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RESEARCH ARTICLE

Brain mechanisms of valuable scientific problem finding inspired by heuristic knowledge

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Abstract Heuristics through the application of heuristic knowledge to the creation of imitation devices may be one of the most common processes in scientific innovation. In particular, heuristics suggests that innovation includes the automatic activation of heuristic knowledge and formation of novel associations between heuristic knowledge and problem situations. In this study, 76 scientific innovation problem situations were selected as materials. Among these, 36 contain related heuristic knowledge and 40 have no such information. Through functional magnetic resonance imaging, the learning–testing paradigm was used to explore the brain mechanisms of scientific problem finding inspired by heuristic knowledge. Participants were asked to find a problem on the basis of a given innovation problem situation. Two scenarios were presented: finding scientific problems with related heuristic knowledge and finding conventional problems without related heuristic knowledge. The authors assumed that the regions in the brain significantly activated by the finding scientific problems with related heuristic knowledge condition compared with the finding normal problems without related heuristic knowledge condition are relevant to the brain mechanisms of scientific problem finding inspired by heuristic knowledge. The first scenario more significantly activated the left precuneus and left angular gyrus than did the second scenario. These findings suggest that the precuneus is relevant to the successful storage and retrieval of heuristic knowledge and that the left angular gyrus is involved in the formation of novel associations between heuristic knowledge and problem situations for finding scientific problems.

Keywords Scientific problem finding · Heuristic knowledge · Event-related fMRI · Precuneus · Angular gyrus

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Introduction

Creativity is the foundation of human civilization and depends on the human ability to break from existing thinking patterns and build something new (Dietrich and Kanso 2010). Throughout the history of human civilization, creative behavior appears to occur when inspired by some heuristic knowledge in real-life scientific innovations. For example, Newton obtained insights into the law of universal gravitation after observing a ripe apple drop from the tree under which he was sitting.

Most previous studies investigated creativity through insightful problem solving (Dietrich and Kanso 2010). The development of creative problem solving has attracted considerable research attention, especially the issue of brain mechanisms that take place during creative problem solving. Research has shown that the hippocampus (Luo and Niki 2003), the right anterior superior temporal gyrus (Jung-Beeman et al. 2004), the anterior prefrontal gyrus (Fink et al. 2006, 2007), the anterior cingulate cortex, the lateral prefrontal cortex (Luo et al. 2004), the superior frontal gyrus (Wang et al. 2009), the inferior occipital gyrus, the inferior occipital gyrus, and the cerebellum are activated during creative problem solving (Qiu et al. 2010; Luo et al. 2013). The precuneus, which is considered the hub of the brain (Tomasi and Volkow 2011), plays an important role in the creative process, for which the ability to connect information is important (Takeuchi et al. 2010, 2011a, b, 2012).

Other studies asserted that problem finding also is an important and distinct component of the creative process (Chand and Runco 1993; Hu et al. 2010). The ability to find a problem, which is distinct from problem solving and perhaps more important, is a key element of creative thinking and creative achievement (Jay and Perkins 1997). However, the mechanisms of problem finding are underrepresented and have received less attention (Chand and Runco 1993; Hu et al. 2010). Despite years of study, very minimal theoretical analysis and empirical data have been provided to accurately examine the nature of problem finding and its relationship with problem solving (Jay and Perkins 1997). To date, no study has investigated the validity of fMRI-based studies on problem finding using real-life scientific innovations. Despite the fact that problem solving facilitates the understanding of creativity, different studies present inconsistent findings regarding the active brain regions involved in this process. Furthermore, whether problem finding is identical to the processes investigated by the above-mentioned empirical studies remains unclear.

As a specific creative process, problem finding in the present context pertains to the independent generation of problems after reading about a scientific innovation problem situation with or without heuristic knowledge, either generally or associated only with a particular context (e.g., problems related to submarine travel). The initial results of the current work show that participants with related heuristic knowledge exhibited better performance in finding valuable scientific problems than did participants who were not equipped with related heuristic knowledge. This result indicates that related heuristic knowledge plays a critical role in creative scientific problem finding. That is, after reading about a problem situation, participants may encounter two types of problems. The first is the conventional type of problem, in which participants find only the distinction between initial and final states; similar to "experimental hypothesis," the valuable scientific problem includes one new problem solving idea and a technical route that can eliminate the distinction (this type of hypothesis has high operability and possibility for problem solving). That is, a conventional problem is general and unclear (e.g., how a task is performed), whereas a scientific problem is specific and practical (e.g., whether we can solve problems using certain objects). Therefore, the process of finding scientific problems may be equivalent to the process of proposing scientific hypotheses.

For this study, therefore, the heuristic knowledge and problem situations that scientists encounter in their daily life were chosen as materials to explore the brain mechanisms of inspiration. Participants were asked to complete two cognitive processes: retrieve previously derived heuristic knowledge and form a new association between the problem situation and the heuristic knowledge to identify a scientific problem. Previous works have indicated that retrieving previously derived heuristic knowledge may involve the precuneus (Qiu et al. 2010; Takeuchi et al. 2011a, b; Tomasi and Volkow 2011; Luo et al. 2013), and forming a new association may be associated with the angular gyrus (Dehaene et al. 2003; Ansari 2008; Grabner et al. 2009). In addition, recent studies on creative cognition have reported that the regions of the default mode network play a crucial role in creativity (Fink et al. 2010, 2012). Therefore, we predict that the inspiration effect induced by heuristic knowledge will activate precuneus and angular gyrus regions.

Materials and methods

Participants

Seventeen healthy, right-handed undergraduates (9 females, aged 19–24, mean = 22.1 years, SD = 2.0; 8 males, aged 19–24, mean = 22.1 years, SD = 1.4) were recruited from Southwest University in China, who had never taken part in similar experiments, and participated in the research. Exclusion criteria were pre-existing psychiatric conditions, head injury, drug abuse, and feelings of discomfort while in the fMRI machine. Participants gave written informed consent, and they were paid for their participation.

Materials and tasks

Scientists have always been inspired by certain related heuristic events as they identify scientific problems for practical scientific innovations. An example of a proposed scientific problem is whether a material similar to a shark's skin will enable a submarine to more rapidly and more efficiently move. Similar to Einstein's definition of valuable problem finding, this type of scientific problem gives rise to new questions and possibilities and requires old problems to be analyzed under a different perspective. Creative imagination is necessary for this task. In the aforementioned example, the problem situation is that the submarine moves slowly because sea plants and organisms attach to the hull; the related heuristic knowledge is that a shark's skin is uniquely grooved and consists of rectangular bases with tiny spines that prevent sea plants and organisms from attaching to it, consequently reducing drag.[1] In situations wherein heuristic knowledge is unavailable, people are more likely to identify conventional problems, such as how submarines can move fast? In this study, each material for a scientific innovation problem includes a scientific problem situation, related heuristic knowledge, and a scientific problem. We collected 76 scientific innovation problem materials from various media channels, such as books, television, and the Internet. The problem materials are all recent scientific innovations encountered by scientists and almost unknown to college students. The participants in our study were asked to find problems on the basis of the scientific innovation problem situations with or without related heuristic knowledge. Nevertheless, however recent the scientific innovation problem materials were, we could not guarantee that they were unknown to the participants. To overcome this problem, the participants who informed the researchers that they had prior knowledge of the problem materials were excluded. The 76 scientific problem situations were equally divided into four groups, and the difficulty of the scientific problem situations was standardized. The average difficulty of these four groups was 80.50 (SD = 15.2), 81.56 (SD = 14.3), 79.75 (SD = 15.1), and 80.66 (SD = 14.7). Therefore, the variations in difficulty among these groups [F (3, 72) = 0.427, $p > 0.05$] were nonsignificant. Each group included 19 scientific problem situations (9 with heuristic knowledge and 10 without heuristic knowledge).

Procedure

To familiarize the participants with the experimental procedure, we trained them with a set of similar materials before they underwent fMRI scanning (similar to Luo et al. 2013). In the formal experiment, 76 scientific innovation problem situations (36 with heuristic knowledge and 40 without heuristic knowledge) were randomly presented in an event-related design in four separate blocks with 19 scientific innovation problem situations per block. No repetition of stimuli was conducted in the formal test. The words that appeared in the experiment were almost of high frequency. By manipulating whether heuristic knowledge was presented, we delineated two scenarios: finding scientific problems with heuristic knowledge and finding conventional problems without heuristic knowledge. The flow of the experimental procedure is shown in Fig. 1. First, each trial was initiated by a "+" sign randomly flashed at the center of the screen for 2 or 6 s. Second, heuristic knowledge was presented at the center of the screen one at a time for 10 s each (accompanied by heuristic knowledge), or two rows of asterisks were presented for 2 s (heuristic knowledge omitted), each time in random order. The participants were then asked to attempt to understand the heuristic knowledge without pressing any keys. Subsequently, one problem situation was presented for 14 s, and then the participants were required to press the "1" key as soon as they had thought of one problem but could make no response. Finally, one reference problem was shown at the center of the screen for 6 s, during which the participants were asked to evaluate whether the problem they thought of was the same as the reference problem or not. They were asked to press the "1" key if the problem was similar to the reference problem; otherwise, they were asked to press the "2" key. The participants were allowed to rest for a short period between each pair of blocks. After undergoing fMRI scanning, they were required to write the problems they thought of while in the scanner with the help of a questionnaire that includes all the problem situations in the formal test. The software package E-Prime (Psychology Software Tools Inc., Pittsburgh, PA, USA) was used to deliver the visual stimuli and record responses. The stimuli were projected onto a screen positioned at the end of the bore, which is visible through a mirror attached to the head coil. Cushions were used to minimize head movement.

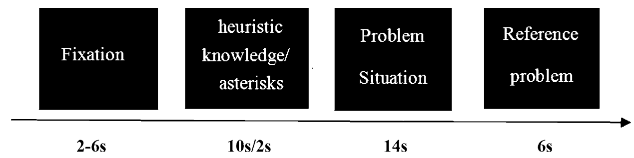

Fig. 1 Task sequence of the experiment

Imaging data acquisition

Images were acquired with a 3T Siemens Magnetom Trio MRI scanner (Siemens Medical Systems, Erlangen, Germany). Functional data composed of 948 volumes were acquired with T2*-weighted gradient echo planar imaging (EPI) sequences (TR = 2,000 ms; TE = 30 ms; 3 mm × 3 mm in-plane resolution; field of view [FOV] = 220 × 220; flip angle = 90°). Slices parallel to the AC–PC plane with a thickness of 3 mm were acquired. High-resolution T1-weighted 3D fast-field echo sequences were obtained for anatomical data (176 sagittal slices, TR = 1,900 ms; TE = 2.52 ms; slice thickness = 1 mm; FOV = 256 × 256; voxel size = 1 mm × 1 mm × 1 mm).

[1] This statement was quoted from http://baianbai.com/shark/indexe.asp?list=16.

Imaging data analyses

Data were analyzed using the Brain Voyager QX software (Brain Innovation, the Netherlands). To avoid T1 saturation, the first five volumes for each run were skipped. The functional data were preprocessed following four steps: slice scan time correction, 3D motion correction, spatial smoothing (FWHM = 6 mm), and temporal filtering (GLM-Fourier). The EPI images were then co-registered to anatomical ones and subsequently normalized into the Talairach space by transformation. The Talairach transformation of functional data resulted in normalized 4D volume time course data for each functional run (Kriegeskorte and Goebel 2001).

The vectors of onsets for separate predictors were each convolved with a hemodynamic response function (double-gamma) to form covariates in a general linear model (GLM). The onset and duration of the trials under the different conditions (fixation, the heuristic knowledge, two rows of asterisks, the problem situations, and reference problem) were derived for each run of each participant's paradigm in the experiment. For the aforementioned conditions, the BOLD responses of two events (the current problem finding in the problem situations for finding scientific problems with related heuristic knowledge and finding conventional problems without related heuristic knowledge condition) were considered the effects of interest. A whole-brain directional comparison between the two tasks was carried out in a random effect model for group analysis. To correct multiple comparisons, we used a cluster threshold of 8 contiguous voxels (Forman et al. 1995; Goebel et al. 2006). This cluster threshold was assessed at a statistical threshold of $p < 0.001$ ($t = 3.22$, corrected to $\alpha < 0.01$) using a Brain Voyager QX Cluster-level Statistical Threshold Estimator plugin. The peak Talairach coordination of each region in statistical maps (and corresponding Brodmann areas) and the volume across participants are shown in Table 1.

Results

Only the correct responses in both questionnaires and during scanning were considered correct trials. The behavioral data show that the accuracy of scientific problem finding was visibly affected by heuristic knowledge [$t\ (16) = 6.41$, $p < 0.001$] and that accuracy was higher under the presence of such knowledge. In addition, the mean reaction time used to correctly find a scientific problem with related heuristic knowledge and a conventional problem without related heuristic knowledge was 6,707 ms (SD = 1,495) and 7,014 ms (SD = 1,085), respectively. The mean reaction time of scientific problem finding was also visibly affected by heuristic knowledge [$t\ (16) = 2.81$, $p < 0.05$], and reaction time was shorter under the presence of such knowledge condition. Contrasts were set up between the two tasks (i.e., finding scientific and conventional problems with and without heuristic knowledge, respectively). The random effects analysis indicates that the main contrast between these two tasks is the activation of the left precuneus (BA 31) and left angular gyrus. The reverse analysis (finding conventional problems without related heuristic knowledge condition vs. finding scientific problems with related heuristic knowledge) revealed no significant cluster activity. These results are summarized in Fig. 2. To specify the nature of this activation, the mean beta coefficients of the precuneus and angular gyrus are summarized in Fig. 2. Finally, we determined whether the region responses to the act of finding scientific problems with heuristic knowledge and finding conventional problems without heuristic knowledge are related to participants' behavioral tendencies. We first calculated the difference scores of beta values (finding scientific problems with heuristic knowledge—finding conventional problems without heuristic knowledge) by subtracting the beta values for the conventional problem without heuristic knowledge task from those of the scientific problem with heuristic task, separately for the precuneus and angular gyrus (similar to Freeman et al. 2009, 2010). The higher the score for the precuneus and angular gyrus, the better the use of heuristic knowledge in finding scientific problems. We then examined the relationship between these difference scores and the participants' behavioral record (the subtraction of the accuracy of scientific problem finding affected by heuristic knowledge). The correlation analyses revealed a significant correlation between these beta values for the two brain regions and behavioral record: precuneus ($r = 0.501$, $p < 0.05$; Pearson correlation

Table 1 Brain regions showing significant differences as indicated in the comparison of finding scientific problems with heuristic knowledge (FSP) versus finding normal problems without heuristic knowledge (FNP) in the experiment

Regions activated	Hem	BA	Talairach coordinate			*t*	*N* of volume
			X	*Y*	*Z*		
FSP > FNP							
Precuneus	LH	31	−3	−52	31	12.137	4,185
Angular gyrus	LH	–	−39	−67	31	6.486	3,286

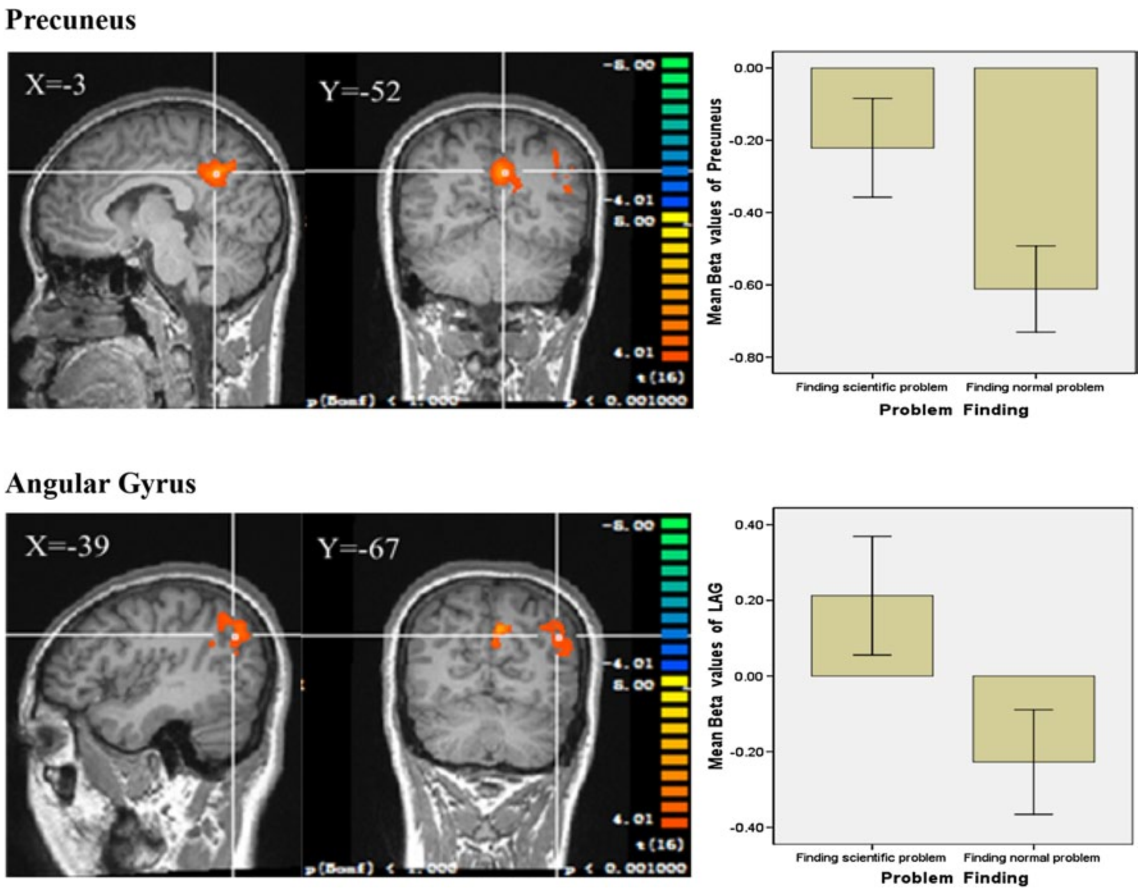

Fig. 2 The neural activation and the mean β-values in the contrast of finding scientific problem with heuristic knowledge versus finding normal problem without heuristic knowledge

coefficient) and angular gyrus ($r = 0.623$, $p < 0.01$; Pearson correlation coefficient) (Fig. 3).

Discussion

Through the comparison of the two experimental scenarios (finding valuable scientific and conventional problems), this study suggests that the cognitive process of valuable scientific problem finding inspired by heuristic knowledge may involve two processes. The first is the automatic activation of related heuristic knowledge as individuals read about one problem situation. The second process is the application of heuristic information to identifying new ideas for removing the distinction between the initial state and final goal. The fMRI data show that the left precuneus and left angular gyrus were more active under the identification of scientific problems with related heuristic knowledge than under the identification of conventional problems without related heuristic knowledge. These regions were not activated under the conventional problem scenario. In what follows, we discuss the implications of these results for finding valuable scientific problems in heuristic creativity.

Precuneus

Previous studies have shown that the precuneus may be involved in recollection processes, particularly in retrieving spatial or other contextual details (Dörfel et al. 2009). This region was activated when participants were asked to recall pictures and answer verbal questions about spatial details (Woodward et al. 2006). The precuneus is also important for regenerating rich episodic contextual associations and is activated during correct source retrieval (Lundstrom et al. 2005). This kind of episodic memory in insightful problem solving entails the recollection of heuristic knowledge that is related to an individual's previous learning experiences (Tulving 2002; Qiu et al. 2010). The current study suggests that the activation of heuristic knowledge (e.g., shark's unique grooved scale surface) is associated with the understanding and reconstruction of scientific innovation problem situations (e.g., sea plants and organisms attach to the hull of a submarine causing the submarine to move very slowly)

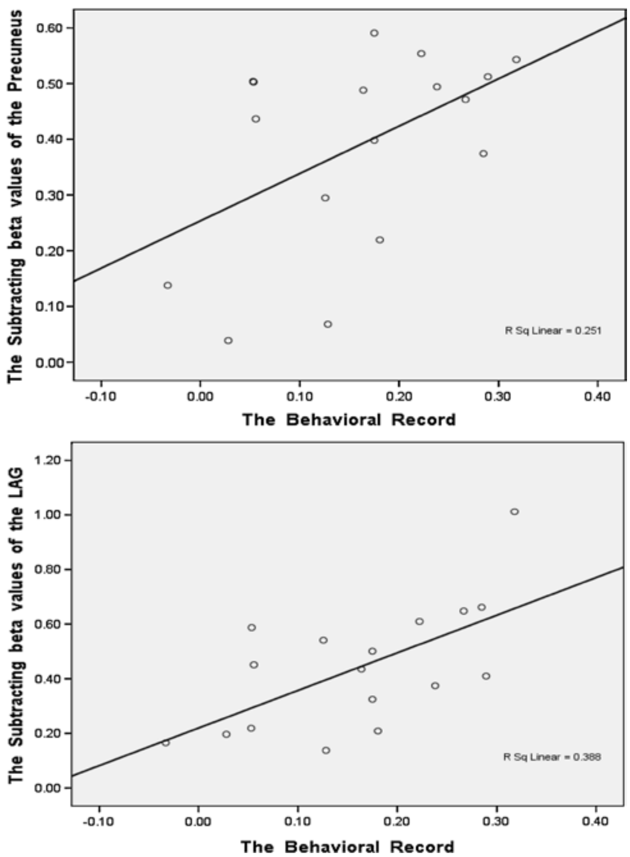

Fig. 3 The correlation analyses between subtracting beta values of the two brain regions and behavioral record: precuneus ($r = 0.501$, $p < 0.05$; Pearson correlation coefficient) and angular gyrus ($r = 0.623$, $p < 0.01$; Pearson correlation coefficient)

under highly creative scientific problem finding. That is, episodic memory is responsible for storing previously experienced information (i.e., heuristic knowledge that the participants learned earlier in the experiment). Previous studies have also indicated that the precuneus is affected by the quality or amount of knowledge retrieved (Nyberg et al. 2000; Qiu et al. 2010). Takeuchi et al. (2011b) found that "the higher the creativity scores, the less the deactivation during the task in precuneus." This finding suggests that the stronger activation (or less deactivation) in the precuneus in creative participants may actually help them retrieve an idea from an irrelevant cognitive activity (Takeuchi et al. 2011b). On the basis of these findings, we speculate that the left precuneus is associated with the storage and retrieval of heuristic knowledge, which may be the most important process in scientific innovation. In a similar vein, the strong activation of the precuneus may be involved in the automatic retrieval of heuristic information (i.e., automatic retrieval of a heuristic prototype from an irrelevant cognitive activity, which may enable the combination of the heuristic prototype and problem) (Luo et al. 2013).

Angular gyrus

Earlier research has demonstrated that the left angular gyrus is a region mostly associated with newborns because of its comprehensive language function; it appears to moderate word recognition (Harasty et al. 1999). Many studies have shown that the left angular gyrus is an association area in the cerebral cortex that connects with other speech areas. Its function is information transfer, receiving, organizing, and coordinating information inputs of various presentation styles (Cohen et al. 2003; Catani 2005). In the present study, heuristic knowledge always contains information useful for scientific problem finding. Therefore, the participants needed to understand the potential relationships between heuristic knowledge and a problem situation in order to find scientific problems, and similarly form a novel association between unrelated words. The similarities between heuristic knowledge and problem situations most likely facilitated problem finding. The presentation of heuristic knowledge helped stimulate problem finding and influenced the generation of new ideas and manners of thinking. The left angular gyrus has been speculated to mediate the retrieval of verbally stored arithmetic facts (e.g., multiplication table) from long-term memory (Dehaene et al. 1999; Delazer et al. 2005). This assumption is supported by direct empirical evidence that the left angular gyrus exhibited strong activation as participants reported arithmetic fact retrieval by relating strategy self-reports; such activation was stronger than when the participants calculated arithmetic problems (Grabner et al. 2009). Thus, the present study suggests that the left angular gyrus is involved in conveying retrieved heuristic knowledge for further processing, particularly in forming novel associations between heuristic knowledge and problem situations as highly creative scientific problems are identified.

Advantages and deficiencies

To the best of our knowledge, the present study is the first fMRI study to investigate brain mechanisms of scientific problem finding inspired by heuristic knowledge using real-life scientific innovation problem materials. Moreover, the real-life scientific innovations used in the experiment have higher ecological validity and are more related to real-life situations. The fMRI study results are valuable in revealing the brain mechanisms of creative scientific problem finding.

Although we selected interesting and novel scientific problem as materials and use fMRI, the two scenarios (finding scientific problems with related heuristic knowledge and finding conventional problems without related heuristic knowledge) in present study have substantial differences that could affect the differences of activities. One is the difference of long sentences and picture of asterisk (differences of cognitive demands which can affect subsequent event-related brain activation change before the main event) and the second is the length before the main event (10 s/2 s), which can again affect the subsequent event-related brain activation change. Therefore, in the future, we would use other more reasonable paradigm to investigate brain mechanisms of scientific problem finding inspired by heuristic knowledge.

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