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Probing the Cognitive Mechanism of Mental Representational Change During Chunk Decomposition: A Parametric fMRI Study

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Abstract

Chunk decomposition plays an important role in cognitive flexibility in particular with regards to representational change, which is critical for insight problem solving and creative thinking. In this study, we investigated the cognitive mechanism of decomposing Chinese character chunks through a parametric fMRI design. Our results from this parametric manipulation revealed widely distributed activations in frontal, parietal, and occipital cortex and negative activations in parietal and visual areas in response to chunk tightness during decomposition. To mentally manipulate the element of a given old chunk, superior parietal lobe appears to support element restructuring in a goal-directed way, whereas the negatively activated inferior parietal lobe may support preventing irrelevant objects from being attended. Moreover, determining alternative ways of restructuring requires a constellation of frontal areas in the cognitive control network, such as the right lateral prefrontal cortex in inhibiting the predominant chunk representations, the presupplementary motor area in initiating a transition of mental task set, and the inferior frontal junction in establishing task sets. In conclusion, this suggests that chunk decomposition reflects mental transformation of problem representation from an inappropriate state to a new one alongside with an evaluation of novel and insightful solutions by the caudate in the dorsal striatum.

Key words: caudate, Chinese character, inferior frontal junction, insight, presupplementary motor area

Introduction

The chunking mechanism, originally proposed by De Groot (de Groot and de Groot 1978) based on studies of problem solving and theorized by Chase and Simon (1973), has been established as one of the key mechanisms of human information processing in perception, learning, and cognition (McLean and Gregg 1967; Reitman and Rueter 1980; Klahr et al. 1983; Gobet and Simon 1998). The usage of chunks helps to overcome cognitive capacity limitations by integrating a number of pieces of information into a single unit. For example, chess masters are capable of recalling more chess pieces on a board than novices because they are able

to perceive well-known configurations of chess pieces as chunks, thus reducing cognitive load, rather than perceiving individual chessmen separately from each other (Chase and Simon 1973). Although chunking processes are applicable in most cases, it is often necessary to in turn decompose the inappropriate chunks into their component elements so that they can be reorganized in a new meaningful manner, such as, the invention of movable-type printing by decomposing the full page of text into their components (i.e., the single letters). This process is referred to as chunk decomposition in insight problem solving (Knoblich et al. 1999; Luo et al. 2006; Wu et al. 2013). Chunk decomposition means to restructure one's knowledge according to the changing environmental demands, which is a key feature of human cognitive flexibility and creativity (Scott 1962; Nijstad et al. 2010; De Dreu et al. 2011).

In the seminal study of Knoblich et al. (1999), chunk decomposition has been proposed as a mental transformation of problem representation, which would result in sudden insight during problem solving. In this regard, tight and loose chunks are defined on the basis of whether their components are meaningful perceptual units. For example, "VI" composed of "V" and "I" is a loose chunk while "V" composed of "\" and "/" is a tight chunk. The participant's task was to move one stick to resolve a false arithmetic equation of roman numbers such as "VI = VII + I." Results showed that chunk decomposition performance (e.g., solution rate) is inversely proportional to the tightness of the chunk. However, the limited number of variations in the matchstick roman arithmetic task does not allow investigating the neural mechanism underlying the accomplishment of chunk decomposition with brain imaging techniques. To resolve this issue, Luo and colleagues conducted a series of event-related potential (ERP) and fMRI studies of chunk decomposition using Chinese characters as experimental materials because simple and complex characters are perfect examples of tight and loose chunks, respectively (Luo et al. 2006; Tang et al. 2009; Wu et al. 2009, 2013). Simple Chinese characters are composed of strokes, which are the most basic components of a Chinese character and usually do not carry meaning on their own. Therefore, simple characters are tight chunks in the same way that "V" composed of "\" and "/" represents a tight chunk. Complex characters, which consist of radicals are loose chunks, because radicals convey information about the meaning or the pronunciation of a character. Studies that contrasted such stroke-level character decomposition with radical-level decomposition revealed a functional role of visual cortex (Luo et al. 2006; Wu et al. 2009), dorsal and ventral visual pathways (Wu et al. 2010), visual-spatial processing areas, and linguistic processing areas (Wu et al. 2013). The above-mentioned regions are relatively function-, or modality-specific, as these are regions involved in processing and memorizing visual-spatial and linguistic information. Conversely, the role of prefrontal cortex (PFC) and other related areas that mediate executive functioning and top–down control in chunk decomposition was less straightforward, and their functional role reveals to be less consistent. While lesion (Reverberi et al. 2005) and transcranial direct current stimulation (tDCS) (Chi and Snyder 2011) studies indicated that an enhanced ability of chunk decomposition could be associated with frontal damage or inhibition of the left anterior temporal lobes, brain imaging studies in normal adults found that the anterior cingulate cortex (ACC) area is selectively activated in the decomposition of tight, meaningful chunks but not for decomposing tight but meaningless chunks (Wu et al. 2013).

Our previous neuroimaging studies found activations of bilateral inferior (BA47), middle (BA9, BA6), and medial (BA8)

frontal gyrus in a direct contrast between insightful (tight) and noninsightful (loose) chunk decomposition (Luo et al. 2006; Wu et al. 2013). However, the results might have confounded the effects of chunk tightness (tight vs. loose) and creativity (insight vs. noninsight), because insightful or creative ways of thinking are usually much more difficult to achieve or to be successfully represented in one's mind relative to the noninsightful or ordinary solutions. This is probably due to a difference of chunk tightness. Such a confound between insight and difficulty could be critical for understanding the role of activations in areas such as the PFC whose function are known to be sensitive to both aspects of the task (Schneider and Chein 2003; Luo et al. 2004; see also Dietrich and Kanso 2010, for review). For example, Luo et al. (2004) found both ACC and lateral PFC involved in the processing of insight relative to noninsight events. However, further analysis clarified that lateral PFC was responsive primarily to item difficulty and showed higher levels of activation in the difficult relative to easy insight trials, whereas ACC selectively activated in all insight events (relative to noninsight events) regardless of difficulty. This implies that ACC and lateral PFC might be differentially involved in detecting and solving cognitive conflicts in insight, respectively. Therefore, a parametric design that can systematically manipulate the chunk tightness in chunk decomposition is essentially needed to elucidate the distinctive roles of executive function areas, which were reported to be involved in chunk decomposition, just as the n-back design that is important in separating the executive components of working memory by parametrically manipulating task difficulty (Smith et al. 1998).

To this end, in this study, we performed a parametric design that consists of a chunk decomposition task with 3 levels that systematically varied in their difficulties. The tightness of a chunk is based on objective and clear operational definitions, but not on the inferences from participants' subjective ratings, their response times, and solution rates. In the easy or loose chunk decomposition condition (Level 1), the to-be-removed parts are radicals that carry meanings on their own and are located separately from other parts of the character. In the intermediate or moderately tight chunk decomposition condition (Level 2), the to-be-removed parts are meaningless strokes that are spatially connected with other parts of the character. Finally, in the hard or tight chunk decomposition condition (Level 3), the to-be-removed parts are also meaningless strokes, but these strokes are tightly embedded in, or, depict an intersectional connection with other parts of the character (see Fig. 1A, for examples). On the dimension of chunk tightness, these 3 conditions varied parametrically. Therefore, the present design allows identifying the executive functional areas that reveal activations with a linear change with chunk tightness.

Chunk decomposition is a hypothetical mechanism of representational change, which explains how impasses can be broken in insight problem solving. During chunk decomposition, people need to override the existing representations of chunks and restructure their constituent elements in an alternative way by employing top–down cognitive control. Even though this explanation appears reasonable from a cognitive perspective, their underlying neural correlates are not specified. First, we hypothesize that, when considering the material characteristic of Chinese characters, the restructuring of old chunks should recruit visual and visual-spatial components in posterior visual and parietal cortex. Second, restructuring is determined by the cognitive control network in frontal areas, such as dorsolateral prefrontal cortex (DLPFC), presupplementary motor area (pre-SMA), dorsal premotor cortex (dPMC), inferior frontal junction (IFJ) (Cabeza and Nyberg 2000; Duncan and Owen 2000; Schneider and Chein
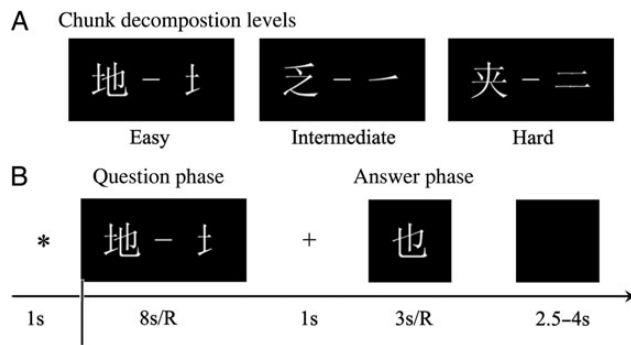
Figure 1. Experimental protocol. Subjects were asked to remove the stroke or radical from the characters on the left side. (A) Chunk decomposition levels. Three levels of chunk decomposition were determined by the spatial relationship between the target characters and their to-be-decomposed parts. (B) Timing of a sample trial. A trial started with a central asterisk presented for 1000 ms. During the subsequent question phase, the target character and the to-be-decomposed parts appear on the screen for up to 8000 ms (or until a response key was pressed). Subsequent to a fixation delay of 1000 ms, the answer character was presented for up to 3000 ms or until a response was collected. The final black screen during the inter-trial-interval varied randomly from 2500 to 4000 ms.

2003; Brass et al. 2005; Chein and Schneider 2005; Dosenbach et al. 2006). In the present study, participants were asked to mentally decompose chunks with the help of cues that are provided for each trial. Such cues prevent participants from searching for relevant solutions themselves and allow adopting the instructed way of restructuring. Participants had to break up existing chunks by overriding the prepotent representations through inhibition, which would be accomplished by right dorsolateral frontal gyrus (Evans 2003; Goel et al. 2009). Subsequent to restructuring, a new mental representation is supposed to become established, which should be marked by a change from one mental representation to another. This change should in turn activate brain regions consistently involved in set-shifting, such as the presupplementary motor area and the IFJ (Brass and von Cramon 2002; Brass et al. 2005; Derrfuss et al. 2005; Hikosaka and Isoda 2010). Finally, experiments used various methods, including eye-movement recordings (Knoblich et al. 2001), fMRI (Luo et al. 2006), ERPs (Tang et al. 2009; Wu et al. 2009), combined fMRI and ERP measurements (Wu et al. 2013), neuropsychological patient testings (Reverberi et al. 2005), and tDCS (Chi and Snyder 2011), have revealed converging evidence that characterizes the process of chunk decomposition as a specific type of insight problem solving. Insight problem solving usually comes with an unpredictable or novel solution. We thus suggest that the adoption and evaluation of alternative solutions may require procedural memory systems engaging in basal ganglia circuits (Barnes et al. 2005).

Materials and Methods

Participants

Twenty-two students (12 females; aged 19–26 years) participated in this study as paid volunteers. Participants were right-handed, had normal or corrected-to-normal vision, and reported no history of neurological or psychiatric disorders. Ethical approval was obtained from the institutional review board of Beijing Normal University Imaging Center for Brain Research and all participants gave written informed consent before the experiment.

Materials

As a logographic writing script, Chinese characters constitute a spatial rather than a phonological system. The orthographic structure makes Chinese characters to be ideal examples of perceptual chunks (Tan et al. 2001; Fu et al. 2002; Perfetti et al. 2005; Tan, Laird et al. 2005; Tan, Spinks et al. 2005; Luo et al. 2006). The chunk tightness of Chinese characters is defined by their basic identifiable component; compound characters combined by radicals are loose chunks and isolated characters formed by strokes are tight chunks. Luo et al. (2006) and Wu et al. (2013) have already employed loose and tight chunks of Chinese characters to investigate the neural mechanisms of chunk decomposition. The present study advanced their investigations by introducing 3 difficulty levels of chunk decomposition and the levels of chunking were classified based on the spatial relationship between to-be-removed parts and characters in an initial question phase (Fig. 1A). The 2 component parts were spatially separated in the easy condition (Level 1); to-be-removed parts were peripherally adjacent to and embedded in the characters as questions in the medium difficult (Level 2) and hard condition (Level 3), respectively. The characters used in the experiment were selected according to the above criteria and all Chinese characters selected as experimental materials are frequently used characters. Besides, the chunking task was introduced as a vigilance task, in which strokes and radicals were added to a character (Question Phase) to constitute a new character (Answer Phase). The 3 levels of the chunking task were categorized in a similar way.

Procedure

Participants were instructed to decompose strokes or radicals from existing characters to constitute a new character. Stimuli were presented via an LCD projector onto a mirror placed in front of the participant in the scanner (Fig. 1B). The characters and to-be-removed parts were connected by a minus sign, with characters in the left and to-be-removed parts in the right half of the display. Participants had 8 s to determine the target character and they were instructed to press a button as soon as they constructed the target character. Next, they had to decide whether their target character was the same as the character that appeared on the subsequent screen within 3 s. The resting interval between trials was randomly jittered from 2.5 to 4 s. There were 30 trials for each level of the decomposition task and 30 trials with no requirement to remove radicals or strokes, with the latter serving as a baseline condition. In addition, 90 filler trials, which required chunking processes, served to keep participants' attention. All of the 210 trials were randomized in the 5 experimental sessions.

fMRI Data Acquisition and Analysis

All scanning was performed on a 3-Tesla Siemens TIM scanner using a standard radiofrequency head coil at the State Key Laboratory of Cognitive Neuroscience and Learning, Beijing Normal University. Whole-brain T_2*-weighted gradient-echo EPI images were acquired based on blood oxygenation level–dependent contrast. The imaging parameters were 30 axial slices, repetition time = 2000 ms, echo time = 30 ms, slice thickness = 4 mm, slice gap = 0.8 mm, interleaved slice acquisition, field of view = 200 mm × 200 mm (64 × 64 mesh), flip angle = 90°. There were 5 runs of 10 min each. High-resolution structural images were acquired using a T_1-weighted 3D gradient-echo pulse sequence (128 sagittal slices, repetition time = 2530 ms, echo time = 3.39 ms,

flip angle = 8°, voxel size = 1.33 × 1.33 × 1.33 mm, field of view = 256 mm × 256 mm).

Image preprocessing and statistical analysis were performed using SPM8 (Statistical Parametric Mapping; Wellcome Department of Cognitive Neurology, UCL, London, UK). The first 4 functional volumes of each run were discarded to avoid a potential T_1-equilibration effect and remaining images were corrected for slice acquisition timing. The images were then rigid-body motion corrected, co-registered with the corresponding T_1-weighted image, and spatially normalized into 3-mm isotropic voxels using the standard MNI T_1 brain. Finally, the normalized images were smoothed with an 8-mm full-width at half-maximum Gaussian kernel and high-pass filtered with a 128-s cutoff period.

In the first-level model, for each participant an event-related statistical model was composed of task effects, a mean and linear drift for each of the 5 runs and 6 motion parameters. Tasks effects were computed by creating a boxcar function for each event type with its respective response period, which was convolved with the canonical hemodynamic response function. Three decomposition events and a baseline event at the problem-solving phase were modeled as task conditions of interest. Incorrectly, solved trials at the problem-solving phases and all events at the solution judgment phase were modeled as separate regressors of noninterest. Except for task effects, a mean and linear drift for each of the 5 runs and 6 motion parameters were also included in the statistical model. At the second level, the contrast images of interest at the individual level were submitted to a one-way within-subjects ANOVA for all participants using a random-effect model. In order to detect changes in the hemodynamic response that exclusively can be ascribed to chunk decomposition, a t-contrast with linearly increasing weights {−3 −1 1 3} throughout the baseline and the 3 decomposition conditions was performed to look for linear increases in activation across the 4 experimental conditions. A positive activation would reveal a linear increase throughout the 3 conditions, whereas a negative activation then simply refers to a linear decrease as a function of the different condition. For the whole-brain exploratory search, the initial threshold of t-maps resulting from a one-way ANOVA was set to $P < 0.001$ (uncorrected) with a spatial extent of more than 50 voxels. No voxel-based correction was employed, but we adopted a cluster-level family wise error (FWE) correction in that only clusters significant at $P < 0.05$ FWE-corrected are reported.

Results

Behavioral Results

Overall behavioral performance (accuracy and mean reaction times) for the baseline and decomposition conditions are shown in Table 1. Repeated-measures analyses of variance (ANOVA) showed highly significant effects on both dependent variables: accuracy, $F_{3,63} = 29.28$, $P < 0.001$; response times, $F_{3,63} = 171.87$, $P < 0.001$. Pairwise comparisons (Bonferroni corrected)

Table 1 Behavioral performance (Mean ± SD)

Condition	Percentage correct	Reaction time (ms)
Baseline	97.42 ± 5.24	864.42 ± 194.26
Easy	96.97 ± 7.90	1222.02 ± 246.08
Intermediate	94.39 ± 7.08	1844.68 ± 408.18
Hard	86.21 ± 11.09	2765.27 ± 686.24

SD represents standard deviation.

demonstrated statistically significant differences in accuracy and response times for chunk tightness increments, that is, loose versus intermediate (accuracy, $P = 0.007$; response times, $P < 0.001$), and intermediate versus tight (accuracy, $P < 0.001$; response times, $P < 0.001$). The predicted difference in accuracy between baseline and loose chunk condition failed to reach statistical significance ($P = 0.525$) but the response time of baseline condition was significantly less than that of loose chunk condition ($P < 0.001$).

Brain Imaging Results

To assess the effect of chunk decomposition, fMRI data were entered in a random-effects analysis using a one-way within-subject ANOVA. A t-contrast with linearly increasing weights was used to reveal brain areas that showed linear parametric BOLD responses to increasing chunk tightness during decomposition. Positively significant parametric activations to increasing tightness (tight > intermediate > loose > baseline) were found in the right inferior frontal gyrus (BA44/47), bilateral inferior/middle frontal gyrus (BA9/46), bilateral middle/superior frontal gyrus (BA6), bilateral medial frontal gyrus (BA8), caudate, bilateral posterior parietal cortex (BA7/40), and bilateral superior occipital cortex (BA19) (Fig. 2A). To maintain consistency of anatomical terms, medial frontal gyrus (BA8) is referred to as presupplementary motor area (pre-SMA, Fig. 2C) and middle/superior frontal gyrus (BA6) is referred to as IFJ (Fig. 2B), corresponding to the terminology by Derrfuss et al. (2005) in a meta-analysis of task-switching and Stroop studies. Activations negatively associated with tightness (tight < intermediate < loose < baseline) were revealed in the posterior cingulate cortex (BA31/23), cuneus, precuneus, bilateral lingual gyrus, bilateral superior occipital gyrus (BA18/19), bilateral fusiform gyrus, bilateral middle superior temporal gyrus (BA21/22), bilateral angular gyrus (BA39), and bilateral supramarginal gyrus (SMG) (BA40) (Fig. 2A). Anatomical labeling in statistical maps of interest were reported by the xjView Toolbox for SPM (http://www.alivelearn.net/xjview) (Tables 2 and 3).

Discussion

Combining a chunk decomposition task with Chinese characters and a parametric approach of fMRI, we aimed to detect brain regions specifically involved in chunk decomposition. As to the fMRI result, we observed widely distributed positive activations in response to chunk tightness during decomposition in frontal, parietal, and occipital cortex and associated negative activations in parietal and visual areas. Specifically, the positive activation map included DLPFC, presupplementary motor area (pre-SMA), dPMC, IFJ, anterior insular cortex (AIC), caudate, and posterior parietal cortex (PPC). On the basis of the expected results, we sketched a preliminary model of chunk decomposition that defines the functional role played by each region. The model suggests that the decomposition of an existing chunk activates the right lateral PFC in order to inhibit the predominant chunk representations; the presupplementary motor area may then initiate a transition from the inappropriate mental task representation to a new one, while IFJ serves to establish a task set during or after the manipulation in the posterior parietal lobule, while being involved in the mental manipulation of the chunk components. Moreover, the caudate is, within this model, responsible for the selection and evaluation of the proposed solution.

Our behavioral analysis revealed significant effects, which showed that participants made significantly more errors when
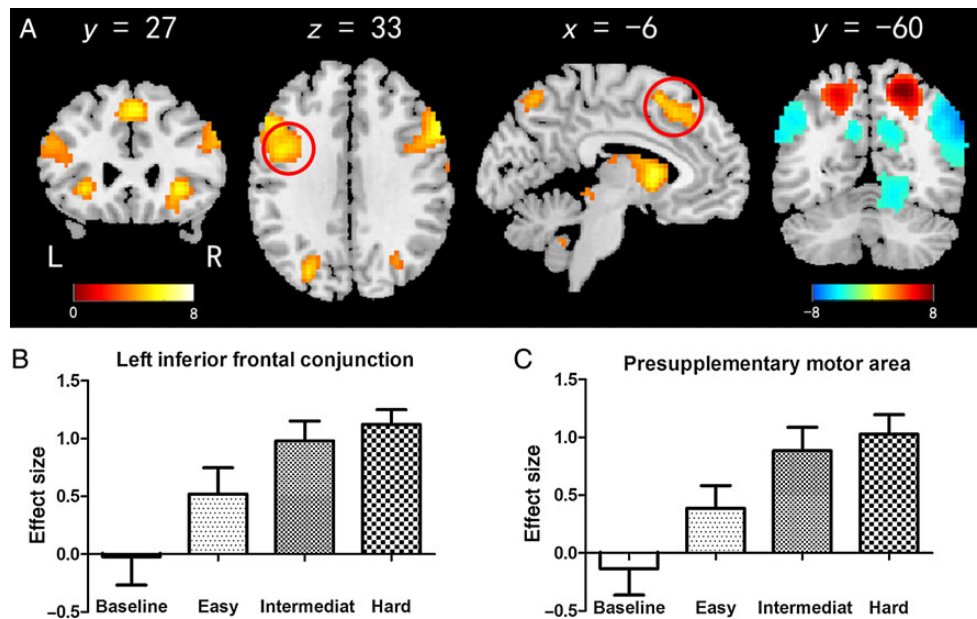
Figure 2. Overall linear effects of increasing chunk tightness. (A) Illustration of brain activations at several regions of interest derived from parametric effects of chunk tightness (MNI: $x = 51$, $y = 27$, $z = 27$; $x = -39$, $y = 6$, $z = 33$; $x = -6$, $y = 15$, $z = 54$; $x = 21$, $y = -60$, $z = 57$). (B and C) Effect sizes from left inferior frontal gyrus (IFG, $x = -39$, $y = 6$, $z = 33$) and presupplementary motor area (pre-SMA, $x = -6$, $y = 15$, $z = 54$), showing a linear trend across different levels of chunk tightness.

the tightness of characters increases and they spent more time to decompose tighter chunks, which replicated the results of previous reports (Knoblich et al. 1999; Luo et al. 2006; Wu et al. 2013). In the present study, participants had been cued how to decompose the chunk and would therefore follow a predefined task instruction, thus excluding the potential confounding factor of searching for variable solutions to break up chunks (as in Knoblich et al. 1999). Consequently, our results directly demonstrated the linear relationship between chunk tightness and response times.

Brain activations in visual cortex and parietal lobule have demonstrated its indispensable role in chunk decomposition. However, further evidence would be required to clearly specify their involvement in the respective cognitive processes. Luo et al. (2006) reported a deactivation of early visual cortex and a concurrent activation of higher visual cortex, whereas Wu et al. (2013) demonstrated that overcoming chunk tightness required visual-spatial processing in bilateral parietal lobes. In the current study, we administered a parametric design to address brain areas specifically involved in chunk decomposition. Although there were discrepancies between experimental paradigms, the present results corroborate main previous findings, especially those in posterior brain regions like parietal and visual cortices. Moreover, the present research furthers previous relevant studies by identifying brain areas that reveal significant negative activations to chunk tightness, for instance in bilateral inferior parietal cortex and superior temporal gyrus.

In consideration of the positive activation in superior parietal cortex and alongside with a negative activation in inferior parietal cortex, we suggest that the posterior parietal cortex may be involved in the coordination of chunk decomposition. The posterior parietal cortex may in turn support element restructuring of old chunks in an alternative way, which was modulated by the frontal cortex. Research in the field of attention has shown that superior parietal lobe (SPL) regions are involved in goal-directed attentional orienting, whereas inferior parietal lobe regions are involved in stimulus-driven attentional orienting

(Corbetta and Shulman 2002). Using transcranial magnetic stimulation techniques in a categorical syllogistic reasoning task, Tsujii et al. (2011) found that bilateral SPL (BA 7) stimulation impaired abstract and incongruent reasoning performance while congruent reasoning performance remained intact, which suggests that bilateral SPL may correspond to the analytic system of dual-process theory of reasoning. Moreover, patients with superior parietal damage have reliably shown deficits on the manipulation of information in working memory but not on rehearsal processes of working memory (Koenigs et al. 2009). We therefore suggest that SPL serves to mentally recombine chunk components during chunk decomposition and as such shows a parametric increase in activation with the gradual tightness of chunks.

The deactivation observed in bilateral ventral parietal gyri, which was more robust in the right hemisphere, was not addressed in previous relevant studies. Shulman and colleagues have found in a monitoring task that right SMG became deactivated when distracter objects appeared and re-activated once the target was detected. The authors propose that this deactivation was associated with filtering of irrelevant inputs from temporal–parietal junction (Shulman et al. 2007). For the same reason, Shulman et al. (2007) hypothesized that a larger degree of deactivation to distracters should be observable when a subsequent target was detected rather than missed, and brain responses in right ventral parietal gyrus confirmed this prediction. In the present experiment, participants were required to mentally restructure chunk components, and the deactivation observed in bilateral ventral parietal gyri may reflect filtering of distracting information in bottom-up attention networks (Corbetta and Shulman 2002). Furthermore, the complexity of mental transformations, which would correspond to the tightness of chunks, will increase the need to prevent irrelevant solutions from being attended. From our point of view, the suppression of stimulus-driven attentional orienting could best explain the parametric deactivation in bilateral ventral parietal gyri, especially in right SMG. In a similar vein, early visual cortex

Table 2 Brain areas positively correlated to chunk tightness

Anatomical areas	BA	Cluster size	Talairach coordinates			t value
			X	Y	Z	
R. precuneus	7	878	21	−56	55	8.38
R. inferior parietal lobule	40		45	−30	43	6.81
R. postcentral gyrus	2		59	−21	45	5.66
R. inferior frontal gyrus	44	413	50	10	22	7.62
R. middle frontal gyrus	46		53	33	23	4.74
R. middle frontal gyrus	46		45	36	15	4.62
R. subgyral	6	194	24	6	52	6.45
R. middle frontal gyrus	6		27	−4	44	6.24
L. precuneus	7	518	−18	−62	50	6.45
L. precuneus	19		−27	−71	34	5.01
L. inferior parietal lobule	40		−33	−33	38	4.57
R. caudate		328	6	9	2	6.36
L. caudate			−9	12	5	5.86
L. caudate			−9	1	17	4.57
L. middle frontal gyrus	6	510	−21	−3	47	6.21
L. medial frontal gyrus	8		0	34	40	6.15
L. superior frontal gyrus	6		−24	11	52	5.99
R. inferior frontal gyrus	47	110	33	26	−4	5.68
R. inferior frontal gyrus	47		27	23	−11	4.47
R. middle frontal gyrus	11		30	34	−17	4.22
L. inferior frontal gyrus	9	536	−48	1	25	5.57
L. middle frontal gyrus	9		−50	22	29	5.44
L. inferior frontal gyrus	46		−50	44	1	4.31

L, left; R, right; BA, Brodmann's area.

may also deactivate to inhibit visual distraction. Besides, the remaining negatively activated areas including the posterior cingulate cortex, Precuneus and bilateral parietal cortex are posterior parts of the default mode network, which are shown to be deactivated during goal-oriented activity (Buckner et al. 2008; Zhang and Chiang-shan 2012; Horn et al. 2014).

As hypothesized, chunk decomposition may include components that relate to the inhibition of inappropriate prepotent representations, the establishment of a new mental representation and a restructuration of the elements in an alternative way. In the following, we will discuss the functional roles of each activated area during the process of chunk decomposition.

In order to break up existing chunks, participants had to override prepotent representations through inhibition, which was accomplished by right lateral PFC, including inferior/middle frontal gyrus (BA9/46). According to the dual-process model of reasoning, right mid-dorsolateral prefrontal cortex (mid-DLPFC) serves to inhibit the dominant heuristic system in order to perform logic tasks with the analytic system when there is a conflict between the heuristic and the analytic system (Evans 2003). Goel et al. (2009) have also demonstrated that the right mid-DLPFC ($x = 53$, $y = 28$, $z = 23$ in Talairach coordinates) is more active when participants were required to overcome a heuristic system. As to right inferior frontal gyrus, our findings are highly consistent with its role in inhibitory control (Bunge et al. 2002; Aron et al. 2004; Buchsbaum et al. 2005). For instance, patient studies showed that lesions in right inferior frontal cortex lead to a deficit of response inhibition in a stop-signal task (Aron et al. 2003). Therefore, the right lateral PFC activity confirmed our hypothesis about how to override the existing representations.

Activation of the right lateral PFC may contribute to the suppression of semantic inference upon old chunks. However, inhibition does not guarantee the transition from an inappropriate mental task set to a novel one. To mentally break up a chunk, participants must know when and how to adopt an alternative routine to combine information. During the process of chunk decomposition, the transition was triggered not by exogenous cues but by the endogenous awareness of a context change, which is a defining feature of proactive switching (Hikosaka and Isoda 2010). Hikosaka and Isoda (2010) suggested that this particular function is specifically represented in the presupplementary motor area (pre-SMA). Rushworth et al. (2002) have shown that a larger BOLD signal was evoked in the pre-SMA region in response to cues that indicated to switch when compared with maintain response rules in subsequent trials. To further determine the functional role of the pre-SMA in task-switching, repetitive transcranial magnetic stimulation pulses were administered to these regions and the stimulation disrupted performance only on switch trials. These results suggest that the pre-SMA generates switch-related signals whenever needed and thus enables participants to initiate an alternative way of combining information.

Subsequent to the relaxation of current constraints over existing chunks, we predicted that brain regions consistently involved in set-shifting should show greater activity in response to switching difficulty as introduced by the tightness of chunks. Among the activated brain regions, the IFJ, which is interpreted as a major neural component of the cognitive control network, was most often involved in the switching process (Brass and von Cramon 2002; Brass et al. 2005; Derrfuss et al. 2005). Derrfuss et al. (2005) conducted a meta-analysis on task-switching and Stroop studies and found that the IFJ was commonly activated in a within-subject investigation of these tasks. In task-switching paradigms, participants typically alternate between 2 different tasks, and in the Stroop task participants have to inhibit dominant but irrelevant task representations to implement

Table 3 Brain areas negatively correlated to chunk tightness

Anatomical areas	BA	Cluster size	Talairach coordinates			t value
			X	Y	Z	
L. postcentral gyrus	3	412	−50	−15	50	7.58
L. precentral gyrus	4		−36	−21	48	7.43
L. precentral gyrus	4		−36	−20	62	6.24
R. supramarginal gyrus	40	1120	59	−56	36	7.27
R. superior temporal gyrus	39		45	−51	30	6.04
R. supramarginal gyrus	40		62	−48	25	5.32
L. insula	13	654	−50	−22	20	6.77
L. precentral gyrus	6		−48	−2	8	6.07
L. inferior parietal lobule	40		−50	−31	24	4.87
R. culmen		349	18	−50	−13	6.42
R. lingual gyrus	19		15	−61	1	4.16
R. lingual gyrus	19		24	−73	−6	3.95
L. medial frontal gyrus	6	1709	−6	−3	50	6.12
L. cuneus	18		−12	−83	21	5.85
R. cuneus	18		12	−80	23	5.72
L. inferior parietal lobule	39	222	−50	−65	39	5.66
L. supramarginal gyrus	40		−56	−60	31	4.91
R. precentral gyrus	44	187	48	1	11	5.44
R. claustrum			27	9	11	4.30
R. insula	13		39	9	8	4.25
L. lingual gyrus	19	176	−18	−61	−2	4.67
L. lingual gyrus			−15	−76	−1	4.52

L, left; R, right; BA, Brodmann's area.

nondominant but relevant task representations. Considering the commonalities between task-switching paradigms and the Stroop task, the authors conclude that a conceptual cognitive process underlying the cognitive control paradigms is the update of task representations, which are associated with the IFJ. In the present study, the decomposition of tight relative to loose chunks requires the removal of unfamiliar elements in an unpredictable fashion, which would inevitably lead to a larger switching effort that scales with the number of attempts. Thus, the switching effort may reflect the gradual tightness of the chunk that needs to be decomposed and will also result in parametric activation of the IFJ in addition to the presupplementary motor area.

Of particular interests in the present study was a subcortical region, the caudate, which is connected to frontal lobe regions responsible for executive functions, such as the DLPFC, rostral anterior cingulate, inferior frontal gyri, and presupplementary motor area (Lehéricy et al. 2004; Postuma and Dagher 2006). We would speculate that the caudate plays an important role in the selection and evaluation of alternative solutions, which may be a key feature that differentiates insightful chunk decomposition from general cognitive tasks. Although caudate activity was not observed in common set-shifting tasks which mostly show activations in the cognitive control network, a study with Parkinson patients has demonstrated deficits in switching motor or cognitive behaviors (Cools et al. 2001). Monchi et al. (2006) have also shown that the caudate nucleus is particularly important in a set-shifting task when a novel rule needs to be established without indications. A reasonable inference could therefore be that the caudate was indispensable in set-shifting tasks only when a novel rule needed to be established. This is the case with chunk decomposition in that the unpredictability of how to decompose tighter chunks is proportional to the novelty of the solution. This would explain the parametric activation of the

caudate in response to chunk tightness as revealed here. In a recent study, we intended to further specify the feature of novelty in chunk decomposition (i.e., the contrast between novel vs. familiar ways of decomposition), which generally involved functional areas for procedural memory (caudate), for mental reward (substantia nigra), and for visual-spatial processing (Huang et al. 2015). Furthermore, Seger and Cincotta (2005) have found that activity in the head of the caudate is associated most strongly with feedback processing, which decreases across trials. In the present experiment, we did not provide feedback to participants but we presented them with correct solutions of how to decompose chunks they have never seen before. During chunk decomposition, participants had to reconstruct the elements in an alternative way, which reflects unusual or novel solutions to a problem, especially when insight is required.

We have tentatively discussed the specific role of the activated areas overlapped with the cognitive control network during chunk decomposition, but dPMC and insular areas were not covered in the present discussion. Note that, in the present study, the key idea for chunk decomposition was not generated by participants themselves but was defined beforehand. Although spontaneous idea generation is in principle important, it is not well suited for neuroimaging research especially for an event-related design, which requires clearly defined mental events and accurate onset times (Luo and Knoblich 2007). Therefore, the use of cues during chunk decomposition was employed in the present study, since a lack of the generative task component may be compensated by tight control of key cognitive components and reliable data extraction. Moreover, studies on self-generated chunk decomposition (Wu et al. 2009) confirmed the major observation made by the externally cued decomposition (Luo et al. 2006). Therefore, the results obtained from the externally cued chunk decomposition could also be partially applicable to variants of self-generated decomposition,

especially for cognitive control process, that were the major focus in this study.

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Notes

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