comparison of stimuli held in working memory. In the context of the Aha! reaction, one possible function of left lateral PFC is semantic selection. Here, selection refers to choosing suitable alternative meanings of the critical concept. This function is consistent with Thompson-Schill *et al.*'s hypothesis that left lateral PFC mediated semantic selections among competing alternatives [8]. Another possibility is that left lateral PFC holds cognitive goals in working memory and allocates attention to the appropriate processing systems to meet those goals. This possibility is consistent with studies that showed left lateral PFC is responsible for establishing and switching between attentional sets [17,21]. Accordingly, left lateral PFC

might subserve verification, where the key interpretation is applied to the entire context of the sentence.

However, the contrast between Aha and difficult solution showed that only left lateral PFC, but not ACC, indexed the solution difficulty and time-on-task. The overall pattern of activity in lateral PFC and ACC was consistent with the role of conflict resolution for lateral PFC and conflict detection for ACC. The critical difference between difficult solution and Aha event lies in the demands imposed on conflict resolution processes. Once conflict is detected, difficult solution events require more time to resolve the conflict.

The brain areas involved in the Aha! reaction were different from those typically observed in semantic integration. fMRI studies showed semantic integration activated bilateral lateral frontal and anterior temporal cortex, left posterior fusiform gyrus, and bilateral precentral gyrus [22]; whereas "the Aha! reaction" activated ACC and left lateral PFC. In our parallel ERP experiment, subjects did the same cognitive task while the EEG was recorded [20]. We observed that the Aha event elicited a more negative ERP deflection than non-Aha events in the time window 250–500 ms. Mean latency of the difference wave was around 380 ms (N380) and dipole source analysis suggested the generator of N380 was around ACC. Given that it took about 2000 ms for an Aha! reaction event to be completed, it suggests that the N380 wave marks the beginning of competition between the old and new ways of thinking. Although the latency of N380 is close to the N400 wave linked to semantic integration, there are several differences: (a) The peak amplitude of N380 was at Cz, whereas N400 was located at centroparietal sites. (b) N400 usually had greater amplitude and duration over the right hemisphere, whereas there was no hemisphere difference for N380. (c) The generator of N380 was located in ACC.

The brain areas involved in the Aha! reaction also differed from those observed in cognitive set shifting in the WCST. WCST studies showed only left lateral PFC but not ACC in the negative *vs* positive feedback contrast that signaled the need for a mental shift to a new response set [9]. In WCST, the decision criterion is repeatedly changed among two or three stimulus dimensions, which allows subjects to establish some task-general strategy. A task-general strategy permits successful top-down intentional control, and so ACC is not required. Consistent with this view, we found that activation of ACC, but not left lateral PFC decreased as subjects became familiar with the cognitive task. We examined the involvement of ACC and left lateral PFC across the first, second and third blocks of the experimental session. The ratios of Aha events were comparable in the three blocks. Random effect analysis (thresholded at $p < 0.001$, uncorrected) of 13 subjects showed that, relative to the resting state, all three blocks were associated with robust ACC and left lateral PFC activity; however, only the activation in ACC significantly decreased from the first block to the second and third ones. This result is consistent with Milham *et al.*'s observation that practice-related decreases in ACC activity were more rapid and more pronounced than those in the lateral PFC [14].

CONCLUSION

The Aha! reaction was associated with activity in ACC and left lateral PFC, suggesting that these two areas may

mediate the conflict monitoring and resolution respectively in breaking mental impasse.

REFERENCES

1. Auble PM, Franks JJ and Soraci SA. Effort toward comprehension: Elaboration or "aha"? *Mem Cogn* 1979; 7:426–434.
2. Kutas M and Hillyard SA. Reading senseless sentences: brain potentials reflect semantic incongruity. *Science* 1980; 207:203–205.
3. Ohlsson S. Restructuring revisited: II. An information processing theory of restructuring and insight. *Scand J Psychol* 1984; 25:117–129.
4. Botvinick MM, Braver TS, Barch DM, Carter CS and Cohen JD. Conflict monitoring and cognitive control. *Psychol Rev* 2001; 108:624–652.
5. Barch DM, Braver TS, Sabb FW and Noll DC. Anterior cingulate and the monitoring of response conflict: evidence from an fMRI study of overt verb generation. *J Cogn Neurosci* 2000; 12:298–309.
6. Maril A, Wagner AD and Schacter DL. On the tip of the tongue: an event-related fMRI study of semantic retrieval failure and cognitive conflict. *Neuron* 2001; 31:653–660.
7. Jonides J, Smith EE, Marshuetz C, Koeppe RA and Reuter-Lorenz PA. Inhibition in verbal working memory revealed by brain activation. *Proc Natl Acad Sci USA* 1998; 95: 8410–8413.
8. Thompson-Schill SL, D'Esposito M, Aguirre GK and Farah MJ. Role of left inferior prefrontal cortex in retrieval of semantic knowledge: a reevaluation. *Proc Natl Acad Sci USA* 1997; 94:14792–14797.
9. Monchi O, Petrides M, Petre V, Worsley K and Daghe A. Wisconsin Card Sorting revisited: distinct neural circuits participating in different stages of the task identified by event-related functional magnetic resonance imaging. *J Neurosci* 2001; 21:7733–7741.
10. Talairach J and Tournoux P. *Co-planar Stereotaxic Atlas of the Human Brain: 3-Dimensional Proportional System: An Approach to Cerebral Imaging*. Thieme: New York, 1988.
11. Brett M. The MNI Brain and the Talairach Atlas. (<http://www.mrc-cbu.cam.ac.uk/Imaging>) 1999.
12. Lancaster JL, Woldorff MG, Parsons LM, Liotti M, Freitas CS, Rainey L et al. Automated Talairach Atlas labels for functional brain mapping. *Hum Brain Mapp* 2000; 10:120–131.
13. Friston KJ, Holmes AP and Worsley KJ. How many subjects constitute a study? *Neuroimage* 1999; 10:1–5.
14. Milham MP, Banich MT, Claus ED and Cohen NJ. Practice-related effects demonstrate complementary roles of anterior cingulate and prefrontal cortices in attentional control. *Neuroimage* 2003; 18:483–493.
15. Carter CS, Macdonald AM, Botvinick M, Ross LL, Stenger VA, Noll D et al. Parsing executive processes: strategic vs evaluative functions of the anterior cingulate cortex. *Proc Natl Acad Sci USA* 2000; 97:1944–1948.
16. Knoblich G, Ohlsson S, Haider H and Rhenius D. Constraint relaxation and chunk decomposition in insight. *J Exp Psychol Learn Mem Cogn* 1999; 25:1534–1556.
17. MacDonald III AW, Cohen JD, Stenger VA and Carter CS. Dissociating the role of the dorsolateral prefrontal and anterior cingulate cortex in cognitive control. *Science* 2000; 288:1835–1838.
18. Nelson JK, Reuter-Lorenz PA, Sylvester CY, Jonides J and Smith EE. Dissociable neural mechanisms underlying response-based and familiarity-based conflict in working memory. *Proc Natl Acad Sci USA* 2003; 100:11171–11175.
19. Luo J and Niki K. The function of hippocampus in 'insight' of problem solving. *Hippocampus* 2003; 13:274–281.
20. Mai XQ, Luo J, Wu JH and Luo YJ. "Aha!" effects in guessing riddle task: an ERP study. *Hum Brain Mapp* 2004; 22:261–270.
21. Luks TL, Simpson GV, Feiwell RJ and Miller WL. Evidence for anterior cingulate cortex involvement in monitoring preparatory attentional set. *Neuroimage* 2002; 17:792–802.
22. Kiehl KA, Laurens KR and Liddle PF. Reading anomalous sentences: an event-related fMRI study of semantic processing. *Neuroimage* 2002; 17:842–850.

Acknowledgements: We thank Mrs. Shihomi Hori for helping us to translate the ambiguous sentences into Japanese. This work was supported by National Natural Science Foundation of China (30270464 and 30370480) to J.L.