"Aha!": The Neural Correlates of Verbal Insight Solutions

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Abstract: What are the neural correlates of insight solutions? To explore this question we asked participants to perform an anagram task while in the fMRI scanner. Previous research indicates that anagrams are unique in that they can yield both insight and search solutions in expert subjects. Using a single-trial fMRI paradigm, we utilized the anagram methodology to explore the neural correlates of insight versus search solutions. We used both reaction time measures and subjective reports to classify each trial as a search or insight solution. Data indicate that verbal insight solutions activate a distributed neural network that includes bilateral activation in the insula, the right prefrontal cortex, and the anterior cingulate. These areas are discussed with their possible role in evaluation and metacognition of insight solutions, as well as attention and monitoring during insight. *Hum Brain Mapp 30:908–916, 2009.* © 2008 Wiley-Liss, Inc.

Key words: fMRI; insight solutions; creativity; anagrams

INTRODUCTION

Psychologists generally cite three general categories of solutions to difficult problems: search, insight, and memory retrieval [Novick and Sherman, 2003]. Insight solutions, also commonly called "aha moments," are thought to strongly differ in their cognitive process from the other two solution types.

Archimedes of Syracuse provided the archetypal story of the "aha moment" when he discovered the principle of displacement. The story is that after days of belabored thought over a problem, he discovered the solution in his bathtub, and was so inspired that he supposedly ran down the street shouting "Eureka!" without remembering to put on his clothes. This story reveals the emotional intensity of insight moments, their sudden appearance in thought and gestalt-like quality, and the uniqueness and creativity of the solution.

Insight problems were first studied by Gestalt psychologists. The Gestalt view suggested that the insight strategy involved reconstructing the problem in a novel way. This restructuring may then allow for a new interpretation by attending to information in memory that was previously disregarded [Jung-Beeman et al., 2004; Knoblich et al., 1999].

By contrast, the "search" strategy refers to problem-solving that involves four characteristics: (1) it is effortful, deliberate, and largely conscious; (2) it proceeds incrementally from beginning to solution state; (3) intermediate results are available to working memory; (4) the gradual accumulation of partial knowledge can be tracked while the problem is being solved [see Ericsson and Simon, 1984; Newell and Simon, 1972; Polson and Jeffreis, 1982, cited in Novick and Sherman, 2003]. Typical examples of problems that are solved by the search strategy include physics word problems, multiplying multidigit numbers, and playing chess.

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Insight solutions also differ from memory retrieval solutions. A memory retrieval solution occurs when solutions pop into the mind automatically from memory. The difference between these solutions and the "aha moment" is a lack of greater insight after the solution is reached; memory retrieval involves simply retrieving previously held knowledge and does not result in increased understanding. Problems that commonly use the memory retrieval strategy include naming previous presidents and solving single-digit multiplication problems. The mechanisms of memory retrieval are already well researched and beyond the scope of this study, and here we will focus on the search and insight strategies instead.

In a recent behavioral experiment, Novick and Sherman [2003] documented that anagram problems were unique in that they could yield both insight and search solutions in expert subjects. These solutions could also be elicited within a few seconds. The insight strategies were significantly faster than the search strategies (about 2 and 4 s solution time, respectively). Thus using latency and a self-report measure, the experimenters were able to determine which strategy the subject was using in a particular trial. They also found that the latency measure strongly correlated with the self-report measure, indicating that either could be used to determine the strategy used.

What are the neural correlates of these two different solution strategies? There are at least two general possibilities. The first possibility is that insight solutions involve different brain areas than do search solutions. This theory posits that the inherent qualitative specialness of insight solutions stems from the involvement of a brain area that is not used in search solutions. For example, some researchers have posited that restructuring the problem in a novel way, which is a component of insight solutions, might involve processing the prefrontal cortex (PFC), which is absent in search solutions [for review, see Dietrich, 2004]. Another possibility, which is also commonly posited for creative solutions, is that the right hemisphere is specifically activated [Leonhard and Brugger, 1998; Mashal et al., 2007; Mendez, 2004; Weinstein and Graves, 2002; Winner, 2000].

The second possibility is that the difference between the two solution types is not a matter of different brain areas, but of different processing within the same areas [Atchley et al., 1999; Bogen and Bogen, 1969; Kwong et al., 1992]. For example, the main difference might be interhemispheric interconnectivity, the timing of activation in different brain areas, or a difference in the pattern of activation for a given brain area.

In a recent study, Jung-Beeman et al. [2004] explored the difference between insight and search solutions by asking participants to solve compound remote associates problems. For example, the subject is given three problem words (*pine, crab, sauce*) and attempts to produce a single solution word (*apple*) during an fMRI study and during EEG recording. The results indicated that the right anterior superior temporal gyrus showed more activation for insight solutions when compared with noninsight solutions [Jung-Beeman et al., 2004]. Can this finding be extended to other types of insight solutions or is it particular to the remote associates task?

In this study, we investigate the differences in areas of the brain and their patterns activated by insight and search problem solving for an anagrams task. We conducted an fMRI study utilizing Novick and Sherman's anagram behavioral paradigm. This allowed us to examine different solution types in response to the same kind of problem. We show that while there is a common network involved in both problem solving types, the insight solution involves more interhemispheric transfer. Furthermore, the insight solution seems to involve prefrontal areas not observed with search solutions.

METHODS

Participants

Twelve right-handed healthy volunteers (6 men, 6 women; median age, 26; range, 20–40), screened by questionnaire to have no history of brain damage, participated in the study. All participants were native English speakers and handedness was assessed by a modified Oldfield questionnaire [Oldfield, 1971]. Participants gave informed consent, according to the requirements of the Institutional Review Board of UCLA. Two participants (1 male, 1 female) were excluded from the analysis because of experiencing less than 20% insight or search solutions during the experiment. All participants reported to have normal or corrected-to-normal vision. Prior to scanning, participants completed a screening questionnaire to rule out medication use, a history of neurological or psychiatric disorders, substance abuse, and other medical conditions. Furthermore, participants were preselected for performing well (12+/20 correct solutions) on an anagram pretest [Novick and Sherman, 2003].

Stimuli and Task

Participants completed four functional runs inside the scanner after one practice run outside the scanner. Anagrams were taken from lists created by Novick and Sherman [2003]. These words consist of mainly nouns and have five different letters (e.g. "oxmia" = axiom). Half of them involved two letters being transposed while the other half involved three letters being transposed. All anagrams were considered moderately difficult by individuals with anagram-solving experience. Each anagram was presented visually via magnet-compatible goggles (Resonance Technology Inc.). The participant was asked to mentally solve the anagram as quickly and accurately as possible and to press a button as soon as they had a solution. This marked the length of a given problem-solving event for analysis purposes. The anagram remained on the screen until the button was pressed and participants were asked to press the button if they could not solve the anagram after about 20 s. A 10-s rest during which participants viewed a gray screen followed. Next, the participant was visually presented with the solution and was asked to press one of two buttons to indicate whether or not they had reached the correct solution. A 1-s rest followed. Finally they were visually asked to press one of two buttons to indicate whether they had experienced an insight solution or a search solution. The insight solution was described as a solution that popped into the participant's mind seemingly from nowhere. This sequence was repeated 12 times in each functional run and participants completed four functional runs. Thus each subject completed 48 anagram trials.

fMRI

Images were acquired using a Siemens Allegra 3.0 T MRI scanner. Two sets of high-resolution anatomical images were acquired for registration purposes. We acquired an MP-RAGE (TR = 2,300, TE = 2.93, flip angle = 8°) with 160 sagital slices, each of 1 mm thickness with 0.5-mm gap and 1.33 mm × 1.33 mm in-plane resolution. We also acquired a T2-weighted coplanar image (TR = 5,000, TE = 33, flip angle = 90°) with 36 transverse slices covering the whole brain, each of 3 mm thickness with 1-mm gap, a 128 × 128 matrix, and an in-plane resolution of 1.5 mm × 1.5 mm.

Each functional run involved the acquisition of 186 BOLD-weighted echo-planar volumes (TR = 2,000, TE = 25, flip angle = 90°), each with 36 transverse slices, 3 mm thick, 1-mm gap, and a 64 × 64 matrix yielding an in-plane resolution of 3 mm × 3 mm. A functional run lasted 6 min and 4 s during which time 180 volumes were acquired (after discarding the first two volumes for T1 equilibrium effects), and each participant completed four functional runs.

Data Analysis

Behavioral data

On average, subjects accurately completed 90% of the anagrams (range: 68–100%). Anagrams that were not completed were excluded from the analysis. We classified solutions (from onset of stimulus until the response button was pressed) as insight or search based on self report measure and the response time. Responses which the participant classified as an insight solution and which were under 4 s were classified as an insight solution. Trials which the participant classified as a search and were greater than 4 s were classified as a search solution. All other combinations were classified separately and not utilized in later analysis. Because the search trials showed greater variability than the insight trials we decided to restrict our analysis to trials close to the mean. Thus to normalize the data, trials that were outliers (response times that were more than 1.5 standard deviations away from the mean) were excluded from the analysis. On average, 2.8 search trials and 0.47 insight trials per run were excluded on this basis. Furthermore, on average, insight solutions were completed in 1.64 s (standard deviation = 0.62), whereas search solutions were completed in 5.34 s (standard deviation = 1.01), and insight solutions constituted 70% of the trials and search solutions 30% of the trials. The large number of insight solutions is probably due to the expert status of our participants in the task. There was no consistency on which anagrams produced search vs. insight solutions; subjects varied on which anagrams they solved by insight and which ones they solved with search strategies. Thus, the properties of a specific anagram do not seem to be relevant to the problem solving.

Imaging data

Preprocessing. Data were spatially smoothed with a 10-mm FWHM Gaussian filter and motion corrected using MCFLIRT [Jenkinson et al., 2002]. Individual subject's data were registered to the MNI-152 atlas space using FLIRT (part of FSL, FMRIB's Software Library, www.fmrib.ox.ac.uk/fsl). Each subject's functional data were first aligned to the high-resolution coplanar image using a linear transformation with 6 degrees of freedom, and then to the MP-RAGE with a linear transformation with 6 degrees of freedom. Finally, images were registered to the standard MNI atlas using an affine transformation with 12 degrees of freedom.

Time course analysis. Our analysis procedure was designed to characterize the hemodynamic response to each stimulus, and compare signal changes between trials which had different solution types. Because our two experimental conditions differ in the speed of response, we examined the data at each time point after stimulus onset in relation to a pre-stimulus baseline. Thus we conducted a stimulus-locked analysis. A response-locked analysis with these data is problematic because of the difference in the response times between the two experimental conditions. A response centered baseline would capture initial stimulus processing for the insight solutions but not for the search solutions. Thus a response-locked baseline would be inconsistent between the two conditions and render such an analysis uninterpretable. To conduct our stimulus-locked analysis, we first linearly interpolated the data from the original 2-s resolution down to half-second resolution. This was done because stimulus presentation did not always coincide with the start of a TR; interpolated data should obtain a more accurate estimate of the BOLD signal at the moment of stimulus presentation. Next, for each trial, we created maps of the BOLD signal at each time point following stimulus presentation, and averaged them for each subject to obtain a map of the average signal for each stimulus type at each time point. Each time point map was then compared with the signal at stimulus onset using a t-test to produce t maps that represent the signal change from baseline. A separate analysis compared the signal at each time point between search and insight solutions using the same method. t statistics were transformed

TABLE I. Brain areas activated for aha solutions when compared with search solutions

Region	Hemisphere	BA	*x*	*y*	*z*	*t*	Voxels
Inferior frontal gyrus	Left	45	−54	20	0	3.98	102
Inf/middle frontal gyrus	Right	10, 46	40	44	0	4.77	534
Anterior cingulate	Midline	32, 24	−6	26	44	6.08	1,513
Insula	Right	13	38	12	−14	3.81	333
Angular gyrus	Left	39	−48	−52	24	3.97	57
Angular gyrus	Right	39	58	−52	36	3.95	309
Temporal pole	Right	38	42	6	−40	4.57	164
Pons	Midline		−6	−20	−26	3.39	97

Hemisphere (left, right, midline), Brodmann area, and MNI coordinates are listed. The cluster t value is the mean value for the given cluster. Number of voxels active in each area is also listed.

to z statistics for thresholding. We identified regions of significant signal change using the following criteria: (1) z greater than 2.3 for at least three consecutive time points, (2) at least 10 spatially contiguous voxels, and (3) a given cluster is active beyond the first 5 s after stimulus presentation. Criteria 1 and 2 were chosen to ensure that activations persisted in time and space. z of 2.3 corresponds to a P value of about 0.01. This is a common threshold to use when also correcting spatially (like for cluster size). Thus, we corrected both spatially and temporally. The third criterion was used to account for hemodynamic lag. We then extracted the time courses for significant voxels within those regions identified as showing a significant signal change in either of the two experimental conditions.

RESULTS

Aha-Rest

These contrasts examined brain areas that were more activated during aha solutions when compared with rest. Several peaks of activation were found, including the dorsal premotor cortex bilaterally, the SMA, the right interoccipital sulcus/superior occipital gyrus, the insula bilaterally, the ventral premotor cortex bilaterally, and the tegmentum.

Search-Rest

These contrasts examined brain areas that were more activated during search solutions when compared with rest. Several peaks of activation were found in the superior frontal sulcus bilaterally and the left insula.

Aha-Search Activations

This contrast examined the brain areas that were more activated during aha solutions when compared with search solutions. Several peaks of activation were found, including the right insula, Broca's area (left BA 45), the angular gyrus bilaterally, the right PFC (BA 10, 46), the anterior cingulate, the pons, and the right temporal pole. Of note is that the cortical activations are either bilateral or in the right hemisphere (with the exception of Broca's area) for the aha solutions when compared with search solutions (Table I).

Figure 1 depicts these areas of activation along with the time series for each area. We found three patterns in these time series graphs: (1) Areas that are activated by both search and aha solutions, but more strongly activated by aha solutions. These include the right insula, the anterior cingulate, and left BA45; (2) Areas that are only activated by aha solutions but either not activated or deactivated by search solutions. These include the right PFC and the pons; (3) Areas that are deactivated by search solutions and minimally activated by aha solutions. These include the right temporal pole and the bilateral angular gyri.

Because we have contrasted aha solutions from search solutions for time points of every half second, we are also able to determine at which time point an area becomes significantly more active for an aha solution versus a search solution. This may be observed in Figure 1 as the time point that first shows significant difference between search and insight solutions. We have classified these areas into two categories: (1) early activations for aha (0–2.5 s from problem onset, not including hemodynamic lag); (2) late activations for aha (3–5.5 s from problem onset, not including hemodynamic lag). In this categorization, we find that the right insula and left BA 45, both areas which are known to be involved in language processing, show early activation for the aha solution. Instead, the bilateral angular gyri, the anterior cingulate, the pons, right temporal pole, and the right PFC show late activation differences for the aha when compared with search.

Search-Aha Activations

This contrast revealed no voxels that were significantly more active for search solutions than for insight solutions.

DISCUSSION

This study aims to understand not only the brain areas involved in insight solutions, but also the process involved in these areas. Thus we make an attempt to understand

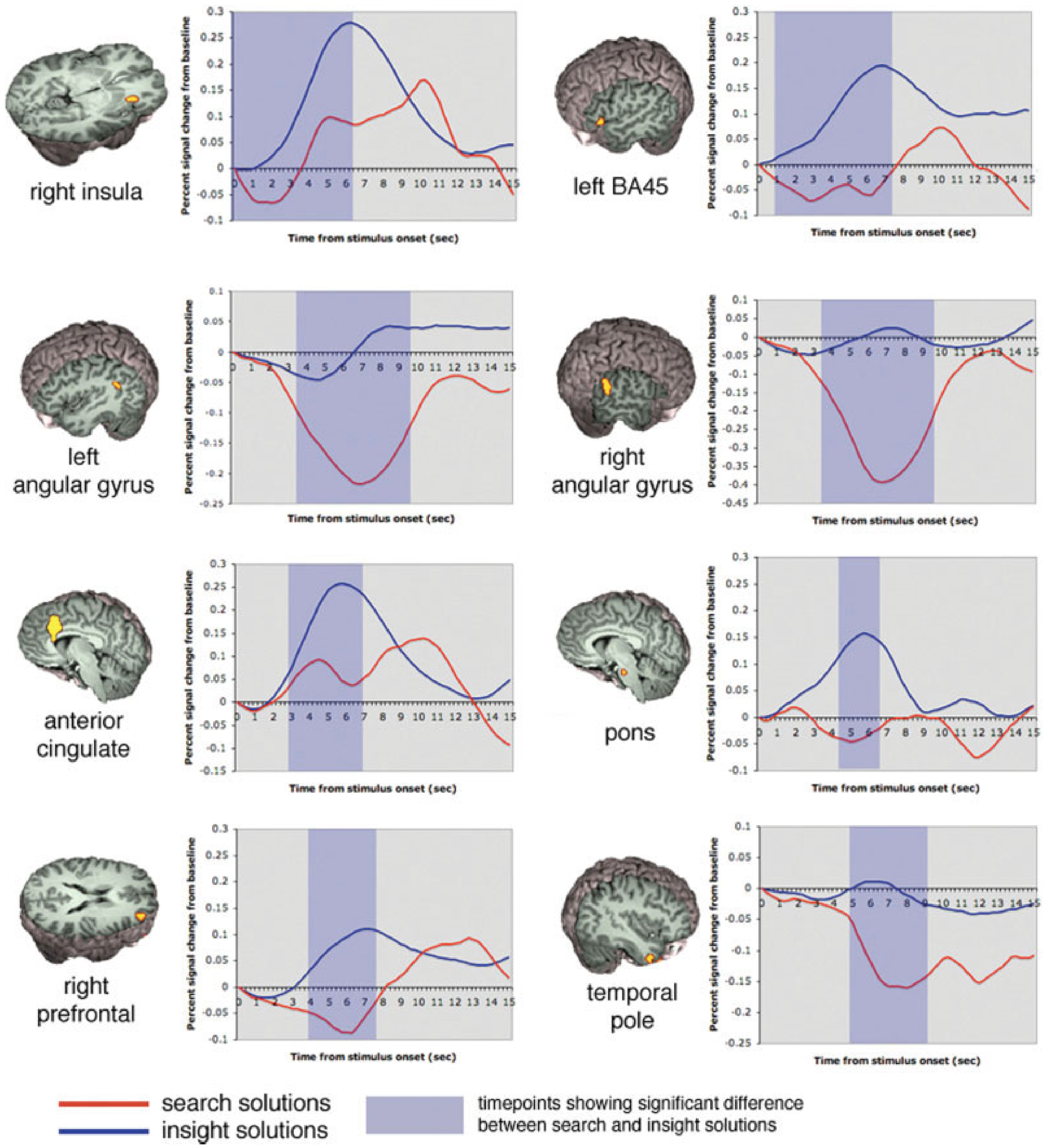

Figure 1.
Brain areas that were more activated during insight solutions when compared with search solutions, along with their time series graphs (blue). These graphs also depict the time series response of these areas during search solutions (red). The time points showing significant differences between insight and search solutions are highlighted in dark blue.

the data both by the region and the time course of activation. As the pons is not an a priori region of interest, we refrain from speculating on the activity in this region.

Early Bilateral Insula Activation for Insight Solutions

The insula was activated during insight solutions both compared with rest (bilaterally) as well as with search (right insula). Thus, starting early in the problem-solving process (1.5 s after anagram is presented, not accounting for hemodynamic lag) it appears that search problem solving is marked by left insula activation, whereas insight problem solving is marked by bilateral insula activation.

Insula activation could be reflective of the insula's involvement in language processing [Ackermann and Riecker, 2004; Blank et al., 2002] or other components of solution processing. While language and analytical processing is canonically thought to be lateralized to the left hemisphere, it is commonly thought that the right hemisphere is involved with gestalt, global processing [Berman et al., 2003; Zaidel et al., 1990]. In the same vein, one of the defining markers of an insight experience (in solving anagrams as in other types of problems) is that the solution seems to appear as a complete gestalt. In the psychological literature, this is noted by the use of "warmth" scales. That is, an experimenter will ask a participant who is solving a particular problem to describe how close they are to the solution for a given problem consistently throughout the problem-solving time period. For search solutions, the participant commonly reports increasing "warmth" as they get closer to the solution, and pieces of the solution become more and more apparent to the subject. By contrast, for aha solutions, the participant commonly reports a lack of warmth consistently until suddenly the solution is reached as a whole, seemingly from nowhere [Metclafe, 1986; Metclafe and Wiebe, 1987].

A right hemisphere gestalt representation of the solution might be an important factor in having an anagram insight solution, as indicated by the right insula activation observed only for insight solutions. However, the main difference in insight solutions from search solutions is not a shift from left to right activation, but of *bilateral* activation. The right insula is activated along with the left insula for insight solutions, whereas the left insula is mainly activated in search solutions. Thus, another key component to insight solutions may not be gestalt representation alone, but the conjunction of this strategy with serial processing in the left hemisphere. Furthermore, bilateral activation might indicate increased interhemispheric transfer. While some have argued that creativity is solely a function of the right hemisphere [Finkelstein et al., 1991; Miller et al., 1996, 1998, 2000; Murai et al., 1998; Rotenberg, 1994], others have argued that both hemispheres are involved and that interrelations between the two hemispheres are the key to creative insight [Atchley et al., 1999; Bogen and Bogen, 1969; Kwong et al., 1992]. Our data support the latter view.

Prefrontal Activations Related to Solution Time

The role of the PFC in creativity and insight has been previously well discussed. In a review, Dietrich argues that the PFC, with its processing of highly integrative computations, enables novel combinations of information to be reorganized. Furthermore, he argues for differential processing of different aspects of creativity by the ventromedial PFC (VMPFC) and the dorsolateral PFC (DLPFC). The DLPFC is thought to process working memory, directed attention, temporal integration, all processes which Deitrich considers to be deliberate deductive problem solving which may be a marker of creative solutions (though search solutions should also utilize this processing to some degree). By contrast, the VMPFC is argued to be involved in metacognitive functions: internalizing values and societal standards (as best observed by a patient who had a lesion to this area, Phineas Gage, and no longer followed societal standards [Macmillan, 1986]). This kind of evaluative role of the VMPFC is considered to be essential to insight, as Deitrich writes,

> Insights are only the first step in converting novel combinations of information into creative work. Once an insight occurs, the prefrontal cortex can bring to bear the full arsenal of higher cognitive functions to the problem, including central executive processes such as directing and sustaining attention, retrieving relevant memories, buffering that information and ordering it in space-time, as well as thinking abstractly and considering impact and appropriateness. Innumerous insights turn out to be incorrect, incomplete, or trivial, so judging which insights to pursue and which to discard requires prefrontal cortex integration.
>
> *Dietrich* [2004]

Previous studies on insight and creativity also indicate that the PFC in particular may be a part of the insight/creativity network. Spontaneous counterfactual thinking, which is thought to be an important component of insight [Mai et al., 2004], was found to be impaired with patients with PFC lesions [Gomez Beldarrain et al., 2005]. In particular, the right PFC has been noted to be an important component for creative solutions. In an fMRI study on semantic divergence and creative story generation, Howard-Jones et al. [2005] found the right PFC to be particularly activated. They attribute this right PFC functioning as increased monitoring as well as higher cognitive control for stringent monitoring for creative insightful solutions. Furthermore, right prefrontal activation has been observed for other creative problem solving tasks, such as processing unusual semantic relationships [Schmidt et al., 2007]. In an fMRI study which explored analogical reasoning, both the left and the right PFC were found to be significantly activated [Geake and Hansen, 2005]. Here again the authors argue that the left PFC is involved in information abstraction, whereas areas in the right PFC play an evaluative role [Geake and Hansen, 2005; Schacter et al., 1997]. Finally, there is evidence that while the left hemisphere PFC might be involved with task complexity and relational integration, the right PFC might be involved in the processing of distant associations [Geake and Hansen, 2005; Schmidt et al., 2007] that might be important for creative thought and problem solving.

In this study we found that insight solutions are marked by right ventral prefrontal activations. Furthermore, our data indicate that the right VPFC is significantly more activated in insight strategies when compared with search strategies late in the problem-solving timeframe; activation in the right PFC is more closely aligned with solution time rather than the initial problem solving time. Thus our results seem to support the hypothesis that the right ventral PFC plays a role in the evaluation and metacognition of insight problem solving rather than the problem solving itself.

Anterior Cingulate

We found increased activation in the anterior cingulate for insight solutions when compared with search solutions. The anterior cingulate has been linked with conflict monitoring and increased information processing demand in a number of tasks [Botvinick et al., 1999; Carter et al., 1998; Scheffers et al., 1996]. It has also been found to be activated by creative story generation [Howard-Jones et al., 2005] and insight associated with solving riddles [Mai et al., 2004]. In the latter study, the authors argue that insight involves a break in mental fixation of an inappropriate attempt to solve the problem [Smith and Blankenship, 1991; Weisberg and Alba, 1981], and that ACC activation might be related to conflict monitoring between old and new cognitive models. Other researchers note that the ACC may be working in conjunction with the PFC by evaluating the need for executive control and relaying the need for such control to the PFC [Dreher and Berman, 2002; Garavan et al., 2002; Gehring and Knight, 2000; Tomaiuolo et al., 1999; Turken and Swick, 1999]. Thus, in this study, activity in this region might indicate that the ACC is part of a tight network involved in focused attention, monitoring, and executive control and might be a necessary component of insight processing.

Deactivations of the Angular Gyrus and Temporal Pole in Search Solutions

In comparing insight solutions to search solutions, the right temporal pole and the left and right angular gyrus were found to be minimally active in insight solutions and largely deactivated in search solutions. While deactivations in fMRI are difficult to interpret, it should be noted that both of these areas are involved in language processing. In particular, damage to the angular gyrus may affect processing of auditory short-term verbal memory. Patients with damage to this region show marked deficits in the ability to repeat sentences especially if the sentences contained low-frequency words [Dronkers et al., 2004]. The right temporal pole has also been associated with processing idioms. In a study investigating the neural correlates of idiomatic sentence processing using fMRI, subjects were presented with literal sentences or idiomatic sentences, each followed by pictures and judged whether the picture matched the sentence or not. The right temporal pole was part of a network of areas that was activated by the nonliteral condition when compared with the literal condition [Lauro et al., 2008]. The role these areas may play in verbal memory and thinking about a problem in a more tangential manner may be important for solving anagrams, and deactivation in them may contribute to why the search strategy was slower.

Caveats

Insight solutions are a relatively new and difficult phenomenon to study. It could be that in studying anagram experts, our study is instead looking at "expert intuition" rather than insight per se. However, it is also well known that paradigm shifts that arise from creative insights most often come from experts in the particular field rather than novices. Thus expert intuition and insight are difficult to disentangle.

The criteria for determining a solution as insight or search is a nebulous one. Others have included additional distinctions in the self-report question including certainty in the correctness of the solution [Jung-Beeman et al., 2004], though still self-report holds strong caveats. Here we tried to combine self-report with an objective measure—time to solution. While the data from Novick and Sherman [2003] indicate that solution time is highly correlated with self-report, there are still limitations with this categorization. Further research is needed in trying to find more objective measures.

Finally, while we used time to solution as criteria for categorizing insight and search solutions, this leads to confounding solution time with our solution type categorization. This limitation in disentangling between these variables, and how it may affect signal modeling in the data analysis should be kept in mind while considering the data. However, considering the time series data (see Fig. 1), if the only difference between insight and search solutions was time to response, then we would expect to see similar hemodynamic responses in BOLD over time, but with a delayed lag for search problems. Instead, our data reveal that most of our active clusters show clearly different responses, not timing lags. Even for clusters that show somewhat similar patterns, the activity for search solutions never quite reach the same level as that for insight solutions. Thus, we believe that at least some active clusters show patterns that are extremely unlikely to be attributable to time lag alone.

CONCLUSION

Our data indicate that a network of areas is more activated in the insight solutions when compared with the search solutions during the initial moments of problem solving. These include Broca's area and the right insula. We did not find any brain areas that were significantly more active for search solutions, which may indicate that insight solutions utilize the same brain areas for problem solving in addition to other areas. It may be that utilizing both hemispheres for task-specific processing may be an important component of insight solutions. In addition, our data indicate that right prefrontal activation, along with anterior cingulate activation, may be important for metacognitive components of insight solutions, including attention and monitoring of the solution. These are important first steps in the study of insight from which hopefully future research can build.

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