

# Lateral inferior prefrontal cortex and anterior cingulate cortex are engaged at different stages in the solution of insight problems

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**Two studies used puzzles that required participants to find a word that satisfied a set of constraints. The first study used a remote-association task, where participants had to find a word that would form compound words with 3 other words. The second study required participants to complete a word fragment with an associate of another word. Both studies produced distinct patterns of activity in the lateral inferior prefrontal cortex (LIPFC) and the anterior cingulate cortex (ACC). Activation in the LIPFC rose only as long as the participants were trying to retrieve the solution and dropped off as soon as the solution was obtained. However, activation in the ACC increased upon the retrieval of a solution, reflecting the need to process that solution. The data of the second experiment are fit by an information-processing model that interprets the activity in the LIPFC as reflecting retrieval operations and the activity in the ACC as reflecting subgoal setting.**

control | memory | ACT-R

Studies of cognitive neuroimaging have shown consistently that medial and lateral areas of the prefrontal cortex are active when participants are engaged in cognitively demanding tasks (1–5). However, the field is still trying to articulate the precise roles of different prefrontal regions. The current work uses event-related functional magnetic resonance imaging (fMRI) to investigate 2 particular components of cognitive demand: the need to retrieve specific information and the need to focus on specific subgoals of the task. The studies reported will test whether a region in the lateral inferior prefrontal cortex (LIPFC) reflects memory retrieval demand, and whether a region in dorsal anterior cingulate cortex (ACC) reflects subgoal setting. The studies use special properties of a class of insight problems to separate the functions of these 2 regions. We will test predictions that follow from the Adaptive Control of Thought-Rational (ACT-R) theory (6, 7).

The human prefrontal cortex is a large structure and consists of many distinct areas, both in terms of structure and function (8, 9). The LIPFC region has been associated with retrieval factors in imaging studies (10–13). It is also active in many tasks, particularly those involving language. It has been suggested (14) that the involvement of this region in such tasks can be understood in terms of retrieving the information needed to perform the tasks. Similar to this suggestion, we have proposed (15) that this region serves the role of maintaining the retrieval cues for accessing information stored elsewhere in the brain. The longer it takes to complete the retrieval successfully, the longer the cues will have to be maintained, and hence the greater the activation. Focused studies that manipulate retrieval difficulty produce systematic differences in the activation of this region. This region tends to respond to manipulations of fan or associative interference (16, 17), retention delay (18), and repetition (15). These are all factors that influence the duration of a single retrieval from declarative memory. Perhaps the major competing interpretation of this prefrontal region is that it is activated in conditions that require difficult selections among retrieved

information (19, 20). On the other hand, it has been argued that these effects are due to greater retrieval demands in the more difficult conditions (13, 21). The research reported here will be relevant to adjudicating this difference.

We have proposed (3, 22) that the ACC region is responsible for setting subgoals that enable different courses of information processing to be taken when participants are in otherwise identical problem states. It thus enables internal control of cognition independently of external circumstances. The subgoals determine which branch is taken at decision points in information processing. This sense of “control” is similar to some theories of the ACC (23–25). However, other theories relate ACC activity to error detection (26, 27), response conflict (1, 28, 29), or the likelihood of an error (30). In the ACT-R theory, ACC activity reflects the effort in setting subgoals. Thus, ACC activity will reflect the number and timing of subgoal changes. Again, the research to be reported here will be relevant to distinguishing this conception from alternative theories.

Cognitively demanding tasks can be characterized as having multiple cycles of a retrieval operation followed by a subgoal setting. For example, the cognitive system may have the subgoal of solving an equation such as  $2x - 3 = 5$ , and this will lead to retrieval of the information that  $5 + 3 = 8$ . With the retrieval of this information, the system may change its subgoal to solving the equation to  $2x = 8$ . This, in turn, can evoke another retrieval request (e.g., what is 8 divided by 2?). Thus, the cycle is one in which the current subgoal evokes requests for retrieval, and the retrieved information leads to a change in the subgoal. According to the ACT-R theory, the retrieval operations will be reflected in the activity of the LIPFC, and the subgoal changes in the activity of the ACC. Many researchers have noticed that these regions tend to activate together, and this is would be expected, given this information-processing cycle (5, 31, 32).

The research reported here will capitalize on a feature of certain insight puzzles that allows us to pull apart these normally highly correlated retrieval and goal activities. The first experiment will use remote-association problems (33–36). Participants saw 3 words (e.g., “pine,” “crab,” and “sauce”) and attempted to produce a single solution word (i.e., “apple”) that can form compound words with each of the hint words (i.e., “pineapple,” “crabapple,” and “applesauce”). In the ACT-R model for this task, a subgoal is set to find a solution, and the retrieval module is continuously engaged until the problem is solved. The important characteristic about these problems is that it takes a long time to retrieve a solution, if one is retrieved at all. This produces a sustained demand on the retrieval module while the subgoal module remains unchanged. However, once the problem is

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**Table 1. Regions of interest**

Region of interest	Brodmann area(s)	Voxel count	Talarach coordinates of center, mm			Correlation with regions		Correlation with modules	
			x	y	z	LIPFC	ACC	Retrieval	Goal
1. Predefined ACC	24, 32	60	-6	10	39	0.318	1.00	0.349	0.927
2. Predefined LIPFC	9, 46	100	-42	23	24	1.00	0.318	0.956	0.157
3. Supplementary motor	8	32	-5	15	50	0.866	0.697	0.871	0.529
4. Left prefrontal	9, 46, 6	481	-42	18	23	0.983	0.233	0.925	0.092
4a. Posterior prefrontal	6	55	-42	3	35	0.960	0.455	0.926	0.308
4b. Anterior prefrontal	9/46	92	-46	24	13	0.905	-0.044	0.824	-0.161
5. Left parietal	7	35	-23	-56	44	0.684	0.820	0.664	0.763
6. Right parietal	7	44	23	-58	41	0.624	0.603	0.548	0.588
7. Left visual	18/19	48	-29	-82	6	0.719	0.743	0.704	0.666
8. Right visual	19	18	32	-79	9	0.729	0.764	0.710	0.695
9. Right fusiform	37	51	40	-60	-3	0.545	0.595	0.488	0.616
10. Left fusiform	37	30	-42	-58	-4	0.604	0.660	0.531	0.612

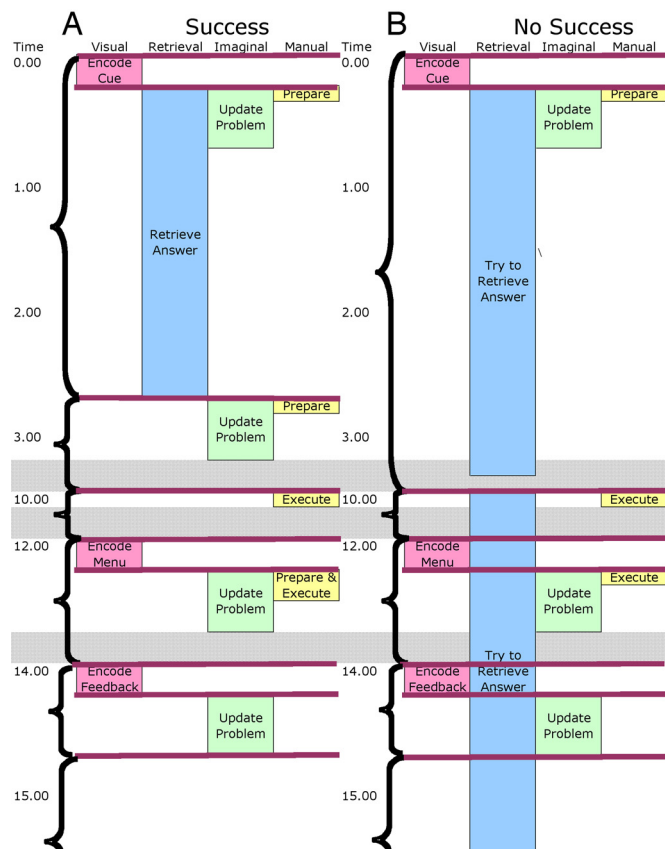
of measurement in the BOLD function. Correcting for this correlation raises the level for a significant deviation from 36 to 52 (41).

Fig. 4 shows the predicted responses for the LIPFC and the ACC. The correlation with the actual data in Fig. 2 is quite strong ( $r = 0.929$ ). The  $\chi^2$  measure of deviation between LIPFC and prediction is 29.44, which is within the acceptable threshold, with

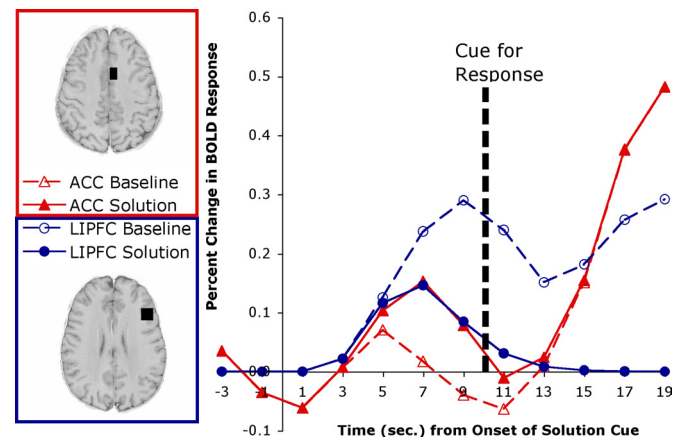
or without correction for correlation. The model captures the fact that the BOLD response will initially show the same rise whether there is a solution or not, but the BOLD response will drop off upon retrieval of a solution. The  $\chi^2$  measure of deviation for the ACC is 45.00, which is below the corrected threshold. Interestingly, the model predicts that in the solution condition, the ACC activity will become greater than the LIPFC activity only after the response cue. We had failed to get a significant difference after solution and before response. This illustrates how a model can serve to show that a qualitative prediction from analysis of the theory (ACC activity greater than LIPFC activity after solution) may need some adjustment when exact parameters of the process are incorporated (the difference should only appear after the response cue).

**Discussion**

The experiments confirmed the predicted distinct responses in the LIPFC and ACC. Activity in the LIPFC region continued only as long as the participants were trying to retrieve the solution and ceased as soon as the solution was obtained. In contrast, activation in the ACC increased upon the retrieval of a solution, reflecting the need to process that solution. There are striking similarities between the patterns found in our data and the patterns reported in studies of perceptual recognition (42, 43). Just as the difficulty of the insight problems extended the retrieval period in our research, this research extended the



**Fig. 3.** Engagement of the modules in the ACT-R model for experiment 2. (A) Success. (B) No success. Time is given in seconds. Lengths of boxes (for visual, retrieval, imaginal, and manual modules) reflect approximate times the modules are engaged. The horizontal lines represent the firing of production rules. Brackets indicate subtasks of activity controlled by a setting of a goal. Gray bars indicate compressed periods of time.



**Fig. 4.** Predictions for the LIPFC and ACC activity in experiment 2 based on the module engagement in Fig. 3. Compare with data in Fig. 2.

period of perceptual recognition by slowly revealing pictures. Regions involved in perceptual recognition, like temporal regions, became active with problem onset and stayed active until the identification of the picture. A prefrontal region very close to our predefined LIPFC was among these regions. In contrast, control regions like the ACC became active only at the point of identification. As in our experiment 2, this research showed that these patterns emerged in advance of response generation. These studies suggest that such paradigms are an excellent means of decoupling processes that are normally close together.

As discussed in the introduction, the principal alternative interpretation of this LIPFC area is that it supported selection among retrieved alternatives (19, 20). If this were the correct interpretation, activation should only have increased close in time with the identification of a solution, when there might be the need to select among alternatives. Rather, activation dropped off upon identification of a solution and continued to rise in the absence of a solution. A number of studies (14, 15, 44) have found an anterior-to-posterior gradient, with more posterior regions more sensitive to interference or competition factors. However, our exploratory study indicated a rather similar response in this task across a wide area of the left inferior prefrontal cortex. This does not seem to be a task that reflects the anterior-to-posterior gradient.

In both experiments, the ACC was more active when the problem was solved. This fact causes difficulty for alternative theories of the ACC. The fact that the ACC response was stronger in the presence of success is particularly hard to reconcile with a view that claims ACC activation is associated with errors—either the actual occurrence of errors or the likelihood of errors. With respect to the response-conflict view, one could argue that in the first experiment, because participants only generated a response if they solved the problem, response conflict could only occur in solution cases. However, this cannot be the cause of the difference in the second experiment, because the response requirements were equated for solution and no solution, and the critical contrast involved scans before the response.

## Materials and Methods

**Procedures for Experiment 1.** Twenty right-handed members of the Pittsburgh community (11 women) ages 18 to 32 years (mean, 23.2 years) completed the study. Participants were presented with 3 hint words that could be combined with a common word to produce a new word. For example, the words “print,” “berry,” and “bird” can all be combined with “blue” (i.e., “blueprint,” “blueberry,” “bluebird”). Participants had 30 s to determine the common word. As soon as they thought of the common word, they pressed a button on a data glove and were taken to a solution screen. They were then given 5 s in which to speak the target word. After this, they were presented with a screen that asked whether they had solved the problem with insight, and they had up to 5 s to respond. The insight screen instructed them to respond “yes” by pressing their index finger button and “no” by pressing their middle finger button. After making their insight response, they were presented with a fixation for 9.5–11.5 s (to the start of a new 2-s scan of a volume), and then a new trial began.

If unable to solve the problem in the 30 s, the participant was then taken to a screen that presented the target word as well as the 3 hint words. This screen lasted for 5 s and was followed by an 11-s fixation before the next set of hint words was presented. Participants were given instruction and 20 practice trials during structural scans. The instruction included 1 example of 3 cue words and a solution word. Participants were asked during 1 scan session to solve 63 problems, which were broken into blocks of 9–10 min. These 83 problem–solution combinations were randomly selected from a pool of 144 found in Bowden and Jung-Beeman (36).

Images were acquired by using gradient echo–echo planar image acquisition on a Siemens 3T Allegra Scanner using a standard RF head coil (quadrature birdcage), with a 2-s repetition time (TR), a 30-ms echo time, a 70° flip angle, and a 20-cm field of view. The experiment acquired 34 axial slices on each TR by using a 3.2-mm-thick, 64 × 64 matrix. The anterior commissure–posterior commissure line was on the 11th slice from the bottom scan slice.

Acquired images were analyzed by using the NeuroImaging Software (NIS; <http://kraepelin.wpic.pitt.edu/nis/>) system. Functional images were motion-corrected by using 6-parameter 3D registration (AIR; ref. 45). All images were then coregistered to a common reference structural MRI by means of a 12-parameter 3D registration (45) and were smoothed with an 8-mm full-width-half-maximum 3D Gaussian filter to accommodate individual differences in anatomy. Spatial F maps were generated by using random-effects ANOVA. Participants were relatively good at controlling head motion during verbal reports—10 kept their maximum movement during the experiment under 3 mm, and 8 had maximum movement under 6 mm.

**Procedures for Experiment 2.** Twenty right-handed members of the Pittsburgh community (10 women) ages 19 to 30 years (mean, 22.4 years) completed the study. Participants were presented with a fragment of a word that was between 5 and 11 letters long, with approximately half of the letters replaced with hyphens, always including the first letter. The participants would then have 10 s to study this word and try to identify the word. If the participants could solve the puzzle within the 10-s period, they would press a button on the data glove and be taken to a solution screen. This first 10-s period was included to eliminate any problems that could be solved without the cue word, and our analysis is limited to the 90% of the problems not solved in this interval. If the participants could not complete the fragment, they would then be presented with both the fragment and a cue word for 10 s. After that 10 s, the participants would be asked whether they believed they knew the answer to the word fragment, which they would indicate by pressing a button on the data glove. The participants had 2 s in which to respond. Independently of how they responded, the participants would be taken to a solution screen, which presented the puzzle word along with 5 choices for its first letter. The participants would have 2 s in which to select the letter that they believed to be the first letter of the word, with 1 corresponding to the thumb button, 2 to the index finger, etc. After this, the participants were given feedback on their response, and the correct word was presented. This screen remained for 6 s before returning to the first screen with a new word to solve.

Participants were presented with 68 randomly ordered words. They solved these problems in scan blocks that lasted from 9.5 to 10 minutes. During structural scans, participants were trained both on responding with the data glove to the numbers 1–5 correctly, and they were given 10 practice problems drawn from a different set of words. The same scanning parameters were used as in the first experiment. Participants were relatively good at controlling head motion—16 kept their maximum movement during the experiment under 3 mm, and the other 4 had maximum movement under 5 mm.

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