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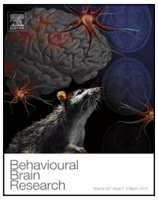

Research report

Brain activity in using heuristic prototype to solve insightful problems

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HIGHLIGHTS

- Functional magnetic resonance imaging, real-life scientific innovation problem materials and experimental paradigm were used.
- The left DLPFC might be responsible for the automatic retrieval of technical problems.
- The left AG might be involved in forming novel associations between technical problems and related prototypes.

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ABSTRACT

When confronted with a real-world problem, heuristic knowledge and experience can guide the solution of a specific technical problem as the key step toward innovation. In particular, a heuristic prototype must be used correctly to cue the technical problem that exists in a particular situation. The present study selected an innovative paradigm and scientific innovation materials to investigate the neural basis of insight induced by heuristic prototypes using event-related functional magnetic resonance imaging (fMRI). The day prior to undergoing fMRI scanning, participants were asked to solve 42 difficult technical problems that scientists might have already encountered but were unknown to the participants. In the subsequent fMRI experiment, the same participants were randomly presented with 84 prototypes classified into two types: related prototypes (RPs), which were useful for solving previously encountered problems, and unrelated prototypes (UPs), which sometimes did not contribute to problem solving. While being scanned, participants were asked to assess whether a prototype is relevant to any of the technical problems. This study comprised two conditions: solving technical problems when presented with a related heuristic prototype and failing to solve technical problems using unrelated heuristic prototypes. The authors assumed that the regions significantly activated by the RP condition, compared with the UP condition, reflected brain activity related to the role of heuristic prototypes in scientific insight. fMRI data showed that the left dorsolateral prefrontal gyrus (left DLFPC, BA9) and the left angular gyrus (left AG, BA39) were more significantly activated when presented with RPs than with UPs. The results suggest that the DLPFC may be involved in the automatic retrieval of technical problems and breaking of mental sets. Moreover, the left AG may be involved in forming novel associations between technical problems and related prototypes.

1. Introduction

Insight events are classified as a subfield of creativity because the first step toward a finished creative product is, frequently, a creative insight [1]. Insight is usually preceded by an impasse and then frustration after a period of no progress, frequently after incubation, during which a problem is set aside. After this process, a new way of looking at the problem, which leads to the solution, is accompanied by great excitement and what is referred to as the “aha” experience [2,3]. Insight problems are defined as problems in which a solution cannot be logically induced [4], but instead obtained through a key process whereby the problem is restructured in a novel way [5,6]. The nature of restructuring with regard to insight necessitates the replacement of an initial faulty representation that cannot lead to a correct solution by a new and more effective problem representation. Specifically, the initial

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misleading representation of the problem is revised, and the inappropriate constraints are eliminated. This approach provides an opportunity to look at a problem from different perspectives that eventually yields a solution [2,7,8]. In particular, heuristics has proved to be a powerful means for producing insights that yield effective problem representations and solutions [9]. In addition, insight has been shown to occur when a prototype event is suddenly activated [10]. The key elements of insight are generally identified as impasse, restructuring, and the "aha" moment [5]. Insight in problem solving has been studied for almost a century using behavioral methods, and such studies have generated a variety of functional models of insight [11,12]. Recent developments in brain imaging techniques have facilitated a further, precise study on the neural mechanism of insight.

Luo et al. [13] conducted an event-related fMRI study using incomprehensible sentences followed by solution cues as materials. The result showed that the "Aha!" reaction is associated with anterior cingulate cortex (ACC) and left prefrontal cortex (LPFC). Aziz-Zadeh et al. [6] conducted an event-related fMRI study using an anagram task. Their results showed that verbal insight solutions bilaterally activate the angular gyrus (AG), insula, and ACC. Darsaud et al. [14] characterized the neural mechanisms of delayed insight using a number reduction task (NRT) with two sessions (training and retest). The results showed that a more enhanced response in ventromedial prefrontal cortex (VMPFC) was associated with processing the memory traces overnight in solvers. Chi and Snyder [15] documented that, after receiving transcranial direct current stimulation (tDCS) to the anterior temporal lobes (ATL), the participants perform significantly better in insight problem solving tasks than when they received sham stimulation. Moreover, other important studies on insightful problem solving have demonstrated activation in the precuneus, left inferior/middle frontal gyrus (left IFG, left MFG), left middle temporal gyrus (left MTG), and inferior occipital gyrus (IOG) [16–21].

Although the aforementioned findings aid the understanding of the insight process, certain gaps remain. First, insight has been examined primarily through compound remote associate problems and insightful problem solving. Few studies have investigated the fMRI study of creativity using real-life scientific innovations. In one recent study, Luo et al. [22] contrasted novel with old scientific actual innovations to explore the neural basis of scientific innovation induced by heuristic prototypes. Although the experimental materials of insightful problem solving are also actual innovations, the paradigm that participants learn prototypes before encountering novel problems is neither close to realistic insightful problem solving nor in accord with the concept of insight. Second, to date, no studies have examined the patterns of neural activity involved in insight by correctly matching a specific prototype with an unsolved technical problem using heuristics. Third, Christensen and Schunn [23] proposed an opportunistic assimilation theory that suggests insight occurs after incubation when relevant cues are processed. The incubation period has been empirically demonstrated as important for increasing the probability of eventually identifying correct solutions [24]. Meanwhile, insight does not necessarily occur after the initial representation of the problem but can emerge at a later date, especially after nocturnal sleep [25]. Nevertheless, few experimental paradigms regarding insight can imitate real-life incubation directly, thus reducing the ecological validity of the previous experimental paradigm.

Insight requires restructuring, a task that is relatively rare and difficult to elicit in a laboratory [11]. One way of dealing with this problem is to use heuristics [9]. The present study was designed to investigate the neural activity of insight induced by a heuristic prototype, specifically by selecting two different types of prototypes, namely, related prototypes (RPs) and unrelated prototypes (UPs), as our experimental materials (see Section 2.2). The experimental materials (including the technical problems and heuristic prototypes) are cases in which the occurrence of insight is stimulated through activation of a related prototype in real scientific innovations. In addition, the participants were asked to learn these technical problems the day prior to scanning, so that they can commit the unsolved problems to memory. Thus, participants could "repeat" the process of scientific insight by linking a related prototype with a technical problem. Therefore, this paradigm is well conceived as a high degree of ecological validity for imitating the incubation of real-life creative processes.

The cognitive process of insight induced by heuristic prototypes may be associated with two major processes: (1) automatically activating related technical problems (e.g., designing a faster and more efficient submarine hull) and breaking mental impasse; and (2) forming novel associations between technical problems and related heuristic prototypes (e.g., using the design of a shark's skin) [13,19,22,26,27]. The activity of breaking the occurrence of mental impasse and restructuring the problem in a novel way most likely reflects processes such as automatic retrieval and the elimination of inappropriate constraints. The present study expects the PFC region to be involved in these cognitive processes [6,28–31]. Forming novel associations between technical problems and related prototypes most likely reflects the recognition of relational semantic similarity. Language-specific representations in the left hemisphere of the brain play an important role in seeking relational semantic similarity, and cognitive control may also have a key part in applying related heuristics appropriately. Thus, this study expects language processing and executive control to be associated with the angular gyrus [30–34].

2. Material and method

2.1. Participants

A total of 21 college students (11 females; mean age = 22.38) from Southwest University, Chongqing, China, participated in this study. Participants reported no psychiatric illness or neurological disorders. Two participants were excluded because they knew the answers to the prepared technical problems. Three participants were excluded because they moved their head too much. Thus, data on 16 participants (7 males, aged 20–27 years, mean age = 22.6 years; SD = 2.2; 9 females, aged 20–25 years, mean age = 22.2 years, SD = 1.9) were retained for further analyses. All of the participants signed an informed consent form before enrolling in the experiment. Moreover, the participants were paid for their participation.

2.2. Materials and tasks

When encountering an unsolved scientific problem in real-life scientific innovations, scientists may store the problem in their mind first or set the problem aside for a while (which seems similar to incubation). Insight occurs in this particular moment when a related prototype that infers a new idea for scientific problem solving is processed.

In the present study, 42 technical problems were taken from contemporary situations in science and engineering collected from various media, such as magazines, the internet, and television. Thus, these technical problems, which scientists recently encountered, are almost unknown to college students. Obviously, the problem materials, however recent, cannot be guaranteed to be unknown to the participants. To reduce influence of prior knowledge, participants were instructed to inform the experimenter if they knew about any of the problem materials, which was a criterion for exclusion.

To investigate the neural activity of insight, two different kinds of prototypes were selected. RPs (related prototypes) includes related heuristic information that helps solve technical problems, whereas UPs (unrelated prototypes) are prototypes that do not include any related heuristic information. For example, scientists attempting to enable the hull of a submarine to move faster and more efficiently for a long time (an unsolved technical problem). After a while, the heuristic prototype that the unique grooved scales of a shark's skin consists of rectangular bases embedded in the skin with tiny spines to prevent sea plants and organisms from adhering to it, consequently reducing drag (related prototype), is processed occasionally. Then, scientists gain inspiration from the related prototype (shark's skin) and finally solve the technical problem.[1] However, the unrelated prototype, such as the drum-type

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[1] Cited from: http://baianbai.com/shark/indexe.asp.

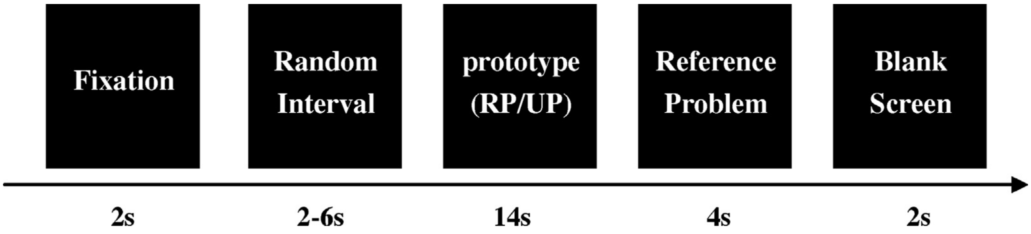


Fig. 1. Task sequence of the experiment.

fisheye camera that can have a field of vision of 220° and can help capture a larger area, cannot inspire the scientists to solve the technical problem. In the experimental process, subjects were simply asked to report the correct related prototype and general method of solving the problem, rather than actually solving the technical problem. For the above example, the correct solution to the questionnaire would be "to imitate the structure of spider silk and produce a special material with incredible tensile strength and elasticity." In order to avoid the difference caused by reading time or the ratio between reading and thinking, the text length between RPs and UPs was matched.

In a preparatory experiment, 36 college students (19 females and 17 males; mean age, 22.3 years; SD = 1.52) were asked to solve 42 technical problems directly. The results showed that the average accuracy was very low (<10%). After being presented with the RP, the results showed that the average accuracy was 73.6% (SD = 0.84). The RPs seemed to have actually helped the college students resolve the problems more effectively.

2.3. *Procedure*

Participants were asked to solve all 42 technical problems without any related prototypes the day before the experiment and then try their best to remember the unresolved technical problems. Thus, the technical problems would not be presented in the MRI scanner.

To familiarize participants with the task, they were trained on a set of similar materials in the same procedure (one block with five prototypes) before entering the fMRI scanner, as described by [19]. Only participants very familiar with the procedure were asked into the scanner. The technical problems, related/unrelated prototypes, or reference problems were not repeated. Words used in the stimulus materials were generally common words with a high frequency of occurrence. Once in the scanner, 84 prototypes were presented in random order in an event-related design in two separate blocks with 42 prototypes per block.

Participants were instructed to read the related or unrelated prototype, and then think of a problem solution for the technical problem. The participants were shown either a correct or incorrect solution for the technical problem and then instructed to respond whether this was the solution they devised for the problem. The procedure of the experiment is shown in Fig. 1. Each trial was initiated by a "+" sign at the center of the screen for 2 s. Then, an interval was presented for 2–6 s randomly. Third, a prototype (RP or UP) was presented in the center of the screen randomly for 14 s. Participants were asked to try to understand the prototype and make the corresponding response by pressing keys. Subjects were asked to press the "1" key if they associated the presented prototype with a technical problem and obtained the simple solution (method for solving the problem) or the "2" key if they did not make the association. After pressing the key, the presented prototype would disappear. After 14 s, the reference answer was presented at the center of the screen for 4 s. During this time, participants needed to judge whether the problem solution they devised for the technical problem was similar to the presented reference solution. They were instructed to press the "1" key quickly if the problem they had devised was the same as the displayed reference solution and press the "2" key otherwise. Finally, a blank screen was presented for 2 s. Between two blocks, participants were allowed a short rest. After scanning, the participants were asked to complete a questionnaire that included all the 42 technical problems presented the day before entering the scanner and then write the answer to each technical problem within 40 min.

2.4. *Imaging data acquisition*

Images were acquired using a 3 T Siemens Magnetom Trio MRI scanner (Siemens Medical Systems, Erlangen, Germany). Functional data comprised of 948 volumes of the experiment obtained using a T2*-weighted gradient echo planar imaging sequences (TR = 2000 ms; TE = 30 ms; flip angle = 90°; field of view = 220 × 220; 3 mm × 3 mm in-plane resolution). In addition, 3D anatomical data were obtained using a T1-weighted for each participant (176 sagittal slices, TR = 1900 ms; TE = 2.52 ms; slice thickness = 1 mm; field of view = 256 × 256; voxel size = 1 mm × 1 mm × 1 mm).

2.5. *Imaging data analysis*

fMRI data were analyzed using Brain Voyager QX v 2.0 software (Brain Invention, The Netherlands). A functional project was created. To avoid the T1 saturation effect, the first five volumes for each run were skipped. The preprocessing of the functional scans included slice scan time correction (using "sinc interpolation"), 3D motion correction (using "trilinear interpolation"), spatial smoothing (FWHM = 6 mm), and temporal filtering (using general linear model–Fourier filter) with four steps. Then, the EPI images were co-registered with anatomical ones and were normalized into Talairach space by transformation. The Talairach transformation of functional data resulted in a normalized four-dimensional volume time course data for each functional run [35].

Table 1
Brain regions showing significant differences as indicated in the comparison of related prototypes (RPs) and unrelated prototypes (UPs) in the experiment.

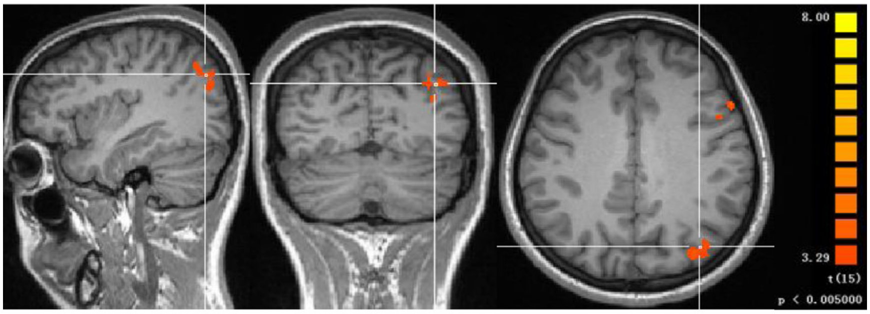
Regions activated	Hem	BA	Talairach coordinate			t	Clusters
			X	Y	Z		
RP > UP							
AG	LH	39	−39	−64	37	4.961	1226
DLPFC	LH	9	−45	8	37	4.195	371

Multiple regression analysis of BOLD signal changes for individual participants was convolved with a canonical hemodynamic response function (HRF, double-gamma) to form covariates in a general linear model [36,37]. To render better estimations, all events that could contribute to the time course were included as predictors, and each predictor was convolved with a double-gamma hemodynamic response function. The onset and duration of the trials for different events (fixation, RP/UP, reference problem, blank screen; the correct activation of the technical problem from the RP/UP conditions were considered effects of interest) was derived for each run of each subject's paradigm in the experiment [37]. Whole-brain directional comparisons between the RP and UP (RP > UP) problems were carried out in a random effect model for group analysis. To correct for multiple comparisons, a cluster threshold of eight contiguous voxels was used [38,39]. This cluster threshold was based on the corrected threshold of $\alpha < 0.05$ ($t = 3.29$, uncorrected voxel-wise $p < 0.005$ combined with a voxel size of >8 voxels (216 mm^3) using a Brain Voyager QX Cluster-level Statistical Threshold Estimator plugin, which uses a "Monte Carlo simulation (with 1000 iterations) to establish the critical cluster size threshold corresponding to a family-wise a of 0.05 corrected for the whole brain volume." Peak Talairach coordination of each region in statistical maps (and corresponding Brodmann area) and volume across participants are shown in Table 1.

3. Results

Only correct responses both in the scanner and in the post-scanning questionnaires were considered as correct trials. According to the behavioral response in the scanner (RP and UP accuracies were 73.6% and 48.3%, respectively) and written questionnaire answers outside the scanner (the accuracy of RP was 70.6%), the final accuracy rates of RP and UP tasks were 59.61% (SEM = 0.022) and 48.3% (SEM = 0.038), respectively. In addition, the reaction times of correct RP and UP were 7606 ms (SEM = 4.75) and 7709 ms (SEM = 4.44), respectively. The mean accuracy rate was higher for RP than for UP [t (15) = 2.367, $p < 0.05$] but the mean reaction time for RP and UP reflected no significant difference [t (15) = −0.864, $p > 0.05$].

Contrasts of whole-brain activity were carried out between the two conditions (solved technical problems with a related heuristic prototype and unsolved technical problems with unrelated heuristic prototype) using a random effects analysis, which revealed greater activation in the left dorsolateral prefrontal gyrus (left DLPFC, BA9) and the left angular gyrus (left AG, BA39) for heuristically guided problem solving (Fig. 2).


left angular gyrus

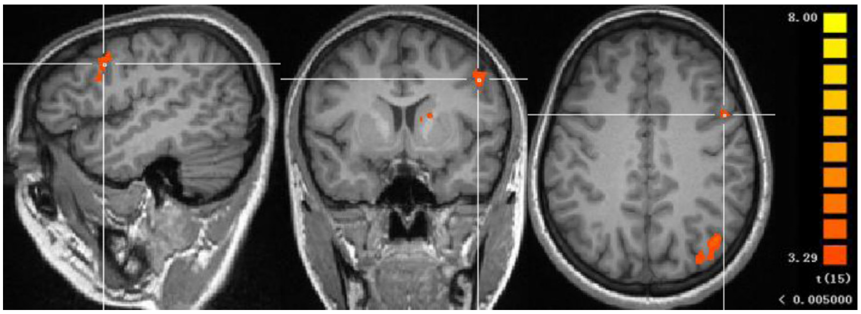

left dorsolateral prefrontal gyrus

Fig. 2. fMRI results showing the random-effects GLM for related prototypes (RPs) and unrelated prototypes (UPs).

4. Discussion

The results supported the prediction that the left DLPFC (BA 9) and left AG (BA 39) are more active under the condition of solved technical problems after presentation of a related heuristic prototype than that after presentation of an unrelated heuristic prototype. Below, we discuss the implications of these results in terms of the role of heuristic prototypes in solving technical problems.

Previous studies have widely found the activation of the prefrontal cortex (PFC) during memory retrieval in several psychological paradigms and test modalities [40]. Empirical studies have also shown that frontal lesions influence organized and monitored memory search [41]. In addition, the lateral PFC (LPFC) has been linked to working memory [42], which may play a decisive role in gaining insight [15,43]. In associating related prototypes with unsolved technical problem correctly, in the present study, unsolved technical problem should be activated first. How is the technical problem activated (or retrieved) automatically from memory? This phenomenon is probably the result of the consistency (inner semantic consistency) between the functions of the heuristic prototype (reducing drag) and the goals of the unsolved technical problem. The technical problem thus moves faster and more efficiently. Previous studies also claimed that the DLPFC is crucial for selecting a set of suitable responses for a particular task and for the efficient encoding of novel stimuli [44–46]. Therefore, the DLPFC, which is generally responsible for encoding the trial in memory, may play a very important role in selecting and retrieving the matched unsolved technical problem from memory to a greater extent and in eliminating unmatched technical problems. In addition, the MFG is associated with mental preparation for successful logogriph solving and "spontaneous conscious effort" to suppress extraneous thoughts [47,48]. The prefrontal network is generally involved in the restructuring of problem representations and representing the "goal state" of the problematic situation [45,49]. A further comparison of successfully versus unsuccessfully completed match problems also reveal that left LPFC have also been linked to conflict resolution in set-shift transformation [50,51]. One lesion study showed that patients with damage to the lateral frontal cortex perform better compared with healthy participants in high-constraint problems, but these results were only obtained from an artificial situation, in which patients could face a problem with a trial-and-error approach without prior hypotheses. Such hypotheses only help researchers deal with the familiar efficiently but prevent the search for better solutions in a different context [45,52]. In the present study, the real-life unsolved technical problem also seems to represent a mental impasse for participants; they are unable solve it because of the influence of existing hypotheses [15,52]. However, when a related heuristic prototype was presented, it inspired the participants and helped reduce the influence of existing hypotheses. Finally, participants restructured these technical problems and solved them in a novel way. Thus, in the present study, DLPFC may be involved in the automatic retrieval of technical problems and in the elimination of inappropriate constraints for breaking mental impasses.

Previous studies show that the left angular gyrus (AG) appears to moderate the word recognition process [53]. Patients with damage to this region show a shortage in repeating sentences especially for low frequency words [54]. Other studies also found that the left AG is associated with certain aspects of lexical access and language comprehension and may serve more broadly to receive, organize, and coordinate information input from various forms of presentation [30,55]. In our study, after activating a technical problem, subjects still needed to form an association between the activated technical problem and the related prototype to solve the technical problem correctly because the functions of the related heuristic prototype play a key role in generating new ideas and solutions for problem solving. The process of forming associations is similar to mapping a symbol and a referent or mapping problems and their solutions. Previous studies have also found that the AG may be associated with general mapping processes [33] because it is a cross-modal integration area involved in language [32,56]. The key element in forming associations is most likely the relational semantic similarity between the heuristic prototype and the technical problem [57,58], similar to understanding the "novel metaphorical meaning" of a metaphoric sentence or an ambiguous idiom. Moreover, the precondition of seeking relational semantic similarity is similar to that of acquiring the potential significations of a technical problem and its related prototype. Specifically, word recognition and organization play an important role in seeking relational semantic similarity, as well as in forming an association between the technical problem and the heuristic prototype. In addition, a previous study found that learning-related responses are significantly activated in insight problem solvers compared with that in non-solvers in the AG, which belongs to a domain-general system that mediates controlled processes [14]. To apply the heuristic prototype to the activated technical problem appropriately in the present study, the participants also needed intensive execution during the process of prototype application. Thus, monitoring and executive functions are also key cognitive processes for successful, insightful problem solving. Therefore, the AG may be involved in forming associations between technical problems and related prototypes through the recognition of relational semantic similarity, whereby a creative method is used to resolve problems by applying heuristic prototypes.

Advantages and future directions

To the best of our knowledge, this research is the first fMRI study to investigate the neural activity of insight in heuristic real-life innovations and real paradigms. Real-life innovations are thus more natural and more closely related to real creative cognition than many "toy problems" generally used in insight research [12]. The present results demonstrate a close relationship between the processes involved in creative cognition and episodic memory retrieval as well as the formation of novel associations and metaphor.

To make our experimental paradigm as similar as possible to the process of scientific insight, an incubation period, in which participants were asked to solve the problem the day before scanning, was carried out as a control variable in the present study. No scan and control group were arranged during this period. The incubation period is also a very important part in the study of insight. Some researchers have reported increased solution rates after an incubation period, but data collection and analysis for such parts are missing in the present study. Thus, future studies should have a better design to be able to investigate the influence of sleep, Qigong exercise, and meditation during the incubation period for insightful problem solving.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.bbr.2013.07.017.

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