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ORIGINAL ARTICLE

The optimal balance of controlled and spontaneous processing in insight problem solving: fMRI evidence from Chinese idiom guessing

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Abstract

Cognitive control is a key factor in insight generation. However, the neurocognitive mechanisms underlying the generation of insight for different cognitive control remain poorly understood. This study developed a parametric fMRI design, wherein hints for solving Chinese idiom riddles were gradually provided in a stepwise manner (from the first hint, H1, to the final hint, H4). By classifying the step-specific items solved in different hint-uncovering steps/conditions, we could identify insightful responses for different levels of spontaneous or controlled processing. At the behavioral level, the number of insightful problem solving trials reached the maximum at a intermediate level of the cognitively controlled processing and the spontaneously idea generating in H3, while the bilateral insular cortex and thalamus showed the robust engagement, implying the function of these regions in making the optimal balance between external hint processing and internal generated ideas. In addition, we identified brain areas, including the dorsolateral prefrontal cortex (dlPFC), angular gyrus (AG), dorsal anterior cingulate cortex (dACC), and precuneus (PreC), whose activities were parametrically increased with the levels of controlled (from H1 to H4) insightful processing which were increasingly produced by the sequentially revealed hints. Further representational similarity analysis (RSA) found that spontaneous processing in insight featured greater within-condition representational variabilities in widely distributed regions in the executive, salience, and default networks. Altogether, the present study provided new evidence for the relationship between the process of cognitive control and that of spontaneous idea generation in insight problem solving and demystified the function of the insula and thalamus as an interactive interface for the optimal balance of these two processes.

KEYWORDS

controlled processing, fMRI, insight problem-solving, representational similarity analysis, spontaneous processing

1 | INTRODUCTION

Problem solving is a common experience that individuals face daily, and sometimes they may reach an impasse until it is resolved, usually accompanied by an insight experience. Insight refers to a process of reconstructing a whole situation via an "Aha" or "Eureka" experience that happens in a sudden and unpredictable way (Köhler, 1985; Scheerer, 1963). Theoretically, it is proposed that insight problem solving, in contrast with the general or non-insight process, is solved via representational change from the initial inappropriate representation of the problem (Knoblich et al., 1999; Luo & Niki, 2003).

The general or particular role of insight processing in problem solving has been discussed (Dietrich & Kanso, 2010; Sawyer, 2011; Kaufman et al., 2010). Insight problem solving is regarded as a kind of automatic and unconscious process that is not typically needed for the general problem-solving (Bowden et al., 2005; Chein & Weisberg, 2014). For example, researchers suggested that insight was realized via broad semantic associations in varied forms of information (Ohlsson, 1992; Öllinger et al., 2008) or sudden acquisition from key hints while searching in the problem space (Qiu et al., 2010). This hypothesis suggests that increased attention and cognitive control may impede insight. Consistent with this, studies have demonstrated that individuals with frontal lobe damage are able to solve more insight-requiring problems (Reverberi et al., 2005). The same is true for individuals with lower working memory (DeCaro & Wieth, 2016) and attention deficits (White & Shah, 2011). They considered insight as more like "Type 1" thinking process (e.g., St Evans, 2008). However, insight problem solving was defined as a process in which individuals reached an impasse in the initial problem representations and formed new problem representations through an active search process (Knoblich et al., 1999). Researchers held the view that there were no fundamental differences between insight and general problem solving, which referred to a "Type 2" thinking process (Fleck & Weisberg, 2004; Kaplan & Simon, 1990; Weisberg & Alba, 1981). Relevant evidence has demonstrated that insight requires the support of working memory and cognitive resources to activate relevant information in memory and maintain attention to suppress interference from irrelevant information (Gilhooly & Fioratou, 2009; Byrne & Murray, 2005; Ash & Wiley, 2006). It has been argued that insight cannot be acquired by entirely spontaneous generation due to the inability to actively search for solutions in a problem space under cognitive control.

Recently, it was proposed that there are two modes of thought, sometimes referred to as associative and analytic thinking, in creative thinking (also known as Type 1 and Type 2 thinking) (Howard-Jones & Murray, 2003; Finke et al., 1992). Further, Allen and Thomas (2011) proposed that both associative and analytic thinking processes are implicated in insight problem solving and that we shift between these two modes consecutively depending on the situation we are in (Gabora, 2002; Gabora, 2003). The capacity to shift between two thinking modes distinctively alters attention because of task demands (Gabora, 2003; Vartanian et al., 2009). Thus, the mechanism underlying cognitive control appears to be related to attentional mechanisms. For example, Kaufman (2011) proposed that spontaneous or unconscious cognitive processes are activated by defocused attention, and that controlled or conscious cognition is activated through focused attention in creative thinking. Moreover, evidence has shown that creative persons perform better at adjusting attentional focus based on task demands by executive inhibition and cognitive flexibility (Bristol & Viskontas, 2006; Vartanian et al., 2007). Thus, Mok (2014) proposes that creative ideas often emerge from "an optimal balance", and this moment occurs between controlled and spontaneous processing. Behavioral studies also reported that moderate alcohol intoxication (Benedek et al., 2017; Jarosz et al., 2012) was associated with creative idea generation and that reduced sleep either impaired or fostered creativity (Randazzo et al., 1998; Razumnikova, 2007). These findings indirectly demonstrate that insight may occur through mild or moderate cognitive control. A key issue is spontaneous processing and controlled processing interplay at an optimal level. Taken together, an appropriate task that could elaborately manipulate and accurately target the "moderate" or "optimal" level of cognitive control was expected to extend the current finding.

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For optimal cognitive control on insight, we predicted that a moderate level of cognitive control or a balance of the spontaneous and controlled processing would maximize the impact on flexibly configuring information processing. Dosenbach et al. (2007) proposed a dual-network hypothesis of task control, in which the frontoparietal network (dorsolateral prefrontal cortex [PFC], intraparietal sulcus) and cinguloopercular network (anterior cingulate cortex [ACC], insular cortex and thalamus) act in parallel to configure information processing. The cinguloopercular regions, especially the insula as a hub, are characterized by independently interpreting cues, implementing top-down control, and processing bottom-up feedback (Dosenbach et al., 2007). Distinct from single-type processing (totally controlled or spontaneous insightful processing), a large amount of inputs from internal or external attention resources compete under moderate control in insightful processing. The insular cortex (insula), is described as an "integral hub" to integrate signals form the executive and default networks, and so on, that are involved in information processing (Uddin, 2015). In addition, previous neural evidence has shown that the insular cortex and other subcortical and limbic structures show greater activation in detecting novel stimuli across visual or auditory tasks, and play a role in integrating automatic and conscious thought processing (Crottaz-Herbette & Menon, 2006; Downar et al., 2000). Thus, the insula and nearby subcortical and limbic structures (e.g., the bilateral thalamus, Dosenbach et al., 2007; putamen, substantia nigra, temporal pole, Seeley et al., 2007) were considered critical regions in the interaction of top-down control and bottom-up feed-back processing during insight generation (Hypothesis 1).

In addition, we aimed to explore the distinct role of controlled or spontaneous processing in insight problem solving. This has been supported by abundant neuroscientific evidence in creative thinking (Amer et al., 2016; Mok, 2014; Marron et al., 2020; Xie et al., 2021). For example, a recent neuroscience review demonstrated that idea generation was always associated with default network activation and idea selection was more related to executive network involvement (Amer et al., 2016). Within the executive control network, the prefrontal cortex (PFC) is considered to support working memory and control attention in cognitive control tasks, such as creative idea processing (Dietrich, 2004; Miller & Cohen, 2001). In addition, the dorsolateral part of the PFC (dlPFC), together with the anterior cingulate cortex (ACC), play a role in the top-town task that demands attention (Duncan, 2006; Mok, 2012). Mok (2012) suggested that the control network coupling worked with a default network for creative idea generation (Mok, 2012). The default network is active during internally directed processing or the awake resting state, and its main cognitive functions are related to spontaneous thinking (Andrews-Hanna et al., 2010), such as mind wandering, autobiographical memory, and future episodic imagery (Buckner et al., 2008). For example, one study found increased activation in the default network such as the posterior cingulate cortex (PCC), angular gyrus/supramarginal gyrus (AG/SMG) and precuneus (PreC) and in a creative metaphors generation task, which was responsible for retrieving and integrating semantic memory (Benedek et al., 2014; McAvoy et al., 2016). Additional neural evidence suggests that the generation of novel word associations, especially under high semantic constraints, is associated with stronger coupling of the default, control, and salience networks (anterior insula) (Beaty et al., 2017). Collectively, the dorsolateral PFC and ACC in the control network are recognized as the neural basis of controlled cognition in insight problem solving. Brain areas, such as the AG and PCC in the default network, work in parallel with the executive regions in insight problem solving and were more activated in spontaneous processing (Hypothesis 2).

From the experimental approach, cognitive control is difficult to manipulate, which raises the methodological dilemma of studying self-generated insights or externally induced insights (under spontaneous or controlled processing). Compound remote associate (CRA) problems have been used to study insight (Bowden & Beeman, 1998; Jung-Beeman et al., 2004; Razumnikova, 2007). The CRA is designed such that participants need to find one word as an answer with hints (three different words), and it can form a new word or phrase. For instance, if the hint is "tree, sauce, and big", and its corresponding answer is "apple" which can form three new words—"apple tree, apple sauce and big apple". This makes tasks more solvable for participants so that they can actively generate insightful solutions. More importantly, the experimental material from the CRA is sufficient and controllable for further cognitive neural research. Additionally, some researchers have tried to directly provide the answer to the participant while they are trying to solve the riddle problem (especially when reaching an impasse) to passively create an "Aha" moment (Luo & Niki, 2003). Previous research has neglected the role of different levels of cognitive control in insight problem solving. Meanwhile, self-generated insight and externally induced insight have been difficult to explore in a continuous paradigm. In this study, Chinese four-character idioms were used as the experimental materials to solve this problem. The task was developed using CRA. Each idiom was disassembled into its Chinese pinyin form or the first letters of its pinyin form, with different levels of hints. A new experimental design was proposed to systematically dissociate controlled and spontaneous insightful processes. The participants were required to associate their corresponding idiom answers. For example, if four hints—m f j l—are presented, the solution is 满腹经纶 (which is spelled as "**m**an **f**u **j**ing **l**un"). During the task, the solution for a given targeted problem was not directly offered but was gradually revealed in a step-by-step manner. Each step provided minor, equivalent hints, thereby systematically varying the ratio of spontaneous processing insights to controlled processing insights across the hint-providing process (i.e., an insight problem that is solved using a high-level hint should involve greater controlled insightful processing, and problems solved using a lower-level hint should have greater spontaneous insightful processing). Through a "step-by-step" analysis, we can detect the exclusive change in different levels of insightful responses and the optimal moment of insight generation and further reveal that the neural correlates in either controlled or spontaneous insightful processing.

In this study, representational similarity analysis (RSA) was employed to investigate the similarity or dissimilarity of neural patterns in decoding cognitive operations during insight generation under different levels of cognitive control. RSA has been adopted to study multiple cognitive processes such as concept representation (Wang et al., 2020), memory consolidation (Xue et al., 2010), affective experience (Chen et al., 2020), creative thinking (Beaty et al., 2020), and so on. Key hypotheses were proposed in the current study: (1) Insights was more easily realized at an "optimal" moment when the interplays or the shift between spontaneous processing and controlled processing reached the maximum; therefore, the number of insightful responses would reach a maximum when moderate hints were presented. Thus, insular activation may represent an insightful response. (2) Greater controlled processing in insight is accompanied by brain activation in the regions of executive network for cognitive control, and greater spontaneous processing in insight is related to the default network. (3) The degree of item-to-item variation within spontaneous or controlled insightful responses could be suitably captured by RSA and could reflect the high or low within-condition neural pattern dissimilarity of self-generated insights or hint-induced insights in insight-related brain regions.

2 | METHOD

2.1 | Participants

According to the sample size estimation based on G*Power 3.1, the required number of participants was 23 ($\alpha = 0.05$, power $(1-\beta) = 0.80$, effect size $(f) = 0.25$, four planned hint conditions). Twenty-six university students (12 females; aged 19–26 years) participated as paid volunteers. First, we obtained the ethical approval from the institutional review board of the Biomedical Imaging Research Center in Tshinghua University. Second, all participants, who reported no neurological disorders before the experiment, were asked to provide written informed consent. Finally, we ensured that they were all right-handed and had normal vision or corrected-to-normal vision in the formal scanning task.

2.2 | Materials

A total of 91 four-character idioms were used during the formal scanning task. The process used to select the idioms is as follows. First, we chose 400 Chinese four-character idioms from the *Chinese Dictionary* (an authoritative idiom dictionary in China). We conducted a pilot study (pilot study 1) to select idioms with moderate familiarity. The idioms were rated from 1–5 points (1 point indicated "most unfamiliar"; 5 points indicated "most familiar") by 41 volunteers. The correct answer to each of the insight problems used in our experiment was a Chinese four-character idiom, which is a fixed word structure unique to the Chinese language whose meaning usually surpasses the simple combination of the four characters; for example, the four-character idiom 满腹经纶 (which in complete Chinese pinyin, the official Romanization system for Standard Chinese, reads as "man fu jing lun") means people who are learned and capable. We ultimately selected 91 moderately familiar idioms (rated 4.05–4.4).

Each idiom was then disassembled into its pinyin form or the first letters of its pinyin form. The participants were instructed to guess the correct Chinese four-character idiom in each trial based on the incomplete pinyin form provided. Different degrees or ratios of spontaneous insights were evoked using hints. These hints started with the most abstract clue, that is, only the first letters of the idiom in the Chinese phonetic alphabet (no hint, marked as H0); in the case of the example, this level of hint would be "m f j l". More letters are gradually provided. Presented with the incomplete phonetic spelling of the idiom, the participants needed to actively search for answers within the prescribed problem space (i.e., the answer must be an idiom whose pinyin form started with the provided letters). If the participants generated the correct answer at H0, we considered the experienced insight to be predominantly self-generated. If the participant could not generate an answer, further hints were presented, such as "man f j l" (i.e., one character was completely spelled out, H1). Additional hints followed the same procedure: "man f jing l" (two characters were spelled out, H2), "man f jing lun" (three characters were spelled out, H3), and then "man fu jing lun" (all four characters were spelled out, H4), and finally "满腹经纶" (the solution, H5) were presented as the participant needed (Figure 1a). Based on the trade-off between difficulty and solution rates, we chose a fixed position to present the complete pinyin hints. Thus, every successfully solved problem could be solved at different hint stages, from H0 to H5, according to the exact point at which the participant generated the answer. Importantly, the degree of hint-induced insight (or self-generated insight) differed with the progression of hint release.

Using this method, we explored the neural correlates of self-generated and hint-induced insight through a parametric contrast that focused on the different hint levels at which insightful responses were generated.

To ensure the effectiveness of this original material, we completed another pilot study (pilot study 2) in which we asked another 22 participants to report whether they had an "aha" experience following the insightful response. The percentage of "aha" experiences for each insightful response condition (H1, H2, H3 and H4) was calculated. Repeated-measure ANOVA showed no main effect in "aha" experiences (H1: 0.88 ± 0.27, H2: 0.85 ± 0.25, H3: 0.86 ± 0.16 and H4: 0.78 ± 0.26; $p = .27$, $\eta p^2 = 0.18$). This result indicated that different levels of insightful responses all led to the "aha" experience.

2.3 | Imaging procedure

2.3.1 | Scanning task

An event-related fMRI design was used for the scanning task. The experiment contained 91 trials, which were divided into seven runs of 13 trials each. Six hint conditions (H0–H5) were presented sequentially for each trial. For

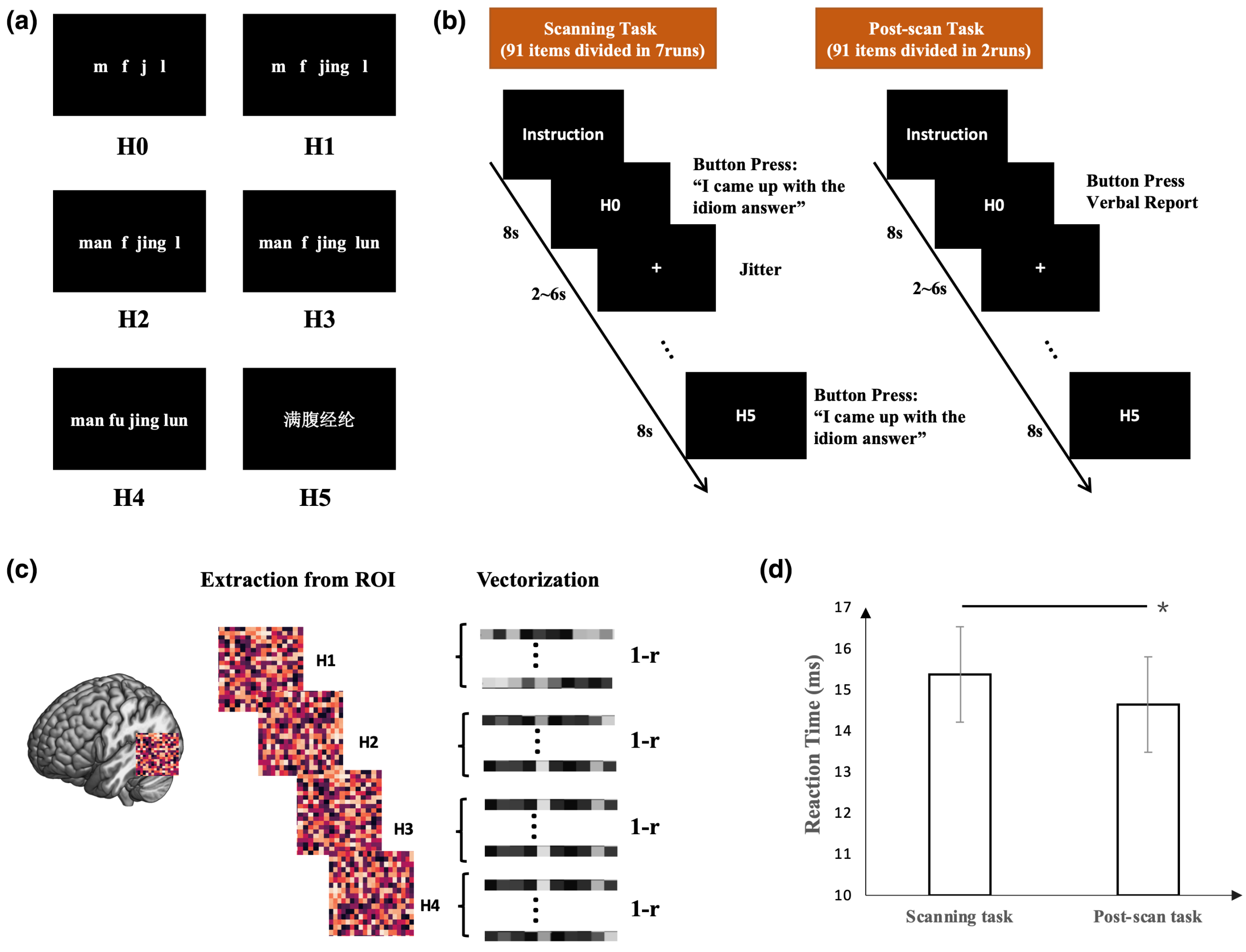

FIGURE 1 (a) The Chinese idiom materials. The idiom materials were divided into six conditions: "m f j l" (no character completely spelled out, H0), "man f j l" (one character completely spelled out, H1), "man f jing l" (two characters spelled out, H2), "man f jing lun" (three characters spelled out, H3), "man fu jing lun" (all four characters spelled out, H4), and "满腹经纶" (the solution, H5). (b) Schematic diagram of one trial and experimental procedure. (c) Representational similarity analysis procedureThe activation patterns in each ROI were extracted for each item under each condition and subjected to Pearson's correlation analysis. We defined the dissimilarity score as 1 minus the correlation coefficient. (d) Mean response time to scanning task and post-scan task for manipulation check. Error bars indicate standard errors of the mean. Asterisks indicate statistically significant differences (*$p < .05$)

example, for H0, “m f j l” was presented, and participants needed to try their best to identify the corresponding idiom within a limited time (8 s). If the participant could not provide the answer within 8 s, the next hint, H1, “m f jing l”, was given. The participants then had another 8 s to provide an answer. Participants were instructed to identify each idiom using the fewest hints. If the participant thought of the correct idiom under any condition within 8 s and pressed the key, the next hint in that trial would not be presented, and after the participant keyed in the response, H5 was presented to provide feedback about whether the answer was correct. The end point of each trial was determined by the participants' keyed-in responses. A cross-viewing jitter that was randomized at 2, 4, or 6 s was presented between the trials. All 91 trials were randomized into 7 experimental runs. The duration of each run was 12 min, and the total duration was 84 min. Participants took a two-min rest between runs. Trials that exceeded the scan time were not included in the analysis, and when the trial ended before the end of the prescribed scan time, participants were told to lie still and wait (Figure 1b).

2.3.2 | Post-scan task

Because the participants were unable to verbally provide answers during the scanning task to ensure that they truly hit the idiom answers, we added the same procedure after the scanning task to ensure that the participants truly responded during the scan. The procedure for the post-scan task was the same as in the scanning task. Participants were required to reassociate the 91 idioms and provide oral answers. When the RT for a certain trial during the post-scan task was longer than the RT for that trial during the scanning task or the answer reported was wrong, the trial was considered invalid and was deleted from the subsequent analysis (Figure 1b). The total duration of the experiment was approximately three hours.

The 91 items were assigned to different conditions according to the participants' specific insightful response stages. The distribution of insightful responses of each participant in the analysis is reported in Table S1. To ensure that we had enough trials for the fMRI data analysis, we included only four conditions (H1, H2, H3, and H4) as insightful response stages in the data analyses. Understandably, the participants seldom solved items with no hints (H0) or required all five hints (H5).

2.4 | fMRI data acquisition and analysis

Neuroimaging was performed using a 3-Tesla Philips MRI machine (Philips) and a 32-channel frequency head coil. T2-weighted images with echo-planar sequences parallel to the anterior commissure-posterior commissure (AC-PC) functional image were obtained. The scanning parameters were as follows: TR = 2000 ms, TE = 35 ms, FoV = 200×200 mm, FA = 90°, 64×64 matrix, voxel size = 2.5×2.5×4 mm^3, 30 slices, thickness = 4 mm. T1-weighted structural scanning with a gradient-echo pulse sequence and the scanning parameters are as follows: TR = 7.65 ms, TE = 3.73 ms, FoV = 230×230 mm, FA = 8°, voxel size = 1 mm×1 mm, thickness = 2 mm. The experimental procedure in the scanning machine was performed using E-Prime 2.0.

2.4.1 | Preprocessing

Brain images were preprocessed through Statistical Parametric Mapping (SPM, version: 12, Wellcome Department of Cognitive Neurology), a tool package plugged in MATLAB (version: 2015a, Mathworks). Four participants were screened out due to head movement problems (exclusion criteria: over 2° of maximal rotation and 2 mm of maximal translation) because of the long duration (approximately 2 h) in the MRI machine. During preprocessing, the T2-weighted volumes were first coregistered with high-resolution gray-matter images segmented from the T1-weighted volumes. Next, they were normalized to MNI templates. Third, these volumes were smoothed with a Gaussian kernel of full-width 6-mm FWHM. Finally, we resampled these volumes into 2-mm isotropic voxels.

2.4.2 | Whole brain analysis

Two participants were excluded because their responses distributed to only two conditions. The remaining participants (11 males and nine females, aged 25.65 ± 2.57 years) were included in the subsequent brain imaging analysis. A general linear model (GLM) was used for whole brain analysis. For the first-level, the task effects of the seven runs and six motion parameters of no interest were included in the evaluation. BOLD signal changes were investigated by using statistical parametric maps for two types of events: insightful response items (H1, H1, H3 or H4) and other invalid items. The insightful response items corresponding to the four hints (H1, H2, H3 or H4) were regarded as the task of interest. The remaining two hint conditions (H0 and H5) were considered as the tasks of no interest. At the second level, we used one-way ANOVA with a random-effects model. To examine the BOLD signal change that was specifically associated with the degree of insightful responses (Hypothesis 2), we performed a linearly increasing t contrast with weights {−3, −1, 1, 3} across insightful items responding to four hints (from H1 to H4). Therefore, positive activation represents a linear increase in controlled processing insight or hint-induced insight, and negative activation represents a linear increase in spontaneous processing in insight or self-generated insight (see Tang et al., 2016). The initial t-map was corrected as a threshold at $p < .05$ (FWE corrected) with >10 voxels spatially.

2.4.3 | Region-of-interest (ROI) analysis

Considering that parametric contrast is mostly sensitive to linearly increased brain activity in response to linearly increased changes in hints, we employed region of interest (ROI) analysis for further exploration. Based on previous assumptions (hypothesis 1) and meta-analyses related to insight, the insula, thalamus, putamen, substantia nigra, and temporal pole (Dosenbach et al., 2007; Uddin, 2015) were drawn as ROIs and defined based on AAL templates acquired from the WFU Pick Atlas package in SPM12 (version: 2.4, http://fmri.wfubmc.edu/software/PickAtlas).

2.4.4 | Representational similarity analysis

In addition, the whole-brain analysis results showed almost no activation in relevant brain regions with greater degrees of spontaneous insight using GLM. We assumed that this is due to the GLMs' inter-item detection insensitivity (i.e., in GLM, items in the same condition should activate homogeneous/same neural responses) (Huettel, 2004). We conducted an RSA to quantify the similarity of inter-item neural activity patterns within conditions (Kriegeskorte et al., 2008). According to our assumption, no significant activation occurred during spontaneous insightful processing because of the dissimilarity or diversity of activation patterns that cause it to go undetected. The RSA we employed could prove the assumption when inter-item representational dissimilarity was greater during spontaneous insightful processing. For this analysis, the four conditions were examined at the group level to detect similarities in patterns across items. First, each insightful response item was modeled as a separate regressor according to its specific onset time. For the individual-level analysis, we modeled 91 regressors in total. We then submitted the contrast images generated from the trial-by-trial analysis to an interim representational dissimilarity analysis.

2.4.5 | ROI-based inter-item representational dissimilarity analysis

According to the third hypothesis, the brain may activate different neural patterns at different levels of insightful responses when solving insight problems. We decided to further expand the ROIs to include most brain regions associated with insight and creativity. Therefore, we identified the following brain regions as ROIs based on abundant neuroimaging reviews, meta-analyses (Beaty et al., 2016; Dietrich & Kanso, 2010; Luo, 2004; Shen et al., 2012; Shen et al., 2016; Shen et al., 2018), and studies on insight: the bilateral superior temporal gyrus (Jung-Beeman et al., 2004), middle temporal lobe (Bekhtereva et al., 2000; Darsaud et al., 2011), dorsolateral and ventrolateral PFC (Darsaud et al., 2011; Luo & Niki, 2003), hippocampus (Luo & Niki, 2003), insula (Aziz-Zadeh et al., 2009; Luo et al., 2004), anterior and posterior cingulate gyrus (Aziz-Zadeh et al., 2009; Luo et al., 2004), inferior parietal lobule including supramarginal gyrus (SMG) and angular gyrus (AG) (Bekhtereva et al., 2000), precuneus (Darsaud et al., 2011), and supplementary motor area (Tang et al., 2016). [A total of 44 ROIs in the brain were chosen from the Anatomical Automatic Labeling (AAL) templates, which were acquired from WFU Pick Atlas 2.4].

To further examine how the brain represents different levels of insightful information processing, multivariate pattern analysis was employed to determine the dissimilarity among neural patterns. The correlation matrix of items within the condition used the mean value as a measure of a participant's inter-item representational similarity. Then, we defined the dissimilarity score as 1 minus r, which was derived from the similarity coefficient (Haxby et al., 2014; Kriegeskorte & Kievit, 2013). The inter-item pattern dissimilarity values under different degrees of insightful responses were obtained (see Figure 1c).

3 | RESULT

3.1 | Behavioral results

The number of insightful responses According to hypothesis 1, the number of idioms solved per hint for each participant in the scanning task was calculated. The number of idioms that each participant answered under each hint, defined as an insightful response, was reported ($N_{(H1)}$: 15.6 ± 5.5, $N_{(H2)}$: 18.6 ± 5.3, $N_{(H3)}$: 29.3 ± 5.8 and $N_{(H4)}$: 18.1 ± 6.9, see Table S1). A repeated-measure ANOVA showed a main effect of six hints ($F_{(3,57)} = 16.50$, $p < .001$, $\eta p^2 = 0.73$). Furthermore, the post hoc result showed that

TABLE 1 Brain regions associated with increased degree of controlled insight (H4 > H3 > H2 > H1)

Brain regions	MNI coordinates x	y	z	t (19)	k	BA
R. Superior Frontal Gyrus (dlPFC)	22	52	26	9.79	3604	10
R. Middle Frontal Gyrus (dlPFC)	44	22	20	8.89		9
	28	56	6	8.4		10
R. Angular Gyrus	56	−52	36	8.73	1476	40
	56	−50	44	8.65		40
R. Middle Temporal Gyrus	58	−18	−14	7.89	395	21
R. Cingulate Gyrus (dACC)	4	32	30	7.88	855	32
R. Superior Frontal Gyrus	10	28	56	7.39		8
R. Supplementary Motor Area	10	18	58	7.3		
R. Middle Cingulate Gyrus (dACC)	4	−28	34	7.29	398	23
R. Precuneus	12	−50	36	6.52	42	31
L. Angular Gyrus	−54	−62	32	7.84	929	40/39
L. Supramarginal Gyrus	−60	−48	32	7.71		
L. Angular Gyrus	−48	−58	28	7.17		
L. Middle Temporal Gyrus	−60	−32	−8	6.47	96	21
L. Middle Frontal Gyrus	−40	22	44	6.3	44	9

Note: Familywise error/FWE corrected.

Abbreviations: BA, Brodmann's area; dACC, dorsal anterior cingulate cortex; dlPFC, dorsolateral prefrontal cortex; k, cluster size; L, left; MNI, Montreal Neurological Institute; R, right.

the number of insightful responses in H3 was significantly larger than the number of insightful responses in H1, H2 and H4 ($p_s < .01$). This result indicates that the participants showed the highest solution rates for H3.

3.2 | Imaging results

3.2.1 | Manipulation check

To further ensure that insightful responses were accurately recorded during scanning, we compared the response times for every trial performed during the scan with those for the same trial during the post-scan task. If the participants correctly determined the idiom during the scan, they were able to solve the idiom problem more quickly when it was presented for the second time. Trials were deleted when the duration of insightful responses in the post-scan task was longer than that in the scanning task. We used H0 as the starting point to calculate the RT of every insightful response and calculated the average RT for each participant. A paired sample t test (scanning task vs. post-scan task) was performed, and the results showed that the RTs of the post-scan task (mean = 14.67 ± 0.33 s) were significantly shorter than the RTs of the scanning task (mean = 15.45 ± 0.12 s; $p < 0.05$, $\eta p^2 = 0.19$) (see Figure 1d). This manipulation aimed to ensure that the trials provided in the neuroimaging analysis were authentic insightful responses.

3.2.2 | GLM analysis results

According to Prediction 2, to assess the effect of different levels of cognitive control processing on insight, a random-effects analysis was used to include into a one-way within-subject ANOVA for brain imaging data. We included only the insightful response trials in which the participants pressed the key, indicating that they had generated a solution under the four hint conditions (H1, H2, H3 and H4) in the analysis. A linearly increased t-contrast was used, and the results revealed BOLD signal changes in response to increasing hints during spontaneous processing. Significant positive parametric activation in response to increased controlled insight (H4 > H3 > H2 > H1) was found in the bilateral AG/supramarginal (SMG) (Brodmann Area (BA) 39, 40), right dorsal lateral prefrontal cortex (dlPFC) (BA9/10), dorsal anterior cingulate gyrus (BA 32, 23) (see Table 1, Figure 1), and precuneus (BA 31).

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No super-threshold (FWE-corrected) brain activity was observed in response to increasing degrees of spontaneous processing (H1 > H2 > H3 > H4). When the super-threshold was adjusted to an uncorrected $p < .001$, the activated cluster was also small ($k \leq 30$) (Figure 2).

For a better visualization of linearly increased brain activation, we extracted averaged beta values from the bilateral AG, right dlPFC, and dACC using functional comparisons (H4 > H3 > H2 > H1) through whole-brain analyses. ANOVAs revealed significant differences in the averaged beta value under the four conditions (H1, H2, H3, and H4) (for dlPFC_R: $F_{\text{dlPFC\_R}\,(3,57)} = 37.76$, $p < .001$, $\eta p^2 = 0.67$; for dACC: $F_{\text{dACC}\,(3,57)} = 24.33$, $p < .001$, $\eta p^2 = 0.56$; for AG_L: $F_{\text{AG\_L}\,(3,57)} = 16.95$, $p < .001$, $\eta p^2 = 0.47$; and for AG_R: $F_{\text{AG\_R}\,(3,57)} = 20.09$, $p < .001$, $\eta p^2 = 0.51$). Multiple comparison analysis indicated a larger average beta value for the bilateral AG, right dlPFC, and dACC with increasing hints (all: $p_{\text{H4-H2}} < .05$, $p_{\text{H4-H1}} < .05$, $p_{\text{H3-H1}} < .05$, Bonferroni corrected) (see Figure 3a).

3.2.3 | ROI analysis results

We performed ROI analysis based on AAL templates for further exploration. The results showed that activation of the bilateral insula and thalamus exhibited a reverse U-shaped tendency, reaching the highest level at H3. Repeated-measure ANOVAs showed the main significant effects under the four hint conditions ($F_{\text{insula\_L}(3, 57)} = 6.97$, $p < .001$, $\eta p^2 = 0.268$; $F_{\text{insula\_R}(3, 57)} = 9.38$, $p < .001$, $\eta p^2 = 0.330$; $F_{\text{thalamus\_L}(3, 57)} = 13.99$, $p < .001$, $\eta p^2 = 0.424$; $F_{\text{thalamus\_R}(3, 57)} = 16.08$, $p < .001$, $\eta p^2 = 0.458$). For the left insula, the beta values at H3 were higher than those at H1 ($p_{\text{H3-H1}} < .05$) and H2 ($p_{\text{H3-H2}} = .064$). For the right insula, the beta value at H3 was higher than that at H1 ($p_{\text{H3-H1}} < .05$) and H2 ($p_{\text{H3-H2}} < .05$). For the left thalamus, the beta values at H3 were higher than those at H1 ($p_{\text{H3-H1}} < .001$), H2 ($p_{\text{H3-H2}} < .01$) and H4 ($p_{\text{H3-H4}} < .05$). For the right thalamus, the beta values at H3 were higher than those at H1 ($p_{\text{H3-H1}} < .001$), H2 ($p_{\text{H3-H2}} < .01$) and H4 ($p_{\text{H3-H4}} = .089$) (see Figure 3b).

3.2.4 | Representational similarity analysis results

Inter-item pattern variability in the ROIs was associated with insightful responses

To verify the third prediction, we investigated multivoxel activity patterns, performed an ROI-based analysis to obtain inter-item pattern dissimilarity values, and compared them across H1, H2, H3 and H4. Repeated-measures ANOVAs revealed that twenty-three ROIs exhibited a significantly greater difference in pattern dissimilarity across H1, H2, H3 and H4 (see Table S2, $p_s < .05$). Multiple comparison correction was used, and ten ROIs continued to show significantly different pattern dissimilarities (Bonferroni's correction). Post hoc analysis showed that the inter-item pattern dissimilarity value (1-r) responses to H4 were significantly lower than those to H3, H2, and H1 in the left precuneus (PreC), left precentral gyrus (PCG), left supplementary motor area (SMA), left inferior frontal gyrus (IFG), left middle frontal gyrus (MFG), left SMG, left temporal gyrus, anterior cingulate cortex (ACC), and insula ($ps < .05$) (see Figure 4).

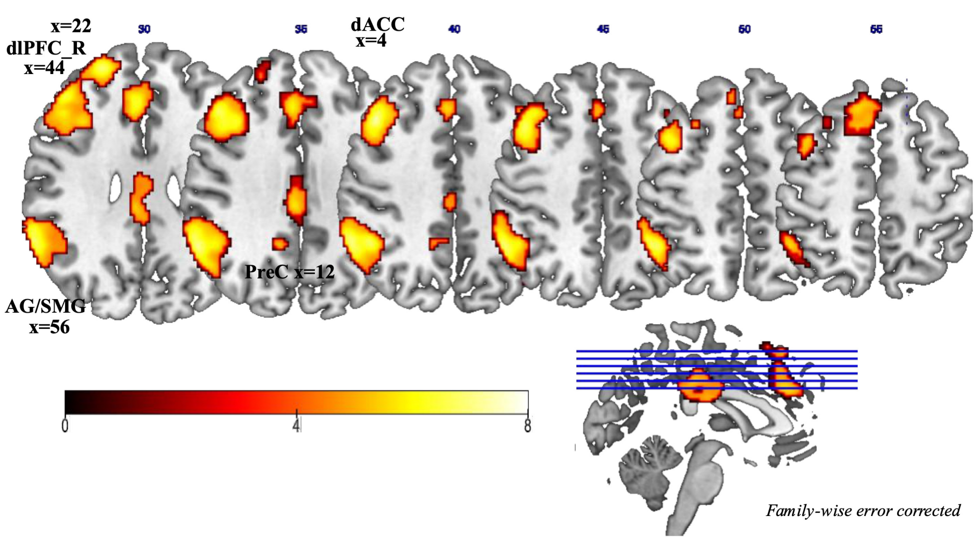

FIGURE 2 Brain regions associated with increased degrees of hint-induced insight based on whole-brain analysis (H4 > H3 > H2 > H1) in right dlPFC ($x = 22, y = 52, z = 26$), dACC ($x = 4, y = 32, z = 30$) and bilateral AG ($x = -54, y = -62, z = 32$; $x = 56, y = -52, z = 32$) (familywise-error (FWE) corrected $p < .05$).

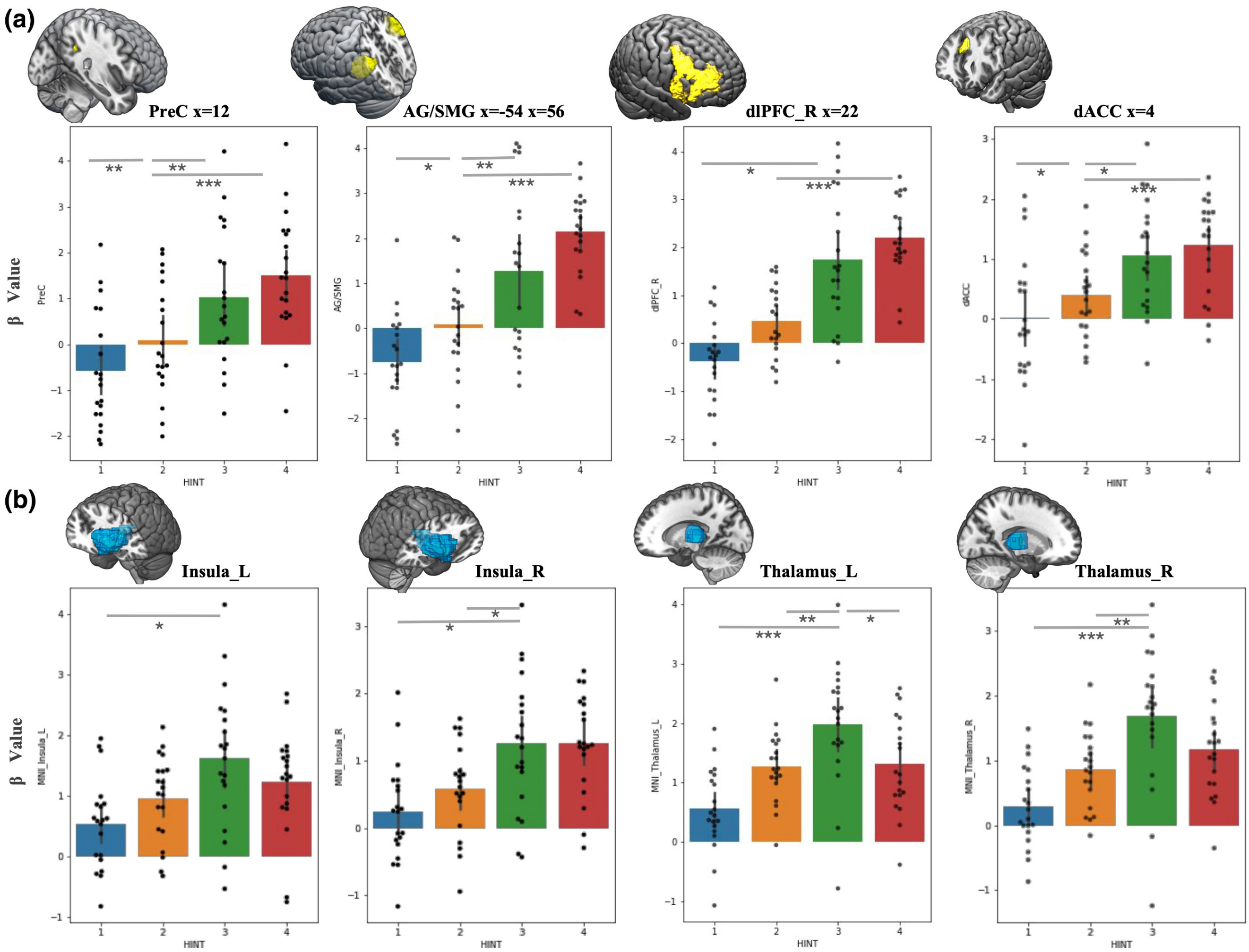

FIGURE 3 (a) Brain activation at several regions of interest derived from the parametric effects of increased degrees of hint-induced insight for visualization. Beta values showed a linear trend across different levels of external hints. Asterisks indicate statistically significant differences (*$p<.05$; **$p<.01$; ***$p<.001$). (b) Brain activation in the bilateral insula and thalamus showed a reverse U-shaped tendency and reached the highest level at H3. Asterisks indicate statistically significant differences (*$p<.05$; **$p<.01$; ***$p<.001$).

4 | DISCUSSION

We employed an experimental design that used Chinese idiom-guessing tasks with the presentation of multiple levels of hints that produced parametric contrasts to dissociate neural correlates that were specifically involved in the spontaneous (H1 > H2 > H3 > H4) and controlled processes of insight (H4 > H3 > H2 > H1). Behavioral results showed that the insightful solution rates were maximal with the moderated level of cognitive control (H3). Positive activation in response to incremental increases in hints were seen in the core regions of the control (right dorsolateral PFC and dACC) and default (bilateral AG/SMG and precuneus) networks. ROI analysis found that the bilateral insula and thalamus exhibited a reverse U-shaped trend, with increased hints reflecting the optimal interaction between spontaneous and controlled insightful processing. However, we did not capture the brain-activated changes related to spontaneous insightful processing under the GLM hypothesis. Further RSA results revealed that increased spontaneous insightful processing was associated with greater neural pattern dissimilarity between items in the control (dorsal lateral PFC, including the middle frontal gyrus and inferior orbital gyrus; ACC; ventral PFC, including the precentral gyrus and supplementary motor areas) and default (SMG; MTG; and precuneus) networks. Together, these results are extended evidence of the coupling effect of brain regions in executive, default, and salience networks in controlled and spontaneous processing in insight problem solving.

4.1 | Optimal balance between spontaneous and controlled insightful processing

At the behavioral level, the solution rates were highest when moderate levels of hints were presented (H3). This finding was aligned with our hypothesis that moderate control

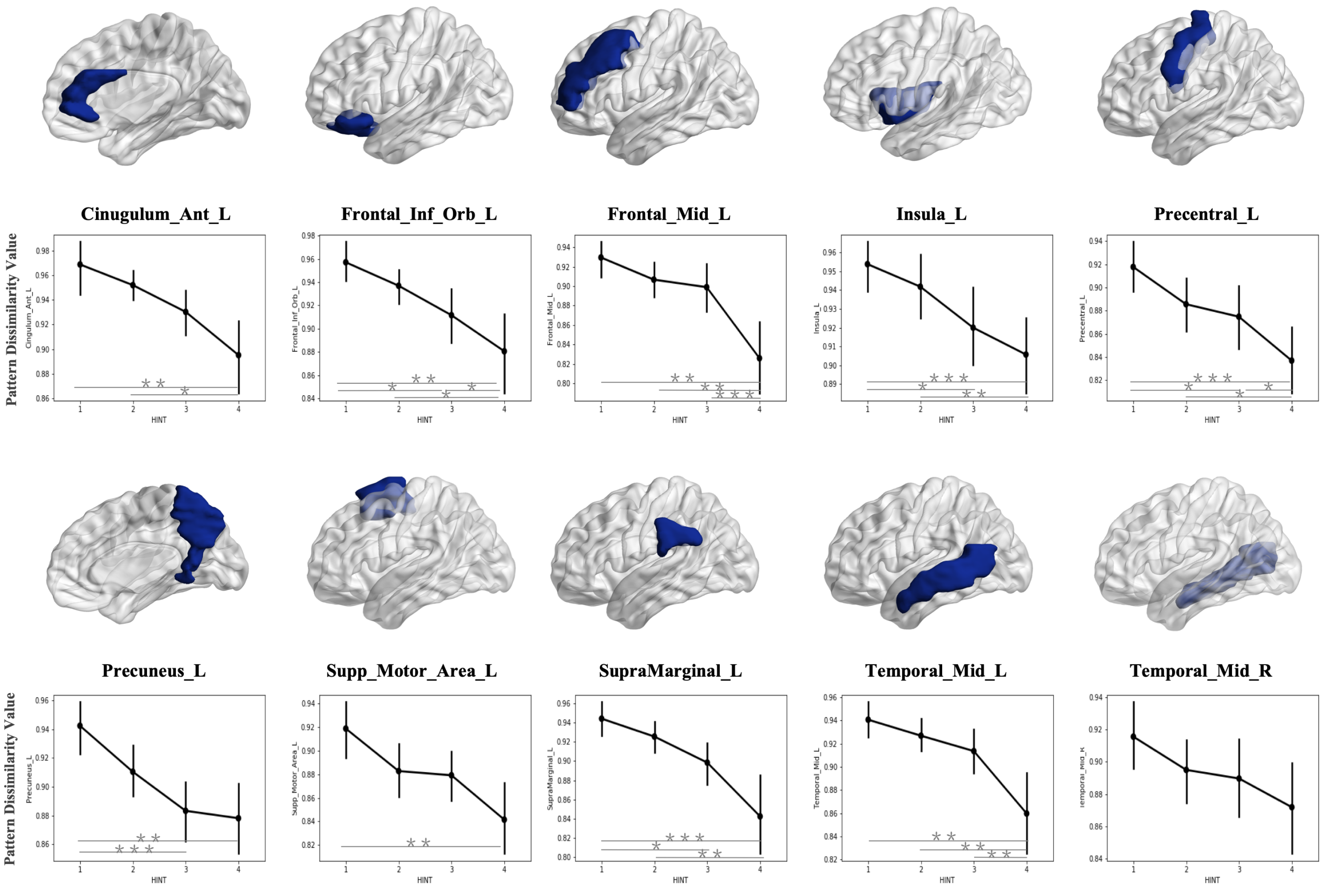

FIGURE 4 Point charts showing the mean neural pattern dissimilarity with increasing degree of self-generated insight in brain ROIs after corrections. Repeated-measures ANOVAs were used to examine the differences under the H1, H2, H3, and H4 conditions. The *p*-values of the ANOVA were corrected for multiple comparisons using FWE with a threshold of $*p < .05$; $**p < .01$; $***p < .001$.

would benefit information processing in insight problem solving. Insights often emerge at an "optimal" moment, when there is a moderate level of controlled or spontaneous processing (Mok, 2014). In addition, neuroimaging showed that nonlinear changes in bilateral insular and thalamic activation (a reverse U-shaped trend) were associated with the progression from spontaneous to controlled insight. Similar to behavioral performance, brain activation in the bilateral insula and thalamus were maximal in the H3 condition. We inferred that the activation of the insula and thalamus explains the underlying mechanism of moderate control processing in insight generation.

As we hypothesized, the insula and thalamus are critical nodes of the cingulo-opercular region that mainly serve to identify relevant internal and external stimuli to guide insight generation (Seeley et al., 2007). The insula facilitates stimulus-driven processing and provides access to executive cognition such as working memory and attention (Menon & Uddin, 2010). Meanwhile, it supports top-down creative generation by both detecting information in memory and facilitating interactions between the control and default networks (Benedek et al., 2017). Similar to the insula, the thalamus is involved several cognitive functions, which supports its role in multimodal information processing coupled with the insula (Craig, 2009; Hwang et al., 2017). A lesion study revealed that the thalamus is associated with integrating diverse modes of information and the thalamus-insula loop together represents all stimuli that have salience in terms of feeling or awareness, including incentives, intentions, and cognition (Craig, 2009; Hwang et al., 2017). We found that the insula and thalamus were most engaged during moderate levels of controlled processing in insight, suggesting that these two regions together serve as an interface for interoceptive and external information processing during insight problem solving. Peak activation reflects the optimal integration of individual internal information and external input information processing under conditions of optimal balance of spontaneous and controlled insightful processing.

4.2 | Linear brain activation during controlled insightful processing

As predicted, linearly increased brain activation in the right dorsolateral PFC and dorsal ACC was found in association with comparisons in controlled processing insight. On the one hand, the dorsolateral PFC showed linear engagement in increased external input information processing, mainly corresponding to sustained attention for top-down cognitive control (Beaty et al., 2017; Dietrich & Kanso, 2010). Additional evidence supports the role of the right dorsolateral PFC in problem representations because of its activation in ill-structured problem solving (Gilbert et al., 2010; Goel & Vartanian, 2005). A greater degree of controlled processing of insight is associated with dorsolateral PFC activation, reflecting attention control and additional representation of idiom-related hints. Similarly, the dorsal ACC exhibited robust engagement as the number of hints increased. The ACC, as a core region of the salience network, forms the basis of attention focusing, shifting, and error detection in problem solving (Enriquez-Geppert et al., 2013). A meta-analysis of insight confirmed that the ACC became more involved in mental representation to successfully solve problems (Shen et al., 2016). Kounios et al. (2006) proposed that the ACC is activated in preparing a focused state for the "aha" experience. In general, the linear activation in response to the linearly increased hints or levels of controlled processing in insight problem solving suggested that the dorsolateral PFC and dorsal ACC mainly engaged in sustaining top-down attention control to represent the problem space and preparing for the "aha" experience.

In contrast to the second hypothesis, the default networks, such as the AG/SMG, precuneus (PreC) and MTG, were more activated in controlled insightful processing. The participation of the MTG and AG/SMG, is in accordance with a previous study that revealed how verbal insight problems require more intensive verbal processing (Aziz-Zadeh et al., 2009). In addition, a study suggested that the MTG, precuneus, and some parietal regions, such as the AG and SMG, together formed the "visual spatial information processing network" to comprehend the hints and participate in memory retrieval (Luo, 2004). Notably, this observation is inconsistent with our hypothesis (Mok, 2014); the default network was also engaged more in controlled processing in insight. Our results are aligned with recent fMRI studies reporting higher functional coordination of networks, including executive and default networks in semantic cognition and generation in more demanding tasks, reflecting the retrieval of semantic memory (Benedek et al., 2017). This demonstrates that the AG, SMG, MTG, and PreC in the default network play a critical role in memory retrieval and semantic integration in controlled insightful processing. We inferred that a holistic heuristic strategy was adopted, and that intensive involvement of specific linguistic processing was avoided during the spontaneous process.

In the whole-brain results, the dominant right-hemispheric activation was observed for the controlled processing of insight. We proposed that the explanation could be as follows: First, the Chinese idiom guessing problem in the present study was developed by the CRA task, and it shared common cognitive processes, such as forming novel associations, searching for solutions in memory, and sustaining attentional control. Based on the neural evidence related to meta-analysis, Shen et al. (2016) compared the activation differences between different types of insight problems and found that the associate insight (CRA task) relied on the right brain. The findings in the present study, together with previous findings of the superiority of the right hemisphere in insight (Jung-Beeman et al., 2004; Shen et al., 2012), corroborated that the associative insight is task-dependent. Meanwhile, we found the common activated regions in the right dlPFC (BA9) (right superior frontal gyrus, in Shen et al., 2016), ACC (Anderson et al., 2009), AG /SMG (Jung-Beeman et al., 2004), PreC (Darsaud et al., 2011), and insula (Becker et al., 2020), similar to previous studies employing the CRA task. However, regions such as the inferior frontal gyrus, MTG, inferior and superior parietal lobe (including AG /SMG and PreC), and insula were noted in this study to be activated in other types of insight problems (e.g., character chunk decomposition task and prototype heuristic task). This indicated the commonality in neural mechanisms between the present task and other insight problems, especially the default and control networks coupled with attention control and memory retrieval during controlled insight processing. Notably, some regions such as the hippocampus and parahippocampus showed activation in previous CRA studies (Luo & Niki, 2003; Shen et al., 2016). These regions might reflect the formation of novel contextual associations (Aminoff et al., 2007) in concrete object representations for CRA, and the Chinese idioms in our study formed purely semantic associations rather than contextual content. In addition, previous CRA tasks usually compared the differences between the insightful condition with the non-insightful condition, whereas we compared different levels of control in insightful responses. Finally, we did not observe activation of brain regions that underlie spontaneous insight processing with controlled processing. Therefore, we also attempted to provide neural evidence to explain this phenomenon using representational similarity analysis.

4.3 | Representational variability during spontaneous processing in insight

Remarkably, we did not observe any activation associated with decreased external hints or an increased degree of spontaneous insight (H1 > H2 > H3 > H4) via whole-brain analysis. We suspect that this was due to the diversity of items or trials under a given condition. The premise of general linear models (GLMs) is based on superimposing and averaging the BOLD signal responses to stimuli within conditions (Huettel, 2004), which might ignore the specificity of activation patterns across items within conditions. Thus, inter-item neural pattern dissimilarity within conditions could support our explanation of the null activation of spontaneous insightful processing.

Regarding spontaneous processing in insight, we found that active pattern dissimilarity maintained a linearly decreasing trend, in accordance with our hypothesis. Thus, we inferred that brain activation could not be easily captured due to the variety of inter-item active patterns during spontaneous insight processing. Specifically, the identified brain regions with the most inter-item pattern dissimilarity during spontaneous insightful processing (H1 > H2 > H3 > H4) were in the prefrontal regions (dorsolateral frontal cortex (PFC), including the MFG and inferior orbital gyrus; ACC; ventral PFC, including the PCG and SMA) and temporal–parietal regions (SMG, MTG and precuneus).

On the one hand, the prefrontal regions were usually defined as the control network (Mok, 2014; Shen et al., 2016) and were functionalized as attention control and the retrieval of working memory (left dorsolateral PFC, Cieslik et al., 2015; Darsaud et al., 2011), maintenance of motivation to solve problems (ventral PFC, Goel & Vartanian, 2005), orientation and supervision of goals in problem solving (left ACC, Huang et al., 2015; Luo & Niki, 2003), and generation of switch-related signals (supplementary motor areas, Hikosaka & Isoda, 2010; Tang et al., 2016). Representation variability in the control network reflects the various spontaneous processes of monitoring and manipulating attention and cognitive resources in insight problem solving. As more hints were presented, the idiom answers gradually became fixed, and the related information seemed to be monitored and controlled in a more consistent manner.

On the other hand, the temporal–parietal regions, which are always regarded as default networks, showed robust engagement in spontaneous insight processing from the multivoxel pattern perspective, co-occurring with the control network (Beaty et al., 2017). Specifically, the supramarginal gyrus, as a part of the temporal–parietal junction (Huang et al., 2015) and inferior parietal lobule (Tang et al., 2016), is active, taking part in remote association formation and flexibility thinking (Bekhtereva et al., 2001). The MTG, precuneus, and nearby parietal regions, such as the SMG, were revealed to together constitute a "visual spatial information processing network" and participate in working memory retrieval (Luo, 2004). These findings indicate that the control and default networks were also coupled in spontaneous insight, but their roles showed differences in representational variety rather than in the controlled processing component. It is noteworthy that the insula also shows decreased neural pattern dissimilarity during increased levels of spontaneous insight processing as a switching system (Menon & Uddin, 2010).

From the multivoxel pattern perspective, the multiple insight-related regions all showed significantly different neural patterns in spontaneous versus controlled insight. We speculated that individuals may adopt various cognitive operations by mobilizing multiple insight-related brain regions to address insight problems when spontaneous insight occurs. Recent studies have supported neural pattern variability in divergent thinking by calculating the dynamic functional connectivity in key regions of the default, salience, and executive networks (Sun et al., 2019) or by measuring brain entropy in control networks such as the dlPFC and dACC (Shi et al., 2020). To some extent, converging evidence might extend the variation-selection theory of creativity proposed by Dietrich and Haider (2015): creativity is a process that comes from blind variation (BV) and selective retention (SR), in which creative thoughts generation is irregular (Dietrich & Haider, 2015). This theory describes idea generation as an evolutionary process that occurs with no subjective certainty. This uncertainty may be manifested in the variability of neural patterns. We used an event-related fMRI task to uncover how the brain represents internally or externally generated ideas at different levels of cognitive control. Greater representational variability in the brain shows an enhanced effect on spontaneous internal insight. This implies that representational variability creates the possibility for insight.

5 | CONCLUSION AND FUTURE DIRECTIONS

In summary, the current study highlights the following findings: First, our study developed a new task that facilitates a "step-by-step" analysis of insight and skillfully solves methodological dilemmas. Second, a critical role of the insula and thalamus was demonstrated, characterized by the interface of internal and external flexible information interactions. This may be the neural basis of successful insight generation. Third, the present finding stripped the neural similarities or variabilities between the external induction of insight and the internal promotion of insight, and successfully observed variability in spontaneous insight generation. Finally, the significance of brain regions in the control, salience, and default mode networks in spontaneous or controlled insight processing was clarified.

Some limitations of this study need to be put forward: (a) The number of participants in this study was relatively small. Some participants were excluded from the study due to head motion during imaging. It is difficult for human subjects to perform prolonged tasks during the scan. In addition, owing to the flexibility of the task, the response rate for each participant varied for the different conditions. Several other participants were removed because of our strict requirements for the analysis of the number of superimposed conditions. (b) The length of the pinyin representation for each hint cannot be precisely controlled. However, subtle differences were seen mainly in the primary visual cortex. The results also showed differences in the neural correlates in brain regions related to high-level cognitive abilities in insight problem solving, which was the focus of the present study. (c) All the participants were required to actively generate insight. Thus, the number of trials for each condition varied for each participant. Under laboratory conditions, it is difficult to balance these issues and ensure ecological validity. (d) To prevent the BOLD signal strength from affecting the RSA results, we performed extra calculations. We left out brain areas with significant overlap from both the whole-brain analysis and the RSA, and analyzed the remaining part in the RSA alone. The results showed the same trend that was previously found (see Supplementary Materials and Figure S1). This indicates that the RSA results are not attributable to the BOLD signal strength. (e) The present study did not use analytical means such as functional connectivity. To interpret the results, we referred to previous studies on insight-related brain networks. Taken together, we suggest that future studies further examine these issues using complementary neuroimaging techniques or develop more specific tasks to overcome the limitations described above.

AUTHOR CONTRIBUTIONS

Di Liu: Conceptualization; data curation; formal analysis; investigation; methodology; project administration; software; validation; visualization; writing – original draft; writing – review and editing. **Lei Hao:** Data curation; formal analysis; methodology; software; writing – review and editing. **Lei Han:** Conceptualization; methodology; resources. **Ying Zhou:** Writing – review and editing. **Shaozheng Qin:** Methodology; resources; software; supervision. **Kazuhisa Niki:** Supervision. **Wangbing Shen:** Supervision; writing – review and editing. **Baoguo Shi:** Funding acquisition; resources; supervision; writing – original draft; writing – review and editing. **Jing Luo:** Conceptualization; data curation; funding acquisition; methodology; project administration; resources; software; supervision; validation; writing – original draft; writing – review and editing.

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CONFLICT OF INTEREST

The author(s) declared that there were no conflicts of interest with respect to the authorship or the publication of this article.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Table S1 The distribution of insightful responses in scanning task.

Table S2 Greater inter-item pattern dissimilarity associated with greater degree of self-generated insight in brain regions that showed significant differences (H1 > H2 > H3 > H4). The brain regions were defined from AAL templates

Figure S1 ROI was defined as brain regions previous defined left out the overlapping significant brain areas in both whole-brain analysis and RSA analysis. a further ROI-based representational analysis to identify changes across H1, H2, H3 and H4 and compare the interitem pattern dissimilarity. The main effect of the hint condition was significant, and the effect of H4 was significantly higher than those of H1, H2 and H3 ($1 - r_{(H1)} = 0.92 \pm 0.03$, $1 - r_{(H2)} = 0.90 \pm 0.04$, $1 - r_{(H2)} = 0.89 \pm 0.03$, $1 - r_{(H4)} = 0.86 \pm 0.05$, $F_{(3, 57)} = 10.98$, $p < .01$).

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