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RESEARCH ARTICLE

Critical thinking and regional gray matter volume interact to predict representation connection in scientific problem solving

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Abstract
Representation connection (RC) is a stable ability that significantly predicts the accuracy of scientific innovation problem solving while critical thinking has been strongly related to problem solving. However, the neural mechanisms underlying this relationship have not been assessed. Using voxel-based morphometry (VBM) and scientific innovation problem solving materials, we investigated the correlation between RC and regional gray matter volume (rGMV) in healthy young participants. We found that RC was positively correlated with rGMV in the right superior temporal gyrus (STG) and in a cluster in the left medial frontal gyrus (MFG). These results indicate that increased rGMV in the right STG may lead to the ability to overcome misdirection more easily, which may result in better semantic integration of the "certain construction" of heuristic prototypes. Increased rGMV in the left MFG may be associated with forming novel associations and retrieving matched unsolved technical problems from memory. Further analysis revealed that the interaction between critical thinking and rGMV predicted RC in insightful problem solving, and found that higher rGMV was correlated with higher RC in participants with lower cognitive maturity, but not in participants with higher cognitive maturity. These findings suggest that rGMV could interact with cognitive maturity to modulate RC in insightful problem solving.

Keywords Representation connection · Heuristic prototype · Scientific problem solving · Critical thinking · Voxel-based morphometry

Introduction

The first step toward scientific and technical innovations is often a creative insight (Sternberg and Lubart 1993; Dietrich and Kanso 2010). Insightful problem solving has been previously used to study the process of gaining creative insights (Kaplan and Simon 1990). Throughout history, in real-life insightful problem solving, scientific innovations have frequently appeared when inspired by some heuristic knowledge. For example, Rutherford used a solar system analogy to arrive at an understanding of the atom. In previous experimental studies, heuristic knowledge was found to have an important role in problem representations and gaining insights. Based on these studies, the Prototype Heuristic Theory was proposed (Dickinson 1999; Dandan et al. 2013a, b; Hao et al. 2013; Luo et al. 2013; Tong et al. 2015).

In previous studies, situations used for solving scientific innovation problems were based on contemporary situations in science and engineering that were collected from various media, such as magazines, television, and the internet. Each situation comprised an unsolved scientific problem,

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heuristic prototype, and a reference solution (Ming et al. 2014; Yang et al. 2016). For example, in the problem “How to design spacesuits?”, the unsolved scientific problem is the following: “Scientists have been trying to find a special material for spacesuits that is hard enough to be able to bear air pressure and can also bend freely in order to perform extra-vehicular activity. How can such material be found?” People kept repeatedly trying to solve this problem until the heuristic prototype of the shrimp shell was developed eventually, which is quite hard and can be bent because of its interconnecting ring structure. Scientists were inspired by this related heuristic prototype (the shrimp shell body) and finally solved the problem. Regarding the example mentioned above, the reference solution would be to “imitate the structure of a shrimp shell, developing a ring connection that allows the spacesuit to bear air pressure and bend freely” (Dandan et al. 2013a, b; Ming et al. 2014).

In the Prototype Heuristic Theory, the term “heuristic prototype” is defined as an object containing the heuristic information for solving insight problems despite being superficially and semantically irrelevant to the insight problem (Cao et al. 2006; Ming et al. 2014). Each heuristic prototype has a key “feature function” along with a “certain construction.” In the above-mentioned problem, the “feature function” is that it is adequately hard and can be bent and the “certain construction” is the interconnecting ring structure. To solve the technical problem, one must fulfill the “required function,” which is the quality of being both hard and bendable (Yang et al. 2016). Insights regarding an unsolved scientific problem can occur if the key “feature function” contained in the heuristic prototype is suddenly recognized and correctly matched with the required function (Ming et al. 2014). This process is called representation connection (RC), which is core to solving scientific innovation problems and plays an important role in gaining insights (Zhang and Jiang 2005; Zhang et al. 2011; Hao et al. 2013; Yang et al. 2016).

While these studies help us understand the process of insightful problem solving, the heuristic prototype is the simplest and most distinct concept in this literature (Dandan et al. 2013a, b; Luo et al. 2013). One behavioral study showed that irrelevant information can interfere with the heuristic prototype, and the more irrelevant the information, the stronger the interference and the greater the decrease in the speed of prototype activation (Zhao and Zhang 2013). The key “certain construction” in a heuristic prototype is theoretically vague and difficult to define in real-life scientific insightful problem solving. Therefore, RC should be assessed in relation to insightful problem solving using a highly ecologically valid heuristic prototype with irrelevant information. That is, the irrelevant heuristic prototype should include not only a related heuristic “certain construction” but also unrelated redundant prototype information. Such situations can also be used to understand why some people are more likely to avoid irrelevant information, extract the key “certain construction” of irrelevant prototypes, and engage in RC.

Previous studies have investigated the neural mechanisms of insightful problem solving induced by heuristic prototypes using scientific innovation problem situations and functional magnetic resonance imaging (fMRI) (Hao et al. 2013; Luo et al. 2013; Tong et al. 2015). Although these task-related neuroimaging studies have contributed to building an understanding of the insightful problem solving process, considerable research suggests that gray matter (GM) structure measured with MRI could predict interindividual variability in a broad range of human behaviors (Masako et al. 2004; Ryota and Geraint 2011; Karl and Katrin 2013). In this regard, results from structural imaging studies have not been limited to specific regions engaged in the task during scanning and can provide information about the neural substrates of human behavior and cognition (Takeuchi et al. 2012; Karl and Katrin 2013). Both functional and structural studies have strengths and drawbacks and, thus, the two methods should complement each other. Until now, no study has assessed the brain regions underlying individual differences using scientific innovation problem situations and structural magnetic resonance imaging (sMRI). Therefore, the use of neuroanatomical tools and highly ecologically valid scientific innovation problem situations may provide a solid foundation for understanding the neural basis of RC in insightful problem solving.

Many factors accounts for the relationship between RC and GM structure, critical thinking which had a close connection to critical thinking is one of them. Critical thinking is reasonable, reflective thinking associated with deciding what to believe or do (Ennis 1962; Parse 1996). Critical thinking preserves individuals from uncertain information and fosters a questioning and criticism attitude to find truthfulness (Yenice 2010). Previous study showed that the use of critical thinking is assumed to result in pharmacy practitioners that are better able to solve problems and think as experts (Miller 2011). Strong critical thinkers display an ability to be open-minded without harboring prejudices toward differing opinions and engaging in systematic analytical thinking to make thoughtful decisions (Facione 2004, Msn and Mary Courtney 2010). Critical thinking disposition has been defined as internal motivation or individual habits and tendencies regarding critical thinking (Facione 2004; Stedman et al. 2007). Cultivating a disposition towards CT is an important element in the promotion of critical thinking skills (Wan et al. 2000). The California Critical Thinking Disposition Inventory (CCTDI) was designed to assess individual’s willingness to engage in critical thinking (Facione 1990). Previous study observed a significant relationship between critical thinking disposition and learning styles, results showed that individuals who are good at retrieving and integrating stored information are more likely to be good critical thinkers. Moreover, critical thinking disposition has been found to be associated with imagination, perspective taking, the generation of diverse ideas, originality scores, and the integration and retrieval aspects of memory (Friedel et al. 2008; Mahmoud 2012; Yalç et al. 2013; Jeong 2015). Considering the close association between insightful problem solving and critical thinking disposition as well as the differences in cognitive features between those individuals with higher and lower critical thinking disposition, we hypothesized that critical-thinking disposition may moderate the relationship between gray matter characteristics and RC in insightful problem solving.

In this study, our primary focus was to clarify the relationship between RC and the volume of regional GM using sMRI and irrelevant heuristic prototype situations with high ecological validity to better understand the role of RC in insightful problem solving. The second aim of our study was to examine whether critical thinking moderates the relationship between RC in insightful problem solving and regional gray matter volume (rGMV).

The studies mentioned above indicate that the RC cognitive process, a core process for problem solving, might involve the following processes: functional feature processing, heuristic information integration, and the formation of novel associations (Bowden et al. 2005; Zhen–Zhen 2008; Hao et al. 2013; Ming et al. 2014). Individuals with high levels of insightful problem solving are better at semantic integration and forming novel associations (Qiu et al. 2010; Tian et al. 2011; Dandan et al. 2013a, b; Hao et al. 2013; Luo et al. 2013a, b; Tong et al. 2015). Previous studies also suggest that critical thinking disposition were significantly negatively correlated with total GM volumes of the bilateral temporal pole and bilateral parahippocampal regions, which are involved in memory retrieval and information integration (Yao et al. 2017). These characteristics are also important factors for problem solving (Parr et al. 2004; Yalç et al. 2013). We hypothesized that (1) RC may be associated with differences in rGMV in the lingual gyrus, precuneus, middle/medial frontal gyrus (MFG), and middle/superior temporal gyrus; and that (2) the relationship between rGMV and RC in insightful problem solving may be moderated by critical thinking, correlations may have different tendency among higher and lower critical thinking disposition.

Methods

Participants

A total of 119 individuals (67 women, mean age = 19.78 years, SD = 1.38; 52 men, mean age = 20.01 years, SD = 1.08) participated in the study as a part of our ongoing project to investigate the associations among brain imaging data, creativity, and mental health (Chen et al. 2014; Wei et al. 2014). Participants were undergraduate or postgraduate students in China. They were recruited through bulletin board advertisements or were introduced by individuals who had participated in previous studies at our laboratory. None of the participants had visual difficulties, substance abuse disorders, or a history of neurological or psychiatric illnesses. All participants gave their written informed consent in accordance with the Declaration of Helsinki (1991). The institutional ethics committee of the Brain Imaging Center Institutional Review Board approved the study protocol. Five participants were excluded because of incomplete data in the California Critical Thinking Disposition Inventory (CCTDI). Therefore, 114 participants (66 women, mean age = 19.67 years, SD = 1.05 years; 48 men, mean age = 20.04 years, SD = 1.09 years) were included in the final analyses.

Assessments and measures

Scientific innovation problem solving situations

Experimental situations were selected from the "Scientific Innovation Problems Database" (Yang et al. 2016), which has been utilized in previous fMRI research in our laboratory (Qiu et al. 2010; Dandan et al. 2013a, b; Hao et al. 2013; Luo et al. 2013a, b). Although scientists have already solved these problems in real life, inexperienced participants can rarely solve them without a heuristic prototype. Thus, a prototype-inspired solution would be novel for such participants. Because the present study included not only related heuristic prototypes but also three unrelated redundant sentences in the heuristic prototype condition, it is more realistic than previous studies.

Procedure of the experiment

The present study utilized the multiple-by-multiple problem-learning prototype testing paradigm. Nine pairs of technical problems and heuristic prototypes with unrelated redundant sentences were selected (see Appendix 1 in Supplementary material). To better imitate real-life scientific innovation problem solving, subjects were asked to first study the nine problems and then learn the nine prototypes. The experimental procedure is shown in Fig. 1.

Problem-learning phase

During the problem-learning phase, each trial was initiated by presenting a "+" sign in the center of the screen for 1 s. Subsequently, nine unsolved scientific problems were presented randomly in the center of the screen, one

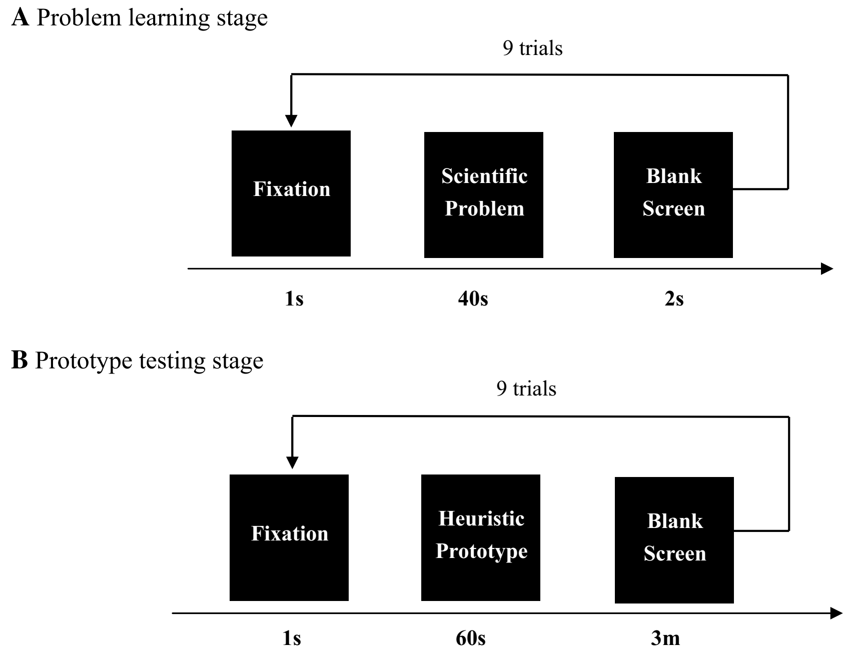

Fig. 1 Task sequence of the experiment

at a time, each one shown for 40 s. All participants were asked whether they knew the problem that had been presented before the experiment. Participants were instructed to press the "F" key if they were familiar with the scientific problem or the "J" key if it was unknown to them. After the key was pressed, the next problem was presented.

Heuristic prototype phase

During the prototype testing phase, each trial was also initiated by presenting a "+" sign in the center of the screen for 1 s. Afterward, nine heuristic prototypes with unrelated redundant sentences were presented randomly in the center of the screen, one at a time, for at most 60 s each. Participants were instructed to try to consider "which scientific problem among the nine presented in the last stage is the current prototype helpful for solving" and make a corresponding response based on the heuristic prototype. They pressed the "F" key if they associated the presented heuristic prototype with the corresponding scientific problem in the last stage. After pressing the key, the heuristic prototype would disappear, and a blank screen was presented for at most 3 min. Participants were instructed to write down the problem that they had thought of or draw "a circle," if they had not yet obtained the corresponding answer when the heuristic prototype was presented, on the answer sheet according to the order of the prototypes presented. After they had finished writing, participants were asked to press the "blank" key to go to the next prototype.

Scoring formula

Answers were scored as "0" or "1." If participants thought of the corresponding problem, a score of "1" was given, and a score of "0" was given if they had not thought about the corresponding problem. The RC score was calculated by summing the number of responses which were scored 1 in the heuristic prototype phase as well as were pressed the "J" key in problem-learning phase.

Assessment of critical thinking disposition

The self-reported California Critical Thinking Disposition Inventory (CCTDI) was used to assess critical thinking disposition (Facione 1990). The CCTDI has demonstrated itself to be formative and useful in research (Duncan-Hewitt 1996; Wan et al. 2000). It assesses seven attributes related to the development and application of critical thinking skills: disposition toward truth-seeking or bias; open-mindedness or intolerance; anticipating possible consequences or being unaware of them; proceeding in a systematic or unsystematic way; being confident in or mistrustful of one's own reasoning ability; being inquisitive or resistant to learning; and mature and nuanced judgment or rigid simplistic thinking. The present study utilized the CCTDI-CV, which contains revised items that are specific to the Chinese culture, with 16 items related to hypothetical situations found in Chinese cultural norms (e.g., the value of modesty as a virtue). The CCTDI-CV contains 70 items and each subscale has 10 items. It uses a Likert-type scale ranging from "strongly disagree" to "strongly agree" (1–6 points). In previous studies, its content validity and Cronbach's alpha coefficients have been 0.89 (Peng et al. 2004) and 0.88 (Yao et al. 2017), respectively.

Assessment of psychometric measures of general intelligence

To exclude the possibility that any significant correlation between GMV and RC in insightful problem solving could be caused by an indirect association between GMV and general intelligence (Takeuchi et al. 2011, 2014), the Combined Raven's Test (CRT; revised by the Psychology Department of East China Normal University in 1994), which is the Chinese version of this intelligence test (Wang 2007), was used in the current study. The CRT consists of Raven's Colored Progressive Matrices and Raven's Standard Progressive Matrices (sets C, D, and E), which can be used for individuals aged between 5 and 75 years, and contains six sets of 12 nonverbal items. Each item comprises a matrix with a missing element for which participants must select the best answer from six or eight alternatives. The internal consistency coefficient of the CRT is 0.93, and the coefficient value for its convergent validity (correlation between the CRT and the Wechsler Intelligence Scale) is 0.56, and 0.57 for criterion-related validity (correlation between the CRT and scholastic achievement) (Wang 2007).

MRI data acquisition

All MRI data were acquired using a 3T Siemens Trio MRI scanner (Siemens Medical, Erlangen, Germany). High-resolution T1-weighted anatomical images were acquired using a magnetization-prepared rapid gradient echo (MP-RAGE) sequence: repetition time (TR) = 1900 ms; echo time (TE) = 2.52 ms; inversion time (TI) = 900 ms; flip angle = 9 °; resolution matrix = 256 × 256; slices = 176; thickness = 1.0 mm; and voxel size = 1mm × 1mm × 1 mm.

Voxel-based morphometry (VBM)

The associations between rGMV structures and various cognitive abilities can identify the brain regions associated with specific cognitive characteristics (Haier et al. 2004; Takeuchi et al. 2011). Thus, structural imaging can provide information on the neural mechanisms of RC in insightful problem solving. Statistical Parametric Mapping software (SPM) 8 implemented in Matlab 7.8 (Math Works Inc., Natick, MA, USA) was applied for the processing of MRI data (Wellcome Department of Cognitive Neurology, London, UK; http://www.fil.ion.ucl.ac/spm). The procedure consisted of five steps. First, each MR image was displayed in SPM8 to check for scanner artifacts or gross anatomical abnormalities. Second, for better registration, the reorientation of the images was manually set to the anterior commissure. Third, the images were segmented into gray matter (GM), white matter (WM), and cerebrospinal fluid using the new segmentation. Fourth, diffeomorphic anatomical registration was performed through exponentiated lie algebra (DARTEL) in SPM8 for registration, normalization, and modulation, which is an additional step based on the change of variables theorem and allows the evaluation of gray matter or white matter volume (van Tol et al. 2010), leaving the images in DARTEL space. A DARTEL template is created based on the deformation fields produced during the segmentation procedure; all individual deformation fields were registered to this template (Ashburner 2007; Hutton et al. 2009). To ensure that regional differences in the absolute amount of GM were conserved, we modulated the image intensity of each voxel by the Jacobian determinants using linear transformations. Then, registered images were transformed to Montreal Neurological Institute (MNI) space. Last, all images were smoothened with a Gaussian kernel of 10-mm full-width at half-maximum to increase their signal to noise ratio.

Statistical analysis

GM images were pre-processed using SPM8. To avoid edge effects around the borders between GM and WM, we included only those voxels that showed GM of > 0.2 in rGMV analyses. Multiple linear regression was used to test the relationship between RC in insightful problem solving and rGMV. In whole-brain multiple regression analyses, the RC score was used as the variable of interest, whereas age, gender, IQ, and global GM volumes were included in the design matrix as nuisance covariates of no interest.

For all analyses, the cluster-level significance was set at $P < 0.05$, corrected using a non-stationary cluster correction (Hayasaka et al. 2004) with an underlying voxel significance level of $P < 0.001$. Non-stationary cluster size tests can be safely applied to data that are known to be non-stationary (e.g., not uniformly smooth), such as VBM data (Hayasaka et al. 2004; Silver et al. 2011; Takeuchi et al. 2014).

Moderation analysis

A moderator variable is a variable that affects the direction and/or strength of the relationship between an independent variable and a dependent variable. The present study used the MODPROBE macro for SPSS to examine under which conditions "X" had a stronger/weaker (positive/negative) association with or effect on "Y" through moderation analyses (Hayes and Matthes 2009). We also investigated whether critical thinking disposition affected the relationship between rGMV and RC using the Johnson–Neyman technique in the SPSS MODPROBE macro (Hayes and Matthes 2009). In a regression analysis conducted in SPSS Statistics 16 (http://www.spss.com), the total and subscale scores of critical thinking disposition were entered as moderator variables separately, RC score as dependent variable, and rGMV as focal predictor. These methods have been successfully utilized in previous studies (Nikolova et al. 2012; Wei et al. 2015; Yao et al. 2017).

Results

Sample descriptive statistics

Table 1 shows the mean and SD by age, CRT scores, and RC scores in insightful problem solving for both genders. There were no significant differences in RC scores between men and women. Table 2 lists the characteristics related to RC and cognitive maturity level of the total sample. As indicated in Table 2, RC scores did not significantly correlate with cognitive maturity (a dimension of critical thinking).

VBM analysis

After controlling for age, gender, IQ, and global GM volume, RC scores in insightful problem solving were found to be positively correlated with rGMV in the right anterior STG and a cluster of the left MFG (see Fig. 2). These results are shown in Table 3.

Moderation analysis

Based on the previous studies, we hypothesized that individual differences in critical thinking and its dimensions would moderate the relationship between rGMV and RC in insightful problem solving. Results indicated a significant interaction between cognitive maturity and STG volume ($\Delta R^2 = 0.061$, $b = -1.50$, $t = -2.99$, $P = 0.0034$), such that higher RC was associated with greater STG volume among participants with relatively low cognitive maturity (80.7% of participants, $n = 92$), but not among those with higher cognitive maturity (remaining 19.3% of participants, $n = 22$).

Table 2 Demographic data and psychometric measures of participants ($N = 114$)

	Mean (SD)	Range	Association with scores[a]
Age (years)	19.83 (1.08)	18–24	
RC	6.03 (1.67)	1–9	
Cognitive maturity	41.18 (6.01)	23–50	0.071

RC representation connection

[a]Pearson bivariate correlations, shown are *P* values

There was a similar significant interaction between MFG volume and cognitive maturity ($\Delta R^2 = 0.041$, $b = -1.36$, $t = -2.36$, $P = 0.019$), such that higher RC was associated with higher MFG volume among participants with lower cognitive maturity (80.7% of participants, $n = 92$) but not among those with higher cognitive maturity (remaining 19.3% of participants, $n = 22$). These results are shown in Fig. 3.

Discussion

The present study revealed that RC was primarily associated with a significant increase in a cluster that included areas of the right anterior STG and left MFG. Consistent with our hypothesis, we further found that cognitive maturity moderates the relationship between rGMV and RC. Specifically, we found that higher rGMV was correlated with higher RC in participants with lower cognitive maturity, but not in those with higher cognitive maturity.

Increased volume in the right anterior STG was positively associated with RC in insightful problem solving. Accumulating evidence suggests that bilateral anterior STG/MTG is associated with sentence integration and complex discourse (Stowe et al. 1999; Friederici et al. 2003; Grabowski et al. 2010), Semantic integration operates on selected concepts to construct complex representations (Jung-Beeman 2005). Moreover, Kounios and colleagues found greater neural activity in bilateral MTG/STG when participants performed compound remote associate problems and suggested that this was related to semantic activation (Jung-Beeman et al.

Table 1 Demographic variables and statistical values compared by gender (males = 52, females = 67)

Measure	Males		Females		*T* value	*P* value
	Mean	SD	Mean	SD		
Age	20.01	1.08	19.78	1.38	1.047	0.297
CRT	66.35	3.20	66.37	3.07	−0.047	0.963
RC	6.21	1.61	5.89	1.73	1.017	0.311

$N = 52$ (males), 67 (females)

CRT combined Raven's test, *RC* representation connection

*Statistical values are the comparative values for each measure for males and females

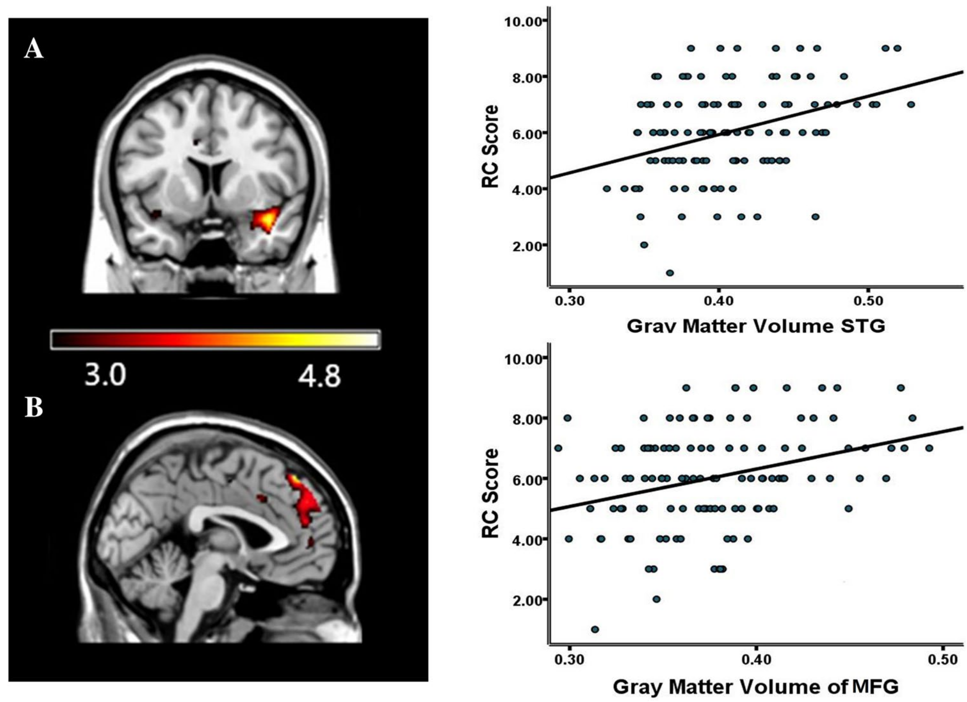

Fig. 2 Regional gray matter volume correlated with representation connection (RC). The right superior temporal gyrus (STG) and the left medial frontal gyrus (MFG) demonstrated a significant positive correlation with RC. Results are shown with $P<0.05$ (corrected). **a** Shows the cluster in the right STG, while **b** shows the left MFG cluster. Scatter plot representation of the correlation between RC and regional gray matter volume (rGMV) of the right STG and left MFG

Table 3 Brain regions with significant correlations between brain structures and representation connection in insightful problem solving

Brain region	MNI coordinates				T score	Corrected *P* value	Voxels size
		x	*y*	*z*			
Positive correlation between GMV and RC score							
Superior temporal gyrus	R	40	9	− 19	4.61	0.044*	556
	L	− 39	1	− 15	3.61	0.506	127
Medial frontal gyrus	L	− 2	42	51	4.50	0.003*	885

Results are $P<0.05$, corrected for multiple comparisons at a cluster level with non-stationary correction, with an underlying voxel level of $P<0.001$, uncorrected

RC representation connection

*$P<0.05$. Pearson bivariate correlations with RC score, shown are *P* values

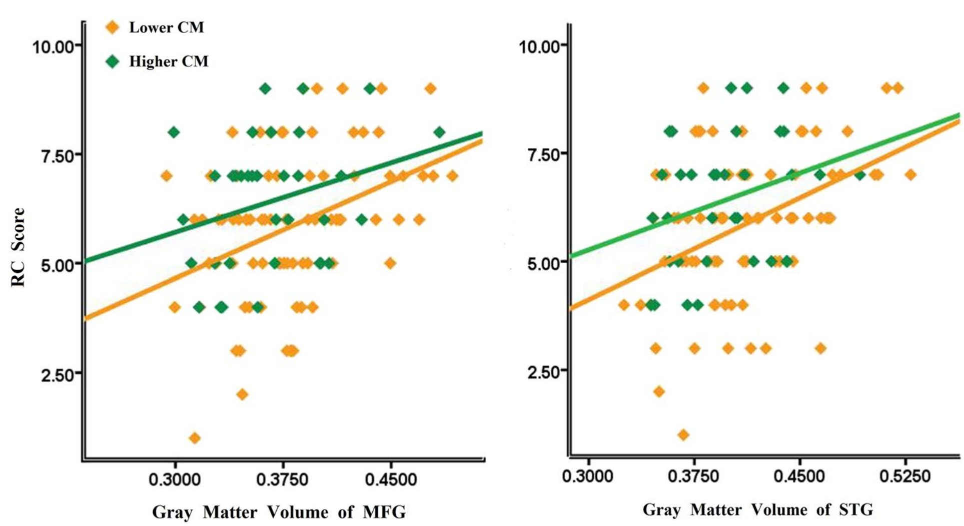

Fig. 3 The level of cognitive maturity moderates the relationship between the gray matter volume of the right superior temporal gyrus (STG) and the left medial frontal gyrus (MFG) and representation connection (RC). RC scores are associated with an increased volume in the right STG and left MFG in participants with relatively lower (yellow line) score of CM. The "*X*" axis represents the decentralization of gray matter volume in the right STG or left MFG. The "*Y*" axis represents the decentralization of RC scores

2004; Kounios et al. 2006). Moreover, compared to the left STG, the right anterior STG is more sensitive to distant or novel semantic relations and maintains a distant and unusual semantic activation of a broader semantic field (Meyer et al. 2000; Jung-Beeman et al. 2004). These semantic fields include information that initially seems irrelevant but later proves to be important (Chiarello et al. 2003; Jung-Beeman 2005). As mentioned above, the heuristic prototype was the object containing the heuristic information for solving insight problems, despite being superficially and semantically irrelevant to these problems. Accordingly, people with higher rGMV in the right STG may integrate an irrelevant heuristic prototype and subsequently activate the key "feature function" along with a "certain construction" of this prototype more successfully. Semantic activation of the "certain construction" of heuristic prototypes may help in building associations with the "required function" in unsolved technical problems.

We also observed that RC in insightful problem solving was positively associated with GMV in the left MFG regions. Previous studies have revealed that the MFG is required for processing novel and creative information and generating unusual verbs (Seger et al. 2000; Mashal et al. 2007). In addition, Rugg and colleagues (1998) indicated that the MFG is involved in "spontaneous conscious effort" to suppress irrelevant thoughts (Rugg et al. 1998). In our study, the heuristic prototype always contained some redundant information, and participants needed to suppress irrelevant redundant information to connect the unsolved scientific problem and heuristic prototype correctly, a process similar to forming novel associations between unrelated words. Therefore, we suggest that increased GMV in this area may be associated with an increased ability for suppressing irrelevant thoughts and, thereby, leading to the successful formation of novel associations.

Furthermore, the association between the left MFG and problem solving scores can be understood in terms of the role of information manipulation. The left MFG plays a role in manipulating the information actively maintained in the working memory, which may perform a decisive role in gaining insights (Cairo et al. 2004; Lang et al. 2006). In parallel, Montaldi and colleagues (2002) found that the MFG was involved in generating scenarios that could lead to increased candidate semantic linkages in the working memory, promoting relational associations among semantic concepts (Montaldi et al. 2002). As mentioned above, the manipulation of information in the working memory could improve the semantic associations among heuristic prototypes and relevant scientific problems. Thus, increased GMV in the MFG may be associated with better information manipulation, which may induce the formation of novel associations, as well as selecting and retrieving matched unsolved technical problems from the memory.

Interestingly, the present study revealed that the relationship between GMV and individual RC in insightful problem solving was moderated by cognitive maturity, which is a subscale of critical thinking disposition. The cognitive maturity subscale targets the disposition to be judicious in one's decision-making. In this regard, higher cognitive maturity has been associated with a greater likelihood of thinking that problems are necessarily ill-structured and that situations admit more than one plausible option in the context of approaching problems, inquiry, and decision-making (Facione et al. 1994). A previous study showed that cognitive maturity is associated with a wide range of brain regions in the lateral and medial frontal, striatal, and parietotemporal regions (Rubia 2013). Participants with lower levels of cognitive maturity were less likely to obtain high problem-solving scores (Macpherson 2002). These findings may indicate that cognitive maturity is moderately correlated with problem solving. In addition, individuals with higher cognitive maturity levels are also likely to make judgments based on standards, contexts, and evidence that preclude certainty, and such individuals may anticipate situations that require reasoning and have confidence in their reasoning ability (Facione et al. 1994; Stedman et al. 2007). In the present study, participants needed to associate the prototype and problem in a novel manner to solve the problem correctly. In this regard, relying on strict standards for decision-making may lead to mental impasse and, consequently, frustration. Based on the present findings, we propose that rGMV interacts with cognitive maturity to modulate RC in insightful problem solving.

In summary, the present study has observed that RC is intimately associated with individual differences in a cluster that included areas of the right aSTG and left MFG. Moreover, the relationship between RC and the right aSTG and left MFG volume are moderated by cognitive maturity. Higher rGMV is correlated with higher RC in participants with lower cognitive maturity, but not in participants with higher cognitive maturity, indicating the potential involvement of cognitive maturity in the relationship between RC and brain morphology. The present findings represent an additional step toward understanding the neurobiology of RC in insightful problem solving.

Strengths and limitations

To our knowledge, this is the first study to use a structural approach (i.e., rGMV) to examine the neural correlates of RC and the association between critical thinking, brain structure, and individual RC in insightful problem solving. Moreover, most previous studies on insight have used artificial problems, while the scientific problem-solving situations in the present study were related to real-life situations, which had high ecological validity. Accordingly, results are more likely to reflect the neural basis of real-world scientific problem solving. Although the present study benefited from the sMRI technique that is considered a highly reliable, reproducible, and effective approach, the conclusions regarding the relationship between critical thinking, brain structure, and individual RC in insightful problem solving remain reserved. Future studies should not only analyze additional structural aspects, such as cortical folding and thickness but also examine the functional brain mechanisms of RC, such as low-frequency oscillations. Additional longitudinal or intervention studies in larger or different samples are required to confirm these results.

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