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People got lost in solving a set of similar problems

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ABSTRACT

A mental set generally refers to the human brain's tendency to persist with a familiar solution and stubbornly ignore alternatives. However, if a familiar solution is unable to solve a problem similar to a previous problem, does it continue to hinder alternative solutions, and if so, how and why? To answer these questions, a Chinese character decomposition task was adopted in this study. Participants were asked to perform a practice problem that could be solved by a familiar loose chunk decomposition (LCD) solution followed by a test problem that was similar to the practice problem but could only be solved by an unfamiliar tight chunk decomposition (TCD) solution or were asked to repeatedly perform 3–5 practice problems followed by a test problem; the former is the base-set condition, and the latter is the enhanced-set condition. The results showed that the test problem recruited more activation of the inferior frontal gyrus (IFG), middle occipital cortex (MOG), superior parietal lobule (SPL) and dorsal anterior cingulate cortex (dACC) than the practice problem in the latter operation and verification stage, but almost equal activation of the dACC occurred in the early exploration stage. This likely implied that people did not think that the familiar but currently invalid LCD solution could not be used to solve the test problem; thus, it continuously competed for attention with the unfamiliar TCD solution, which required more executive control to suppress. Moreover, compared with the base-set condition, the test problem in the enhanced-set condition recruited greater activations of the IFG, SPL and dACC in the latter verification stage but less activations of regions in the left IFG and MOG in the early exploration stage. These results revealed that people less actively explored and had to work harder to operate the unfamiliar TCD solution, particularly to resolve competition from the familiar but currently invalid LCD solution. In conclusion, people lost the ability to identify errors in the familiar but currently invalid solution, which in turn decreased the exploration efforts and increased the processing demands associated with alternative solutions in the form of attentional bias and competition. This finding broadly explains the dilemma of creative problem solving.

1. Introduction

Memory links man's past, present and future, and prior knowledge can affect present performances and those in the future. On a positive note, previously acquired knowledge can enhance performance by efficiently guiding people to retrieve possible solutions that have worked successfully in the past. On the other hand, prior knowledge might also harm performance in the form of mental set (Bilalic et al., 2010; Schultz and Searleman, 2002; Wiley, 1998). Mental set is also known as the Einstellung effect, which is triggered by previous experience with similar situations and prevents the consideration of alternative solutions once a familiar solution comes to mind (Bilalic et al., 2008, 2010; Bilalić and Mcleod, 2014; Ellis and Reingold, 2014; Hagger et al., 2013; Neroni et al., 2017; Sheridan and Reingold, 2013). In both the laboratory and real-life settings, the mental set has been demonstrated using a range of different problem-solving tasks (Schultz and Searleman, 2002). However, the effect of interference from the familiar solution on alternative solutions remains largely unknown, especially when the familiar solution is unable to solve the current problem successfully. Studying this issue may help us to answer why people go into a blind alley without looking

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back, such as in insight problem-solving behaviors.

The most famous example of the mental set is the so-called water-jar problem that was originally developed by Luchins (Luchins, 1942; Luchins and Luchins, 1969). Participants are presented with three jars (A, B, and C), each of which holds a certain amount of water. The goal is to determine how the jars could be used to obtain a designated amount of water. A series of practice problems can only be solved using a complicated strategy (e.g., A – B – 2C) that is quickly learned. Then, a test problem (called the 2-solution problem) is given, and this problem can be solved using the complicated strategy or a much easier system (e.g., A – C). Typically, the vast majority of participants continue to use the complicated strategy instead of the simple one. Participants fail to find the simple solution likely because the similarity between the test problem and the previous practice problems brings the familiar strategy to mind first and thus blinds participants to the alternatives. In this case, the mental set is induced by a small number of similar problems in people who have never experienced the task before, and the effect seems to increase after intense practice (Crooks and Mcneil, 2009; Neroni et al., 2017).

Additionally, the mental set can also be induced by previously acquired knowledge, particularly expertise in a domain (Ricks et al., 2007; Wiley, 1998). For example, chess players were required to find a checkmate position with the fewest number of moves in a laboratory experiment. If the players were given a problem that had two possible solutions, i.e., a familiar solution that took five moves and a less familiar solution that took three moves (the optimal solution), most of the players chose the familiar but nonoptimal solution and failed to notice the shorter solution (Bilalic et al., 2008). Eye tracking technology has demonstrated that players rapidly fixated on the target region that was associated with the familiar but longer solution (i.e., checkmate in five moves) and spent more time looking at these squares than those relevant to the shortest solution (i.e., checkmate in three moves) (Bilalic et al., 2008, 2010; Bilalić and Mcleod, 2014). Even when players reported that they were searching for alternative solutions in an open-minded manner, there was no change in the fixation pattern (Bilalic et al., 2008, 2010; Sheridan and Reingold, 2013). Participants have trouble correcting attentional bias toward information that is relevant to the familiar solution and searching for alternative solutions.

However, when the familiar solution is unable to solve the current problem, can we divert attention absolutely to search for alternative solutions? An example would be participants who were presented with a 1-solution problem that was apparently similar to previous problems but for which the familiar solution does not work. The behavioral performances in this context are contradictory; earlier studies demonstrated that it is impossible to divert attention (Luchins, 1942), whereas some recent studies have reported it is possible (Bilalic et al., 2008; Sheridan and Reingold, 2013). However, eye-movement pattern results have revealed that this phenomenon is not necessarily possible. Specifically, when players realize that a familiar solution does not work, the fixation time for the squares that are important for the familiar solution does not drop sharply but remains at roughly the same percentage as that for the optimal solution squares during the early and middle stages of the problem-solving process (Bilalic et al., 2008, 2010). It is possible that the familiar but currently invalid solution continues to interfere with alternative solutions.

A similar phenomenon is likely to occur in creative insight problem solving. With the "help" of previously acquired knowledge and experience, the problem solver always reaches an impasse since the familiar or conventional solution is insufficient to solve insight problems. To break this impasse and obtain insight, people must abandon the initial failed solution and find a new solution. To date, almost all studies have focused on when and how to search for a new solution. For example, the progress monitoring theory proposes that insight is only sought once it becomes apparent that the distance to the goal is unachievable in the moves remaining (MacGregor et al., 2001; Ormerod et al., 2002). The representational change theory proposes that insight occurs through relaxing self-imposed constraints on a problem and by decomposing chunked items in the problem (Ollinger et al., 2008; Ohlsson, 1992). A common assumption between the two theories is that problem solvers have sufficient knowledge of problems and can solve them without any external help. However, no studies have pointed out why the success rate of insight is very low. One possibility that should be tested is that people cannot correct mistakes after they realize the failure of a familiar solution, and the familiar but currently invalid solution may continuously interfere with alternative solutions.

To reveal what happens in the brain when people are confronted with a problem that is similar to a previous problem but cannot be solved by a familiar solution, this study adopted a chunk decomposition task. As a possible way to solve insight problems, chunk decomposition refers to the decomposing of familiar patterns into their component elements so that they can be regrouped in a different meaningful manner. Based on whether the components of the to-be-decomposed chunks are themselves meaningful perceptual patterns, chunk decomposition can be divided into loose and tight levels; decomposing the numeral "VI" into "V" and "I" is an example of loose chunk decomposition (LCD) and decomposing 'X' into "/" and "\" is an example of tight chunk decomposition (TCD) because 'VI' is composed of meaningful small chunks ('V' and 'I'), whereas 'X' is composed of meaningless small chunks ("/" and "\") (Knoblich et al., 1999). Generally, participants are more familiar with LCD than TCD due to previous knowledge about chunks (Huang et al., 2015; Knoblich et al., 1999; Wu et al., 2013), but the latter is critical to solving insight problems. Studying how the familiar but currently invalid LCD solution interferes with the TCD solution can further reveal the mystery of rare insight.

In the experiment, the participants were asked to perform a practice problem that could be solved using an LCD solution, followed by a test problem that was similar to the practice problem but could only be solved using an unfamiliar TCD solution, or were asked to repeatedly perform 3–5 practice problems, followed by a test problem; the former is the base-set condition, and the latter is the enhanced-set condition, because the performances involved in solving problems with the LCD solution were further enhanced by repeated practice in the set (Chi and Snyder, 2011; Knoblich et al., 2001). In both conditions, the test problem was apparently similar to the practice problem situation that had external elements for the retrieval of the familiar LCD solution, but the LCD solution failed to solve it. By comparing the neural correlates of the test problem and those of the practice problem, it is possible to reveal how the unfamiliar TCD solution was explored and operated. Comparing the neural correlates of the test problem in the enhanced- and base-set conditions can be used to further examine how the familiar but currently invalid LCD solution interferes with the unfamiliar TCD solution. Furthermore, to demonstrate how the familiar but currently invalid LCD solution interferes with both the exploration effort and processing demands of the TCD solution, each trial of the chunk decomposition task was divided into an early exploration stage in which the problem was presented for only 2.5 s and the participants had the opportunity to freely search the solutions; in a later verification stage in which the solution was presented for 3 s, the participants had to operate a given solution and make a judgment about whether it was possible to solve the problem successfully.

We predicted that people might be cautious about believing that the familiar solution was unable to solve problems, and the familiar but currently invalid solution may continue to decrease the exploration tendency and increase the processing demands associated with alternative solutions, likely by means of attentional bias and competition. Particularly, the test problem would recruit greater activations of the conflict detection- and resolution-related regions than the practice problem in the latter verification stage rather than in the early exploration stage. After solving a set of similar practice problems by the familiar solution, activation of these conflict detection- and resolution-related regions will increase in the latter verification stage but decrease in the early exploration stage of the test problem.

2. Methods

2.1. Participants

Twenty-six undergraduate and graduate students (12 females and 14 males, aged 20–26 years old, mean age = 23.15 years, all native Chinese speakers) who were recruited from the University of Science and Technology of Beijing participated in this study as paid volunteers. All participants were right-handed, had normal or corrected-to-normal vision, and had no history of neurological or psychiatric problems. Prior to the scanning session, the participants signed informed consent forms, and the study was approved by the institutional review board of the Beijing Magnetic Resonance Imaging Center for Brain Research. Three participants (one female and two male) were excluded from the analysis because of excessive head motion during scanning.

2.2. Materials and procedure

A Chinese character decomposition task was adopted in this study. Each problem includes two characters: one on the left side and the other on the right, and the participants were explicitly instructed to move some elements of the character on the right side to join them with the character on the left side to produce two new valid characters. Since the Chinese characters are composed of radicals (subchunks that may convey phonetic or semantic information of the character), which, in turn, are composed of strokes (basic elements that do not carry any meaning), character decomposition can occur at both the radical and stroke levels; the former is LCD and the latter is TCD. For example, decomposing and regrouping the radicals "女" (LCD solution) is sufficient to generate two new target characters in the practice problem "因 and 姝", whereas decomposing and regrouping the strokes "丿" (TCD solution) was required to solve the test problem "夫 and 姝". The practice and test problems were similar; in particular, there was a radical element for the retrieval of the familiar LCD solution that was useful for the practice problem but invalid for the test problem (see Fig. 1a).

Two conditions were created in this study, namely, the base- and enhanced-set conditions. In the base-set condition, there were 30 practice problems and 30 test problems that appeared at intervals. In the enhanced-set condition, there were 120 practice problems and 30 test problems, and 3–5 practice problems were repeatedly reinforced before a test problem (see Fig. 1b). In sum, 210 Chinese character decomposition problems were adopted in this study. All of the characters were highly familiar to the participants, who were native Chinese speakers. Sixty trials in the base-set condition were assigned to the first run, and 150 trials in the enhanced-set condition were equally divided into 3 runs with each run consisting of 40 practice trials and 10 test trials. Additionally, in each run, 10% of the trials were also filled trials in which both the LCD and TCD solutions were invalid.

The time course of each trial is illustrated below (see Fig. 1c). Each trial began with a problem-exploration stage that was followed by a solution-verification stage. During the early exploration stage, two characters were presented on the screen for 2.5 s followed by a 2–3 s interval, and the subjects were required to solve the problem in their mind without making any response. During the verification stage, a given solution was presented for 3 s, and the subjects were instructed to execute the solution and make a judgment about whether it was possible to solve the problem successfully by pressing a key with their index finger (left key: yes; right key: no). The given solution was always right for the critical trials but invalid for the filled trials. A cross-viewing stage that ranged from 3 to 4 s was presented between trials.

2.3. Image acquisition

The data were acquired at the Beijing Magnetic Resonance Imaging Center for Brain Research. Functional MRI (fMRI) scanning was performed on a 3.0-T magnetic resonance scanner (Siemens Version, Erlangen, Germany) using a standard radio frequency head coil. To restrict movement, the participant's head was fixed with plastic braces and foam pads during the entire experiment. For functional imaging, the whole-brain coverage of 33 axial slices was acquired with a T2*-weighted echo planar imaging sequence based on the blood oxygenation level dependent (BOLD) contrast with the following parameters: TR = 2000 ms, TE = 30 ms, FOV = 192 mm × 192 mm, FA = 90°, 64 × 64 matrix, 33 slices, 3.5 mm thickness, and voxel size = 3.0 mm × 3.0 mm × 3.5 mm. Additionally, a high-resolution structural T1-weighted anatomical scan was acquired for each participant with a three-dimensional, gradient-echo pulse sequence (TR = 2600 ms, TE = 3.02 ms, FOV = 256 mm × 256 mm, FA = 7°, 178 slices with 1.0 mm thickness, and voxel size = 1.0 × 1.0 × 1.0 mm).

2.4. Image analysis

The image preprocessing and statistical analyses were performed using the Statistical Parametric Mapping software package (SPM8; Wellcome Department of Cognitive Neurology, Institute of Neurology, London, UK) implemented within MATLAB 2014a (MathWorks, Inc., Natick, MA, USA). During preprocessing, the images for each subject were corrected for slice timing, realigned for head motion correction, spatially normalized into a standard echo planar imaging (EPI) template in the Montreal Neurological Institute (MNI) space, and smoothed with a Gaussian kernel with a full-width at half-maximum (FWHM) of 8 mm.

For the first level analysis, two general linear models were separately estimated for the base-set and enhanced-set conditions. For the first model, four key events were defined, namely, the exploration stage and the verification stage of the practice problem and the exploration stage and verification stage of the test problem. For the second model, twelve key events were defined, namely, the exploration stage and verification stage of the practice problem in serials-1, serials-2, serials-3, serials-4,

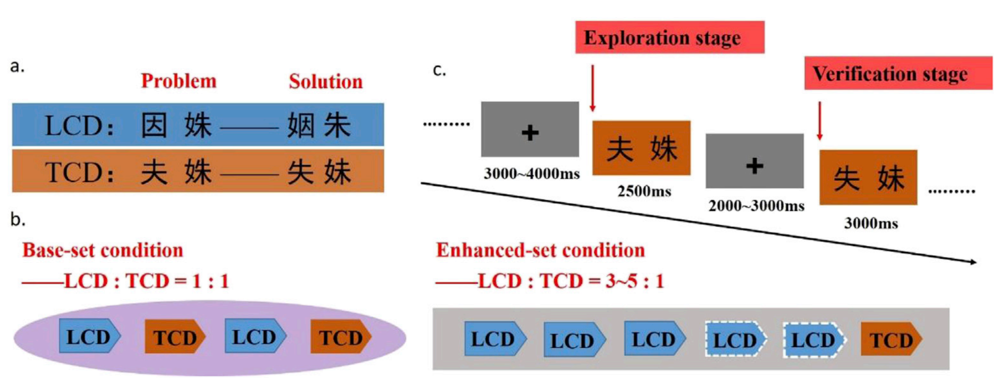

Fig. 1. a. The character decomposition task in the loose and tight levels is illustrated. b. A schematic diagram illustrates the time course of a trial during MRI scanning. c. The presentation sequence of the practice problems and the test problems in the base-set and enhanced-set conditions is displayed.

and serials-5 of the set, and the exploration stage and verification stage of the test problem. The exploration event was time-locked to the onset of the problem display, whereas the operation event was time-locked to the onset of the solution display. There were also two events that were not of interest, namely, the exploration stage and the verification stage of inaccurate or missed response trials in each condition. Each of the two general linear models was estimated in SPM8, and the design matrix included six separate regressors and six movement parameters from the realignment procedure (three rigid-body translations and three rotations). Regionally specific condition effects were tested using linear contrasts for each key event relative to the baseline and for each participant.

The resulting contrast images from the first level were submitted to a random-effects analysis for all participants. The hemodynamic effects of the exploration and verification events of the practice problem or the test problem were separately assessed in the base-set and the enhanced-set conditions. A sample *t*-test was performed to display the neural activity differences between the test and practice problems in both the early exploration stage and the later verification stage, which can help to demonstrate how people explored and operated when considering an unfamiliar TCD solution and whether the familiar but currently invalid LCD solution interfered with the process.

To further examine how the familiar but currently invalid LCD solution interfered with the unfamiliar TCD solution, the test problem-solving-related activations were extracted by region of interest (ROI) analysis (Poldrack et al., 2008) and then compared between the enhanced- and base-set conditions. Specifically, six hypothesis-driven anatomical ROIs were created using WFU PickAtlas (http://fmri.wfubmc.edu/software/PickAtlas) and included the cuneus, middle occipital gyrus (MOG), dorsal anterior cingulate cortex (dACC), superior parietal lobe (SPL), and left and right inferior frontal gyri (IFG_L, IFG_R) (Luo et al., 2006; Wu et al., 2013; Huang et al., 2015; Tang et al., 2016). The percent signal changes were extracted for four events (i.e., the exploration and verification stages of the practice and test problems) in the general linear model for the base-set condition, whereas twelve events (i.e., the exploration and verification stages of the test problem and the practice problem in the different serials of the set) in the general linear model were extracted for the enhanced-set condition using the MarsBar toolbox (http://marsbar.sourceforge.net). After calculating the mean of the five practice problem events in the second model, the percent signal changes in each ROI were assessed using two 2×2 full-factorial ANOVAs with the factors of Set (base vs. enhanced) and Problem (practice vs. test) separately for the problem events (exploration stage) and solution events (verification stage). The main effect of Set could reveal the percent signal changes within the ROIs in the enhanced-set condition compared with the base-set condition.

3. Results

3.1. Behavioral results

Based on the participants' online responses, there were, on average, 30 valid practice and 26 valid test trials in the base-set condition and 117 valid practice and 25 valid test trials in the enhanced-set condition. The following analyses were performed only on the valid trials in each condition.

For the mean reaction times, a 2×2 ANOVA revealed a significant main effect of Chunk [$F(1,22) = 541.64$, $p < 0.001$, $\eta^2 = 0.96$], but the main effect of Set was not significant [$F(1,22) = 1.60$, $p < 0.05$, $\eta^2 = 0.07$]; the interaction between these factors was significant [$F(1,22) = 4.34$, $p < 0.05$, $\eta^2 = 0.16$]. The participants spent more time on the test problems than on the practice problems in both conditions and spent less time on the practice problems in the enhanced-set condition than in the base-set condition. The reaction times for the test problem were not different between the base-set and enhanced-set conditions (see Fig. 2).

3.2. Imaging results

To reveal how the unfamiliar TCD solution was explored in the early stage and operated in the latter stage, the neural activity differences between the practice and test problems were compared. During the early exploration stage of both the base- and enhanced-set conditions, increased neural activities were identified in the bilateral premotor cortex (PMC), postcentral gyrus (PG), IFG and SPL ($p < 0.05$, FWE-corrected). During the verification stage of both the base-set and enhanced-set conditions, increased neural activities were identified in the bilateral MOG, PMC, IFG, SPL, inferior parietal lobule (IPL), right middle temporal gyrus (MTG) and dorsal anterior cingulate cortex (dACC) ($p < 0.05$, FWE-corrected) (Fig. 3, Table 1).

To further examine how the familiar but currently invalid LCD solution interfered with the unfamiliar TCD solution, activations of the TCD solution-related regions were compared between the enhanced-set condition and the base-set condition. Specifically, during the early exploration stage of the test problems, the deactivation of the cuneus and the activation of the MOG and left IFG were lower in the enhanced-set condition than in the base-set condition. During the latter verification stage, the test problem-related activations of the SPL, IFG and dACC were higher in the enhanced-set condition than in the base-set condition (Fig. 4).

4. Discussion

This study was designed to reveal what happens in the brain when people are confronted with a problem that cannot be solved by a familiar solution, and in particular, how the familiar but currently invalid solution interferes with alternative solutions. The results showed that people lost the ability to identify errors in the familiar but currently invalid solution, which in turn decreased the exploration efforts and increased the processing demands associated with alternative solutions, probably by means of attentional bias and competition.

4.1. How does the familiar but currently invalid solution interfere with the unfamiliar solution?

In the early exploration stage of both conditions, the test problem also recruited greater activation in the bilateral IFG, SPL and PMC than the practice problems, but no difference was found in the cuneus or MOG, two important visual areas associated with perceptual chunk decomposition. As an executive control region, the IFG overlaps with the fronto-parietal control network subregions as well as the dorsal attention network subregions (Dodds et al., 2011; Kim, 2017). Increased activity in these areas, along with activity increases in the posterior parietal cortex, are likely responsible for orienting attention from the loose subchunks

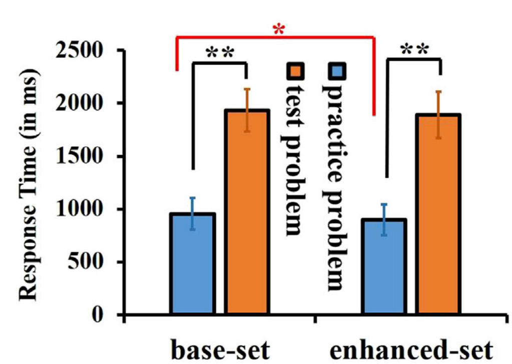

Fig. 2. Behavioral results. The panel shows the mean reaction times (RTs) for the practice problem and the test problem in both the base-set and enhanced-set conditions. Error bars represent the 95% confidence interval. The asterisks indicate significant differences between the two conditions (*$p < 0.05$, **$p < 0.001$).

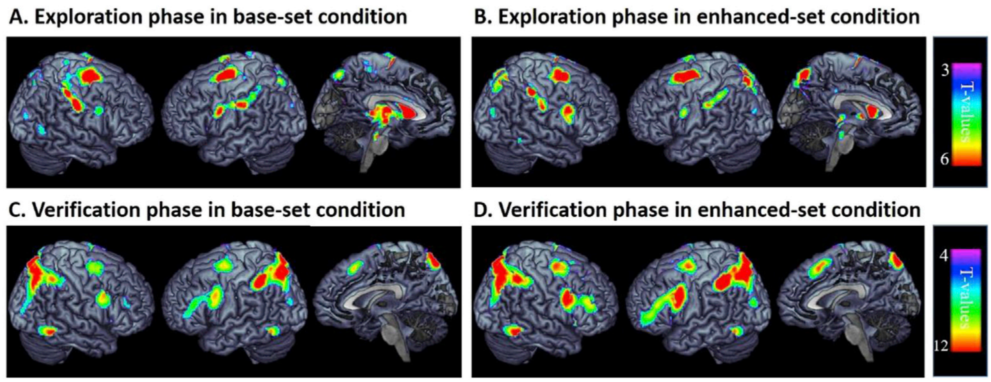

Fig. 3. Imaging results. Brain images showing the activations in the test and practice problems contrasted between the exploration and verification stages in both the base-set and enhanced-set conditions.

Table 1
Brain regions associated with chunk decomposition in the base-set and enhanced-set conditions.

Brain regions	L/R	BA	MNI coordinates			t (20)	k	Brain regions	L/R	BA	MNI coordinates			t (20)	k
			x	*y*	*z*						*x*	*y*	*z*		
test minus practice problem in the exploration stage Base-set condition								*test minus practice problem in the exploration stage Enhanced-set condition*							
PMC	L	6	−24	−10	62	8.73	614	PMC	L	6	−24	−4	64	8.66	739
PMC	R	6	26	−12	60	7.57	689	PMC	R	6	24	4	64	7.15	418
PG	R	3	62	−22	40	7.27	473	PG	R	3	64	−20	38	6.23	119
PG	L	2	−60	−28	40	6.32	237	PG	L	2	−64	−28	42	6.07	186
IFG	L	9	−54	2	30	6.31	110	IFG	L	9	−58	4	28	5.60	31
IFG	R	9	54	6	32	4.96	5	IFG	R	9	52	10	30	6.31	251
SPL	L	7	−12	−72	54	5.23	61	SPL	L	7	−12	−72	54	7.19	328
SPL	R	7	12	−70	54	4.92	21	SPL	R	7	12	−70	54	6.82	291
IPL	L	40	−50	−40	48	4.95	35	IPL	L	40	−56	−40	50	7.25	170
test minus practice problem in the verification stage Base-set condition								*test minus practice problem in the verification stage Enhanced-set condition*							
SPL	L	7	−34	−60	64	15.40	4603	SPL	L	7	−34	−60	64	17.96	4612
IPL	L	40	−44	−46	50	11.76		IPL	L	40	−46	−46	50	12.46	
SPL	R	7	28	−72	42	14.36	4426	SPL	R	7	28	−72	42	15.45	4332
IPL	R	40	30	−52	−52	13.72		IPL	R	40	40	−52	52	13.30	
MOG	R	19	36	−88	10	11.58		MOG	R	19	36	−88	8	7.22	
MOG	L	19	−52	−60	−12	11.48	627	MOG	L	19	−52	−60	−12	11.55	480
MTG	R	37	56	−52	−12	12.46	724	MTG	R	37	56	−48	−10	13.04	689
IFG	R	9	52	8	32	11.22	1525	IFG	R	9	54	10	38	13.45	3371
IFG	L	9	−54	6	38	11.13	3393	IFG	L	9	−54	8	36	13.93	6039
PMC	L	6	−24	−8	60	11.02	1352	PMC	L	6	−26	−4	62	11.82	
PMC	R	6	32	6	64	10.08	1146	PMC	R	6	28	−4	64	11.74	1121
dACC	R	32	8	22	48	9.29	1145	dACC	R	32	8	22	48	11.73	1727
mSFG	L	8	−2	16	56	8.67		mSFG	L	8	−2	16	56	11.60	

Note: the activations were significant ($p < 0.05$, FWE-corrected). The statistics in the *t* column show the values at the peak coordinates. The cluster sizes are represented by k. L, left; R, right. BA, Brodmann's area; MNI, Montreal Neurological Institute; dACC, dorsal anterior cingulate cortex; IFG, inferior frontal gyrus; IPL, inferior parietal lobule; MOG, middle occipital gyrus; MTG, middle temporal gyrus; PFC, premotor cortex; PG, postcentral gyrus; SPL, superior parietal lobule.

(radical) to the tight subchunks (stroke) and shifting executive control for decomposing and rearranging the tight subchunks (Huang et al., 2015; Tang et al., 2016). However, no activation difference between the cuneus and MOG regions was found in the practice and test problems, likely indicating that problem solvers do not successfully find the TCD solution of the test problem in the early exploration stage. Previous studies have frequently demonstrated that the TCD solution produced greater deactivation of the cuneus and higher activation of the MOG than the LCD solution (Luo et al., 2006; Wu et al., 2013; Huang et al., 2015). Thus, the above results show the hierarchical differences in processing priorities for chunk decomposition and that once problem solvers' attention is biased toward the familiar solution, which has higher priority, it is difficult to shift their attention to alternative solutions with lower priority even though the former is unable to solve the problem.

Consistent with previous studies, the test problems that could be solved using the TCD solution recruited greater deactivation of the cuneus and greater activation of the bilateral IFG, MOG, PMC and SPL than the practice problems that could be solved using the LCD solution in the latter verification stage of both conditions. The cuneus is an early visual structure that is involved in basic visual processing. Its deactivation is likely related to the process in which automatically formed visual patterns need to be reinterpreted and higher visual areas become "disconnected" from early visual processing. In contrast, the higher visual cortex (MOG) likely serves to mentally manipulate and reconstruct automatically formed spatial representations (Luo et al., 2006; Wu et al., 2009). This result reveals that, compared with the LCD solution, the TCD solution requires inhibiting the automatic chunking effect to a greater extent and decomposing the perceptual chunks and rearranging the subchunks to greater degrees. Greater signal changes within the visual cortex as well as the IFG, PMC and SPL likely reflect hierarchical differences in processing demands for chunk decomposition, or else interference from the familiar but currently invalid LCD solution on the TCD solution, because the frontoparietal network has also been frequently found to be responsible for interference control (Jonides and Nee, 2006).

Moreover, the test problems in both conditions also recruited greater activation of the dACC than the practice problems in the latter verification stage rather than the early exploration stage. The ACC is an important brain region for error detection and conflict monitoring (Ebitz et al.,

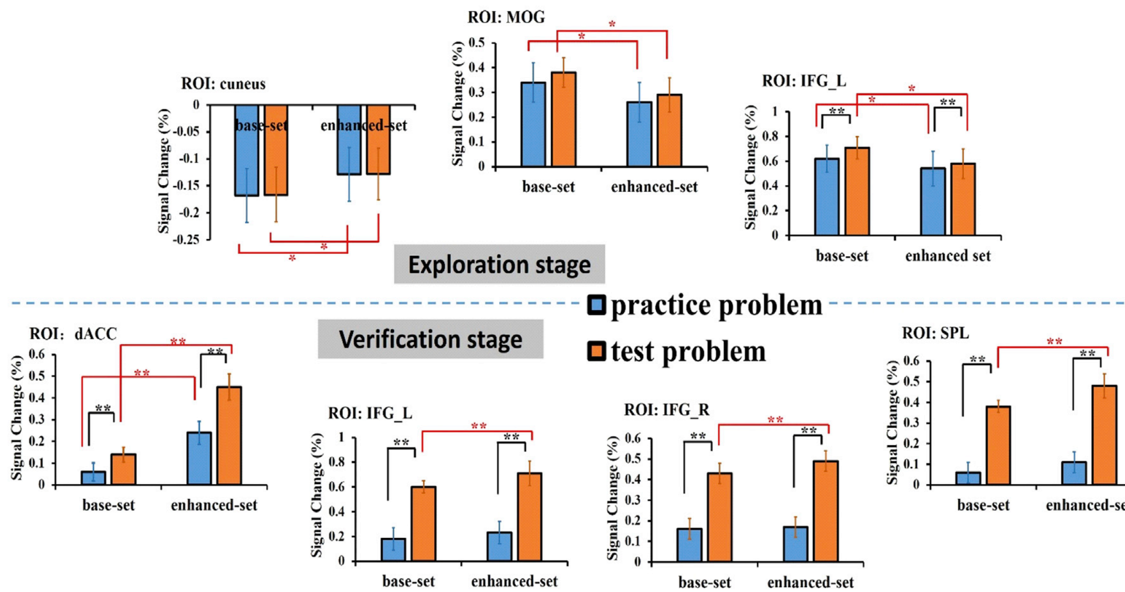

Fig. 4. ROI results. The percent signal changes within the ROIs in both the early exploration stage and latter verification stage of the chunk decomposition task across the base-set condition and the enhanced-set condition. L, left; and R, right. The error bars represent the 95% confidence intervals. The asterisks indicate significant differences between conditions (*$p < 0.05$, **$p < 0.001$).

2015; Heilbronner and Hayden, 2016; Shenhav et al., 2013). Particularly, it has been found to participate in the detection of cognitive conflicts between inappropriately old solutions and appropriately new solutions during insight problem solving (Mai et al., 2004; Qiu et al., 2006; Wu et al., 2013; Zhao et al., 2013). In the present study, its activation patterns likely suggest that participants did not think the familiar but currently invalid LCD solution was wrong in the free-searching stage, and experienced conflicts between the LCD and TCD solutions in the later-operating stage. Thus, problem solvers lack the motivation to reject the familiar but currently invalid solution, which in turn may result in continuous attention competition with the alternative solution. Clearly, it was difficult to win the unbalanced competition to explore and operate the alternative solutions. This finding largely explained why people persisted with the familiar but currently invalid solution and lost the ability to find alternative solutions.

Compared with the base-set condition, the practice problems in the enhanced-set condition recruited less activation of the cuneus, MOG and LIFG in the early exploration stage, which likely implies “cognitive inertness efforts”, i.e., people took less effort to explore a repeatedly reinforced and mechanized solution. Similarly, both the executive control regions and the visual cortex have shown extensive repetition suppression effects when confronted with a repetitive stimulus (Kim, 2017; Segaert et al., 2013), and the default mode network shows both greater activity and connectivity in more automated or mechanized information processing (Vatansever et al., 2017). After repeatedly solving several similar practice problems in a set, problem solvers can recruit less activity in the brain to explore the LCD solution path, gradually leading to mechanization. Surprisingly, the test problems in the enhanced-set condition also recruited less activation of the cuneus, MOG and IFG than the base-set condition, which likely implies participants treated the test problem as the practice problem and enjoyed the cognitive inertness following the repeatedly practiced solution. In other words, after repeated reinforcement of the familiar solution, people became less motivated to explore the alternative solution even though the repeatedly reinforced familiar solution was unable to solve the current problem.

During the latter verification stage, the test problems recruited greater activation of the dACC and IFG in the enhanced-set condition than in the base-set condition. As a region involved in reactive interference control (Irlbacher et al., 2014; Morishima et al., 2010), the dACC likely plays a role in monitoring conflicts between the familiar but currently invalid LCD solution and the alternative TCD solution. In contrast, the IFG is a critical region for proactive interference control in working memory (Braver, 2012; Irlbacher et al., 2014) and is likely to participate in resolving the interference from the familiar but currently invalid LCD solution on the alternative TCD solution. Greater activation of these two regions in the enhanced-set condition likely implies that the conflict between the two solutions become stronger after the advantaged but currently invalid LCD solution was repeatedly reinforced in the set, and problem solvers must utilize more executive control to resolve the unbalanced competition between the familiar but currently invalid solution, which has a higher priority, and the alternative solution, which has a lower priority. Consistently, IFG activation was frequently observed in studies examining prepotent semantic responses and demanding semantic tasks, particularly when people had to overcome interference by suppressing dominant responses (Beaty et al., 2017; Bourguignon et al., 2018; Friedman and Miyake, 2017; Krieger-Redwood et al., 2016). The overlap of findings between this study and previous studies likely further suggests a strong consensus for the neural mechanisms of overcoming interference.

In short, once there were external elements to retrieve the familiar solution in the problem situation, the familiar solution had a higher priority to be chosen and quickly became the center of attention. Even though the familiar solution was unable to solve the current problem, problem solvers lost the ability to reject it, creating the chance for continuous attention competition with the alternative solutions. Repeated reinforcement of the familiar solution likely further decreased the exploration efforts and increased the processing demands associated with alternative solutions by means of attentional bias and competition.

4.2. Why does the familiar but currently invalid solution interfere with the unfamiliar solution?

With the “help” of previous knowledge and experiences, participants become familiar with a solution to a particular problem, which carries a relatively lower cognitive load (Huang et al., 2015, 2018). Given that our brain is a cost-effective structure that tries to accomplish a task with the least cognitive effort (Kovács and Schweinberger, 2016; Renoult et al., 2016), it always gives higher priority to the familiar solution without considering its effectiveness. For example, chunk decomposition always begins at the loose level, and only if failure persists will the process continue to the tight level (Knoblich et al., 1999). After repeated practice of the loose level chunk decomposition, the processing demands are decreased, and the performance is improved (Chi and Snyder, 2011; Ollinger et al., 2008). Thus, people likely give a higher priority to the familiar LCD solution in solving a set of similar problems.

Once the familiar solution comes to mind first and becomes the center of attention, it is not easy to divert attention to alternative solutions, even though the familiar solution is unable to solve problems. As Bilalic et al. (2008) previously demonstrated in an eye-movement study, the eye gaze fixation times of chess players toward squares that were important for a familiar but currently invalid solution did not drop sharply but elicited roughly the same percentage of fixation time as the squares that were relevant to the optimal solution during the early and middle stages of a problem-solving process (Bilalić and Mcleod, 2014; Bilalic et al., 2008, 2010). Even when participants confronted 3 cases of this situation in a row, their attention to the target region containing the familiar but currently invalid solution was still maintained at close to 50 percent of the looking time (Sheridan and Reingold, 2013). The possible reason for this was that people did not think that the familiar solution, which was always successful, was unable to solve problems, since no activation of error detection-related regions was found in the early exploration stage of the test problem compared to that of the practice problem. Problem solvers lack the motivation to suppress the familiar but currently invalid LCD solution, which in turn may continuously compete for attention with alternative solutions throughout the entire problem-solving process.

4.3. Where does the familiar but currently invalid solution interfere with the unfamiliar solution?

In addition to the experimental studies of the mental set effect, interference from the familiar but currently invalid solution on the alternative solution is evident in real-life problem-solving behaviors, explaining the low success rate of creativity or insight events. With the "help" of previously acquired knowledge and experience, problem solvers give a higher priority to the conventional strategy to understand and solve problems that could not sufficiently solve creative insight problems; thus, they inevitably enter an impasse. To break impasses and obtain insight, people must reject the invalid conventional strategy and search for a novel strategy. However, people may lose the ability to reject the invalid conventional strategy, resulting in a chance for continuous attention competition with the novel strategy, which not only decreases the exploration tendency but also increases the operation difficulties of the latter. Thus, problem solvers have a hard time gaining insight even though they have sufficient knowledge of the problems. The findings of this study first answered the question as to why the success rate of insight is very low, from the perspective of interference between the initial but invalid strategy and the new strategy. The results also likely explain why people go into a blind alley without looking back in daily life.

The findings of this study also help to further clarify the neural mechanism of insight, particularly the process of breaking a mental set. In previous studies, effective cognitive control, as reflected by increased activation of the prefrontal cortex and anterior cingulate, seems to generally pave the way for insight solutions (Dietrich and Kanso, 2010; Kounios and Beeman, 2013; Shen et al., 2016; Sprugnoli et al., 2017). The ACC is regarded as an important brain region for conflict detection and performance monitoring; it is activated when problem solvers realize the failure of the conventional strategy or when a novel strategy conflicts with the conventional one (Luo and Niki, 2003; Luo et al., 2004; Mai et al., 2004; Wu et al., 2013; Zhao et al., 2013). In contrast, the prefrontal cortex (PFC) is believed to play a critical role in mediating inhibitory processes, and activation in this region is associated with preventing inappropriate responses and selecting appropriate responses (Luo and Niki, 2003; Luo et al., 2004; Zhao et al., 2013). This interpretation is in line with theories regarding attention control (Bissonette et al., 2013; Westendorff et al., 2016), in which problem solvers have to shift their attention from the inappropriate strategy to the appropriate one. However, creative insight problem solving does not simply shift attention from one strategy to another. There were hierarchical differences in the processing priority between several strategies. In particular, the invalid conventional strategy always had higher priority than the valid novel strategy. In addition to reactivating information associated with a novel strategy and inhibiting information associated with the conventional strategy, people also need to use executive control mechanisms to solve the unbalanced competition between the advantaged but invalid conventional strategy and the disadvantaged novel strategy, which is also mediated by the prefrontal cortex.

4.4. Conclusion

When people are confronted with a problem situation that is similar with one they have experienced, the familiar solution likely comes to mind first and hinders alternative solutions, even though the familiar solution is currently invalid to solve this problem successfully. Because people lost the ability to reject it, there is a chance for continuous attention competition with alternative solutions. Repeated reinforcement of the familiar solution likely further decreases the exploration efforts and increases the processing demands associated with alternative solutions, particularly in the form of attentional bias and competition. This neurocognitive mechanism widely explains the dilemma of creative problem solving and answer the question as to why problem solvers cannot change paths even though they know the conventional path is not working.

Conflicts of interest

The authors declare no competing financial interests.

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