The Role of Chunk Tightness and Chunk Familiarity in Problem Solving: Evidence from ERPs and fMRI

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Abstract: Multiple factors of task difficulty keep problem solvers from finding the crucial thinking steps required to solve insight problems. In this study, we distinguished two difficulty factors, chunk familiarity and chunk tightness, and investigated their effects on chunk decomposition—a specific type of insight that depends on the process of breaking up perceptual patterns or chunks into elements so that they can be reorganized to form a new meaning. Subjects solved problems that required decomposing Chinese characters that differed in chunk familiarity and chunk tightness. Brain activity was recorded using the electroencephalogram and functional magnetic resonance imaging. The results showed that chunk familiarity could be overcome through an inhibition of familiar meanings, whereas overcoming chunk tightness required visual-spatial processing. Furthermore, chunk familiarity posed an additional difficulty when chunk tightness was high. This result demonstrates that the difficulty sources in a problem do not always simply add up. Rather, the difficulty of a problem can reside in the interaction of particular sources of difficulty. *Hum Brain Mapp* 34:1173–1186, 2013. © 2012 Wiley Periodicals, Inc.

Key words: insight problem solving; multiple difficulties; ERP; fMRI; inhibition; representation change

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INTRODUCTION

Previous research on insight in problem solving has focused on the question of whether specific cognitive processes need to be postulated in order to explain why some problems seem to be solved with a sudden flash of insight instead of a sequence of cognitive operations [Bowden, 1997; Glucksberg, 1962; Maier and Janzen, 1968; Ohlsson, 1984, 1992; Ormerod et al., 2002; Schooler et al., 1993; Smith and Kounios, 1996]. More recently, it has been proposed that in insight problem solving, people usually have to overcome multiple difficulty factors in a single thinking step [Kershaw and Ohlsson, 2004].

For example, it has been claimed that the nine-dot problem (connect nine dots arranged in a 3×3 square with exactly four straight lines without lifting the pen from the paper) is difficult to solve because it poses multiple obstacles to the solution, including constraints from interfering prior knowledge [Weisberg and Alba, 1981], perceptual factors [Chronicle et al., 2001], and processing factors during solution generation [MacGregor et al., 2001]. Accordingly, removing one obstacle is not enough to enable problem solvers to reach a solution to insight problems that are often thought to involve a “nonlinear” way of thinking.

The multiple difficulty hypothesis augments the standard theory of problem solving in which problem solving is conceived as taking a stepwise route through a well-defined problem space [Newell and Simon, 1972]. The additional processes required are best characterized as more or less fundamental changes to the initial representation of a problem that problem solvers generate when they first encode the problem [Ohlsson, 1992, 2011]. Many of these perceptual, memory, and monitoring processes may not be under conscious control [Schooler et al., 1993]. For instance, an overly narrow solution space requires relaxation of implicit constraints to be able to reformulate the goal [Knoblich et al., 1999; Oellinger et al., 2008; Reverberi et al., 2005] or overcoming one’s implicit prior knowledge of using tools [Adamson, 1952; Birch and Rabinowitz, 1951]. Solving geometric problems requires perceptual restructuring [Wertheimer, 1959] and coming up with new ideas involves retrieving knowledge elements that are only remotely associated with the problem statement [Bowden, 1997; Jung-Beeman et al., 2004; Kounios et al., 2006, 2008].

Thus, one crucial step for understanding problem solving is to identify the cognitive and neural processes that help problem solvers to change problem representations and to determine how different processes that affect problems representations interact with one another. This study aimed to identify the neural underpinnings of chunk decomposition [Knoblich et al., 1999; Luo et al., 2006; Wu et al., 2009], a particular process of representational change. This process is highly relevant for understanding problem solving research because it allows one to determine how changes originating in the perceptual system

affect conceptual processes that assign a new meaning to problem elements.

TWO ASPECTS OF CHUNK DECOMPOSITION

Miller [1956] proposed the concept of chunking to refer to a process that groups or binds perceptual elements through association to improve the efficiency of information processing. The newer ACT-R framework distinguishes between two types of associations in a chunk. The first type is the connection between the different elements of a chunk and the second type is the association between the chunk and the situation as represented in the perceptual system [Anderson et al., 2004, 2007]. Accordingly, chunk decomposition refers to a process of breaking up chunks into their elements to make them available for reorganizing them in a different manner. In the context of problem solving, the shift in meaning introduced by the reorganization of perceptual elements can open up new possibilities to solve problems that seem impossible to solve [Knoblich et al., 1999, 2001; Ohlsson, 1984, 1992].

Although previous studies have treated chunk decomposition as one process, there are actually two different difficulty factors that need to be overcome in chunk decomposition. The first source of difficulty, chunk tightness, varies depending on whether the components in a chunk are loosely or tightly grouped. In “loose chunks,” the perceptual subcomponents of the chunk are meaningful themselves or there is easy access to these subparts (like the letters “T” and “O” in the string “TO”). In contrast, the components in “tight chunks” are not meaningful themselves (like the strokes “/” and “\” in the letter “X”). Previous research showed that tight chunks can pose an insurmountable obstacle to problem solving, whereas loose chunks are easily decomposed [Knoblich et al., 1999, 2001].

The second difficulty factor is chunk familiarity caused by more or less intimate knowledge of chunks. High familiarity with the mapping between particular perceptual patterns and particular meanings is likely to increase the difficulty of the chunk decomposition process because the components of highly familiar chunks are more closely associated with each other than the components of less familiar chunks.

A Chinese character decomposition task was used to separate these two difficulty sources and to study their interaction because it meets the special requirements of brain imaging research, especially the large number of instances of each problem type that are needed to reliably identify the different brain systems participating in insight [Luo and Knoblich, 2007; Luo et al., 2006]. In this task, people are asked to remove parts of a Chinese character so that the remaining part forms another meaningful Chinese character. Chinese “characters” are composed of “radicals,” which in turn are composed of “strokes.” Radicals always carry some linguistic or semantic information and have obvious nonoverlapping visual patterns, whereas

Figure 1.

Illustration of character decomposition at the radical level and at the stroke level. Loose characters were decomposed at the radical level and tight characters were decomposed at the stroke level. The to-be-removed part (radical or stroke) is depicted in the right grid in the leftmost column (Question). The meaning of the characters is indicated by the English terms in brackets. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

strokes are basic elements and have considerably less meaning than radicals.

Character decomposition at the radical level should be relatively easy (Fig. 1). For example, the components “亻” and “言” in the character “信” form independent visual patterns with specific meanings so that they could be regarded as meaningful subchunks. In contrast, the strokes in the character “四” are tightly embedded in the holistic visual pattern and are not meaningful on their own. We will refer to characters that can be decomposed at the radical level as loose chunks and to characters that need to be decomposed at the stroke level as tight chunks. Previous studies confirmed that Chinese characters forming tight chunks are harder to decompose than Chinese characters that form loose chunks [Luo et al., 2006; Wu et al., 2009].

In contrast to a previous fMRI study addressing processes of chunk decomposition that had confounded processes of problem encoding and processes of chunk decomposition [Luo et al., 2006], the current study clearly separated problem encoding and chunk decomposition in a fully crossed design of chunk familiarity and chunk tightness (familiar-tight, familiar-loose, unfamiliar-tight, and unfamiliar-loose). Problem encoding was separated from chunk decomposition by asking participants to first decide whether the original character was real. This question can only be answered after a character has been fully encoded but it does not require chunk decomposition. Only after this judgment was given, participants were asked whether removal of a component of a character produced another valid character. To provide this judgment, chunk decomposition was required. Thus, the present task isolated the restructuring that is critical to solve insight problems where a perceptual change leads to a change in the meaning of one or more problem components. Furthermore, the same design was used to collect event-related potentials as well as fMRI data. Thus, we combined the advantages of both measures, accurate timing and accurate localization of brain functions, to identify the neural networks that allow problem solvers to break up tight groupings with familiar meanings during chunk decomposition.

PREDICTIONS

Based on the hypothesis of Kershaw and Ohlsson [2004] that multiple difficulties combined together to affect the problem-solving process, we expected that distinct mental operations would be applied when resolving the two different sources of difficulty, chunk familiarity and chunk tightness, in the present task. Following the standard assumption that as the difficulty of insight problem-solving processes changes, the activation in the brain networks would change to the extent that they are needed to overcome the difficulty [Jung-Beeman et al., 2004; Luo and Niki, 2003; Luo et al., 2004, 2006; Mai et al., 2004], we made the following predictions.

Familiar chunks should lead to a higher activation of task-unrelated information (such as phonetic or semantic information) than unfamiliar chunks. Effective inhibition of activation of such unrelated information is needed to enable participants to flexibly consider changes of the perceptual configuration of a character. Previous brain imaging research has associated cognitive inhibition with increased activation in prefrontal cortex [Collette et al., 2001; Jonides et al., 1998], in particular, in the inferior area [Aron et al., 2004; Swick et al., 2008]. Similarly, electroencephalogram (EEG) studies assumed that a frontally distributed anterior P3 (P3a) reflects executive inhibitory processes, such as inhibiting an improper response tendency [Dimoska et al., 2006] or inhibiting a previous task set to enable performance of a new task (e.g., a task switch from color processing to shape processing; Barceló et al., 2002). Thus, we predicted a larger P3a and a higher activation in prefrontal cortex for the decomposition of familiar chunks than for the decomposition of unfamiliar chunks.

The second crucial mental operation to overcome chunk tightness consists in successfully breaking up a holistic visual pattern into its component parts in order to rearrange it. Previous studies have indicated that such an operation may recruit a fronto-parietal network [Luo et al., 2006]. In brain imaging studies, activation in parietal areas is generally thought to reflect visual-spatial processing, including

Figure 2.

Example for the construction of pseudo-character from existing characters. Parts that were removed during the construction processes are illustrated in gray. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

spatial transformations [Harris et al., 2000] and mental rotation [Harris and Miniussi, 2003]. In EEG research, a late positive component (LPC) over parietal areas has been associated with perceptual reversals and perceptual reversals when perceiving bistable images. For instance, a larger LPC is evoked when participants spontaneously reverse their perception of the Necker cube [Isoglu-Alkac et al., 1998; Pitts et al., 2009; Strüder et al., 2001]. Thus, we predicted that the decomposition of tight chunks would lead to a larger activation in fronto-parietal network and to a larger parietal LPC than the decomposition of loose chunks.

Finally, we predicted an interaction between chunk familiarity and chunk tightness. In particular, the influence of chunk familiarity should depend on how tightly the to-be-decomposed chunks are grouped. This prediction is derived from previous findings that the components of loose chunks activate competing meanings in addition to the meaning of the chunk they are part of because they can form independent visual patterns that have their own meaning [Tan et al., 2001]. This could facilitate the decomposition process because it makes the interpretation of a chunk less stable. In tight chunks, the components of the chunk do not activate competing meanings. Thus, the interpretation of the whole chunk is very stable and should be harder to overcome in addition to the perceptual difficulties created by the tight perceptual grouping of the components.

MATERIALS AND METHODS

Participants

Sixteen students from the China Agricultural University (eight females; age range, 19–25 years) participated in this

study as paid volunteers. All participants were right handed, had normal or corrected-to-normal vision, and were free of any history of neurological or psychiatric problems. The participants were all accustomed to using pronunciation, rather than strokes, to input Chinese characters when using computers (stroke input could lead to a blurring of the distinction between tight chunks and loose chunks). All participants gave their written consent to participate in the experiment that was approved by the institutional review board of the Beijing Normal University Imaging Center for Brain Research. Data from two participants (one female) were not included in the analysis because of extensive head movements during fMRI recording.

Stimuli

Two hundred existing Chinese characters with two different chunk tightness levels (tight and loose) were used as material in the familiar-tight and familiar-loose conditions. In addition, 200 pseudo-Chinese characters were constructed from existing characters. This was achieved either through replacing radicals or adding additional strokes (see Fig. 2) and it was possible because Chinese characters constitute a spatial rather than a phonological orthographic system. The modification led to orthographically legal but unpronounceable pseudo-characters. The pseudo-characters matched the existing characters in structure and were used as material in the unfamiliar-tight and unfamiliar-loose conditions. The number of character strokes was comparable between familiar and unfamiliar conditions to equate perceptual complexity. The mean stroke numbers for the target character that needed to be decomposed, the parts that needed to be removed, and the

TABLE I. Summarization of mean stroke numbers for target character, the removed part, and the new generated character between familiar and unfamiliar conditions

	Loose chunk			Tight chunk		
	Target	Removed	New	Target	Removed	New
Familiar	11.61	3.09	8.52	5.83	1.7	4.13
Unfamiliar	11.99	3.06	8.93	5.73	1.5	4.23

new character resulting after chunk decomposition are summarized in Table I.

The study consisted of two consecutive sessions: an EEG session and an fMRI session. Of the two hundred existing characters and pseudo-characters, 120 existing characters (60 tight and 60 loose) and 120 pseudo-characters (60 tight and 60 loose) were randomly selected for the EEG session. The remaining 80 existing characters (40 tight and 40 loose) and 80 pseudo-characters (40 tight and 40 loose) were used in the fMRI session.

Procedure

The EEG session consisted of six blocks of 20 trials that lasted 7 min and 44 s each. The fMRI session consisted of four recording blocks of 7 min and 44 s. The experimental procedure for each recording block was identical in both sessions. Participants could rest as long as they wanted between experimental blocks.

The time course of each trial is illustrated in Figure 3a. Each trial started with a display of the character to be decomposed. The participants decided whether the charac-

ter was an existing character or not with a right or left key press. In this way, it was ensured that stimulus encoding was completed before the chunk decomposition phase so that brain activity recorded during this phase would likely not reflect encoding. Then the character and the to-be-removed part (radicals or strokes) were presented in the middle of the screen together for 3 s, with the character in the left grid and the to-be-removed part in the right grid (see Fig. 3a).

Participants were instructed to judge whether the remaining part of the left character was an existing character after eliminating the radicals or strokes (pressing a right or left key). To make this judgment, participants needed to decompose the target character. Red rectangles with dotted crosses were used to illustrate the exact location of the radicals or strokes in the original target character. The chunk decomposition phase and the answers generated by the participants under four experimental conditions are illustrated in Figure 3b.

Participants were required to focus their attention on the screen at all times. An additional 40 catch stimuli (about 9.1% of the total stimuli consisting of real characters or pseudo-characters that resulted in invalid characters after decomposition) served to keep participants focused on the task. Before the actual experiment, participants received some practice to familiarize them with the task and the procedure.

EEG Data Recording and Analysis

The continuous EEG was recorded from 64 scalp sites using Ag/AgCl electrodes mounted in an elastic cap (NeuroScan), with reference to the right mastoid and off-line algebraic re-reference to the average of left and right

Figure 3.

(a) Illustration of the experimental procedure. First a character in a red grid was presented and participants judged whether it was meaningful. After a cross-viewing delay of 2800 ms, the target character appeared again on the left pane, together with the to-be-removed part and the task was to judge whether or not the remaining part of the target corresponded to an existing

character. The character in gray on the right illustrates that the operation participants had to perform (of course, this was not presented to the participants). (b) Illustration of the chunk decomposition process required in the four different experimental conditions. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

mastoids. The vertical electrooculogram and horizontal electrooculogram were recorded from two pairs of electrodes, with one placed above and below the left eye, and another 10 mm from the outer canthi of each eye. All interelectrode impedances were maintained below 5 k Ω . The EEG and EOG were amplified using a 0.05- to 100-Hz bandpass and were continuously sampled at 500 Hz per channel for off-line analysis.

The EEG data were digitally filtered with a 35-Hz low-pass filter. The onset of the stimuli at the chunk decomposition phase was set as zero point, and the filtered EEG data were epoched into periods of 1,200 ms including a 200-ms prestimulus baseline for each experimental condition. Ocular artifacts were removed from the EEG data using a regressing procedural implemented in the Neuroscan software [Semlitsch et al., 1986]. Trials with artifacts due to eye blinks, amplifier clipping, and burst of electromyographic activity exceeding ± 100 μ V were excluded from averaging. The ERPs were then averaged separately for each experimental condition (familiar-tight, familiar-loose, unfamiliar-tight, and unfamiliar-loose) during chunk decomposition. Data from trials where a participant had not responded, responded incorrectly, or responded too slow (reaction time more than three standard deviations higher than the mean) were not included in the final analysis.

The P3a component was measured from the nine frontal sites (F3, Fz, F4, FC3, FCz, FC4, C3, Cz, and C4) in a 340- to 440-ms time window. For the LPC, mean amplitudes in the time window of 350–650 ms were measured at 18 electrodes from anterior to posterior: F3, Fz, F4, FC3, FCz, FC4, C3, Cz, C4, CP3, CPz, CP4, P3, Pz, P4, PO3, POz, and PO4. Latencies and amplitudes (baseline to peak) of the P3a and the LPC were analyzed using repeated measures analyses of variance (ANOVA). The ANOVA factors included Chunk familiarity (two levels: real character and pseudo-character) $\times$ Chunk tightness (two levels: tight chunk and loose chunk) $\times$ Electrode (three levels: left, midline, and right) $\times$ Anterior–Posterior (three levels for P3a [F, FC, and C] and six levels for LPC [F, FC, C, CP, P, and PO]). The Greenhouse-Geisser correction was used to compensate for sphericity violations.

fMRI Data Acquisition and Analysis

The MRI data were collected in the State Key Laboratory of Cognitive Neuroscience and Learning, Beijing Normal University. The fMRI scanning was performed on a 3.0-T magnetic resonance scanner (Siemens Version, Erlangen, Germany) using a standard radio frequency head coil. Participant's head was fixed with foam pads to minimize head movements during the entire experiment. For functional imaging, whole-brain coverage of 33 axial slices were acquired with T2*-weighted echo-planar imaging sequence based on blood oxygenation level dependent contrast (repetition time [TR] = 2,000 ms; echo time [TE] = 30 ms; image matrix = 64 $\times$ 64; slice thickness = 4 mm; field of view

[FOV] = 200 mm $\times$ 200 mm; voxel size = 3.1 mm $\times$ 3.1 mm $\times$ 4.0 mm; flip angle = 90°). In addition, a high-resolution T1-weighted anatomical scan was acquired with three-dimensional, gradient-echo pulse sequence for each participant (TR = 2,530 ms; TE = 3.39 ms; flip angle = 7°; FOV = 256 mm $\times$ 256 mm; voxel size = 1.33 $\times$ 1 $\times$ 1.33 mm; 128 sagittal slice with 1.33 mm thickness; base resolution = 256).

Image preprocessing and statistical analysis were performed using SPM5 software (<http://www.fil.ion.ucl.ac.uk/spm>). The first five functional EPI volumes of each session were discarded to allow for T1 stabilization. All remaining functional EPI images were slice-time corrected, realigned for head motion correction, spatially normalized into a standard EPI template in the Montreal Neurological Institute (MNI) space, resampled to create 3-mm isotropic voxels, and spatially smoothed by using a Gaussian filter with 8-mm full width half maximum (FWHM).

Given the experimental design of this study, four separate regressors were created and were time locked to the onset of decomposition phase (familiar-tight, familiar-loose, unfamiliar-tight, and unfamiliar-loose). Other regressors were modeled as not of interest conditions, including four regressors computed from the four separate types of event during the target character encoding phase and one regressor for error trials (inaccurate response trials and trials with response time exceeding three standard deviations) as well as catch trials (trials in which invalid characters resulted from the decomposition). In the end, nine regressors were convolved with the canonical hemodynamic response function in SPM5. Additionally, six realignment parameters were also included to account for movement-related variability. A high-pass filter with a cut-off frequency of 1/128 Hz was used to correct for low-frequency components and serial correlations correction by using an autoregressive AR (1) model.

Four parametric contrast images corresponding to the four experimental conditions (familiar-tight, familiar-loose, unfamiliar-tight, and unfamiliar-loose), relative to baseline, were generated at the individual level. They were submitted to a 2-by-2 full factorial ANOVA with the factors chunk familiarity (unfamiliar and familiar) and chunk tightness (loose and tight) at the second level for all participants using a random effect model. For the whole-brain exploratory search, the initial threshold was set to $P < 0.001$ (uncorrected) with more than 50 extent voxels. Only clusters significant at $P < 0.05$ corrected [Worsley et al., 1996] are reported unless otherwise specified. The same threshold is also used for visualization purposes unless otherwise specified. All MNI coordinates for the local maximum of each cluster were converted into Talairach coordinates.

RESULTS

Behavioral Results

Mean reaction times across the four conditions in the experiment are shown in Figure 4a. The reaction times

Figure 4.

Mean reaction times (a, in ms) and accuracy (b, in percent) for different levels of chunk familiarity and chunk tightness during the experiment; $N = 14$. Error bars indicate the standard error of means.

were entered into a 2-by-2 ANOVA with the within-subject factors chunk familiarity (unfamiliar vs. familiar) and chunk tightness (loose vs. tight). The main effects of chunk familiarity [$F(1,13) = 123.284$, $P < 0.001$] and chunk tightness [$F(1,13) = 273.155$, $P < 0.001$] as well as the interac-

tion between chunk familiarity and chunk tightness were highly significant [$F(1,13) = 69.911$, $P < 0.001$].

A further 2-by-2 ANOVA revealed a significant main effect of chunk familiarity on solution rates [$F(1,13) = 26.26$, $P < 0.001$]. There was also a significant effect of

Figure 5.

Brain areas are more active during the decomposition of tight chunks than during the decomposition of loose chunks. (a) The contrast showed higher activations for familiar-tight chunks in parietal areas bilaterally, frontal areas, and occipital areas ($N = 14$; $P < 0.05$, FVE corrected; voxels size > 50). (b) The contrast showed higher activations for unfamiliar-tight chunks in parietal areas bilat-

erally, frontal areas, and occipital areas ($N = 14$; $P < 0.05$, FVE corrected; voxels size > 50). The ERP analysis (wave forms at Pz and scalp topography) showed a higher positive deflection at central electrodes during the decomposition of familiar-tight chunks (c) and unfamiliar-tight chunks (d).

TABLE II. Brain areas that were more active during the decomposition of familiar-tight chunks than during the decomposition of familiar-loose chunks

Brain regions	BA	Cluster, K_E	MNI coordinates			Talairach coordinates			T value	Range
			X	Y	Z	X	Y	Z		
Right superior parietal lobule	7	1,291	27	-69	48	27	-65	47	12.39	1
Right superior parietal lobule	7		33	-54	51	33	-50	49	12.11	0
Right postcentral gyrus	40		51	-33	54	50	-29	51	10.61	1
Left inferior parietal lobule	40	1,132	-42	-42	48	-42	-38	46	11.71	0
Left superior parietal lobule	7		-24	-69	45	-24	-65	45	10.53	0
Left middle occipital gyrus	19		-33	-81	18	-33	-78	20	7.05	2
Left inferior temporal gyrus	37	319	-48	-66	-6	-48	-64	-2	10.32	2
Left fusiform gyrus	37		-45	-45	-18	-45	-44	-13	5.7	3
Right middle frontal gyrus	6	634	27	-3	54	27	0	50	10.18	3
Right inferior frontal gyrus	9		48	9	30	48	10	27	9.86	0
Right precentral gyrus	6		36	0	39	36	2	36	6.01	2
Left subgyral	6	278	-27	0	57	-27	3	52	9.83	2
Right middle occipital gyrus	19	293	51	-57	-9	50	-56	-5	9.48	1
Left pyramis		424	-21	-72	-45	-21	-72	-34	9.04	0
Right inferior semilunar lobule			24	-72	-48	24	-72	-37	7.76	0
Left pyramis			-6	-81	-33	-6	-80	-24	7.01	0
Left inferior frontal gyrus	9	311	-51	6	27	-50	7	25	8.56	1
Left inferior frontal gyrus	47	149	-33	18	-3	-33	17	-3	8.2	0
No gray matter found			-36	33	6	-36	32	4	5.54	
Right inferior frontal gyrus	47	164	33	24	-3	33	23	-4	8.05	3
Right medial frontal gyrus	6	235	6	15	51	6	17	46	7.89	0
Left lentiform nucleus		85	-15	-9	0	-15	-9	0	7.7	1
Right thalamus		88	12	-15	9	12	-14	9	7.19	0
Right lentiform nucleus			18	-3	-3	18	-3	-2	7.17	0

$N = 14$; $P < 0.05$, FWE corrected; voxels size > 50 .

chunk tightness [$F(1,13) = 32.992$, $P < 0.001$]. Moreover, the interaction between the two factors also reached significance [$F(1,13) = 18.966$, $P < 0.001$].

Brain Imaging Results

Chunk tightness

To assess the effect of chunk tightness, we determined from the fMRI data which brain areas were more activated during the decomposition of tight chunks than during the decomposition of loose chunks (familiar-tight minus familiar-loose, and unfamiliar-tight minus unfamiliar-loose; see Fig. 5a,b and Tables II and III). The areas that were more activated during the decomposition of tight chunks included bilateral superior and inferior parietal areas (BA7/40), middle occipital gyrus (BA19), an inferior frontal area (BA9/47), the left superior frontal gyrus (BA8), and the right medial and superior frontal gyrus (BA6/8).

ERP analyses revealed that the amplitude of the LPC was significantly larger when tight chunks were decomposed, resulting in a significant main effect of chunk tightness across the 18 electrodes selected for this analysis [$F(1,13) = 16.458$, $P < 0.001$]. This positive deflection in the ERP waveform was present between 350 and 650 ms after

stimulus presentation (Fig. 5c,d). There were no other significant differences in ERP components between the two conditions of interest.

Interaction between chunk familiarity and chunk tightness

Following up on the analysis of reaction times that revealed a significant interaction between chunk tightness and chunk familiarity, so that tight chunks were particularly difficult to decompose if they were familiar, we located brain regions sensitive to the interaction. The analysis revealed large activation differences in the anterior cingulate (Fig. 6a). Activation of this area was additionally investigated within a spherical region of interest (ROI; radius = 25 mm) centered in a local maxima coordinate of anterior cingulate cortex (ACC; $x = -2$, $y = 28$, $z = 31$, according to Botvinick et al., 1999) in combination with a small volume correction (SVC) for multiple nonindependent comparisons. The local maxima for the anterior cingulate was at [6, 28, 26], cluster $P = 0.007$, SVC corrected. In a further step, ROI analysis was applied to discern the activation patterns across the four conditions within those common regions. In this analysis, the activated regions generated by the second-level interaction contrast were specified as ROI. Parametric estimation values were

TABLE III. Brain areas that were more active during the decomposition of unfamiliar-tight chunks than during the decomposition of unfamiliar-loose chunks

Brain regions	BA	Cluster, K_E	MNI coordinates			Talairach coordinates			T value	Range
			X	Y	Z	X	Y	Z		
Right superior parietal lobule	7	1,621	33	-54	51	33	-50	49	13.55	0
Right postcentral gyrus	40		51	-33	54	50	-29	51	13.07	1
Right superior parietal lobule	7		27	-69	48	27	-65	47	12.83	1
Left inferior parietal lobule	40	1,473	-42	-42	48	-42	-38	46	12.94	0
Left superior parietal lobule	7		-21	-69	48	-21	-65	47	10.94	0
Left superior parietal lobule	7		-12	-75	57	-12	-70	56	9.64	2
Right middle frontal gyrus	6	896	27	-3	54	27	0	50	10.98	3
Right inferior frontal gyrus	9		48	9	30	48	10	27	10.86	0
Right precentral gyrus	6		36	0	39	36	2	36	8.82	2
Left inferior temporal gyrus	37	366	-48	-66	-6	-48	-64	-2	10.96	2
Right middle temporal gyrus	37	462	54	-57	-12	53	-56	-7	10.85	0
Right declive			36	-63	-30	36	-62	-22	6.11	0
Right inferior semilunar lobule		697	24	-72	-48	24	-72	-37	10.58	0
Left pyramis			-21	-72	-45	-21	-72	-34	10.04	0
Left pyramis			-6	-81	-33	-6	-80	-24	7.97	0
Left subgyral	6	652	-27	0	57	-27	3	52	9.70	2
Left inferior frontal gyrus	9		-51	6	27	-50	7	25	8.91	1
Left inferior frontal gyrus	9		-39	3	30	-39	4	27	8.59	0
Left insula	13	72	-30	18	-3	-30	17	-3	6.88	0
Left superior frontal gyrus	8	69	-6	12	54	-6	14	49	6.29	1
Right medial frontal gyrus	6		6	15	51	6	17	46	5.90	0
Right medial frontal gyrus	8		9	27	45	9	28	40	5.79	0
Right middle frontal gyrus	46	70	51	45	18	50	44	14	6.14	0
Right middle frontal gyrus	46		42	33	21	42	33	18	6.06	1

$N = 14$; $P < 0.05$, FWE corrected; voxels size > 50 .

extracted from this ROI using Marsbar, a toolbox that provides routines for SPM that allow one to perform ROI analyses (v0.41; <http://marsbar.sourceforge.net>; Brett et al., 2002). The results showed large activation differences between familiar and unfamiliar chunks during tight chunk decomposition but no differences between familiar

and unfamiliar chunks during loose chunk decomposition (Fig. 6b).

To further investigate the interaction, we analyzed the chunk familiarity effect at different chunk tightness levels (tight or loose). For tight chunk decomposition, we found strong activation in prefrontal areas (familiar-tight minus

Figure 6.

(a) The interaction between chunk familiarity (familiar vs. unfamiliar) and chunk tightness (tight vs. loose) showed activation in anterior cingulate cortex (TAL 6, 28, 26; $N = 14$; $P < 0.001$, uncorrected; cluster size: 46 voxels). (b) Extracted beta values

from this region showed the activation pattern between different levels of chunk familiarity and chunk tightness. Error bars indicate the standard error of means. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Figure 7.

(a) Regions that showed higher activation while decomposing familiar-tight chunks than decomposing unfamiliar-tight chunks. These regions included the anterior cingulate cortex (ACC) and bilateral inferior frontal gyrus. Activation was rendered onto the canonical T1-weighted brain image of SPM5 ($N = 14$; $P < 0.001$, uncorrected; voxels size > 50). (b) Activation observed in contrast of the famil-

iar-loose condition and the unfamiliar-loose condition ($N = 14$; $P < 0.001$, uncorrected; voxels size > 50). (c) ERPs in FCz during the decomposition of familiar-tight and unfamiliar-tight chunks. (d) ERPs in FCz during the decomposition of familiar-loose and unfamiliar-loose chunks. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

unfamiliar-tight; see Fig. 7a and Table IV), whereas for loose chunk decomposition (familiar-loose minus unfamiliar-loose; see Fig. 7b), we observed activation in right cin-

gulate cortex (BA32), right middle frontal gyrus (BA46), right superior frontal gyrus (BA6), left superior frontal gyrus (BA8), left middle frontal gyrus (BA9), left inferior

TABLE IV. Brain areas that were more active during the decomposition of familiar-tight chunks than during the decomposition of unfamiliar-tight chunks

Brain regions	BA	Cluster, K_E	MNI coordinates			Talairach coordinates			T value	Range
			X	Y	Z	X	Y	Z		
Right medial frontal gyrus	32	866	9	12	48	9	14	44	6.48	2
Right anterior cingulate	32		9	27	30	9	28	26	6.44	1
Right cingulate gyrus	32		3	18	45	3	20	40	6.37	0
Right insula	13	362	33	21	6	33	21	4	6.01	0
Right inferior frontal gyrus	47		36	15	-12	36	14	-11	4.51	0
Right middle frontal gyrus	46		42	12	21	42	13	19	4.33	5
Left inferior frontal gyrus	47	335	-36	18	-3	-36	17	-3	4.98	0
Left insula	13		-33	18	6	-33	18	5	4.93	1
Left insula	13		-39	12	9	-39	12	8	4.69	0

$N = 14$; $P < 0.001$, uncorrected; voxels size > 50 .

frontal gyrus (BA45), and left fusiform gyrus (BA37) when using a less stringent threshold ($P < 0.001$, uncorrected; voxel size > 5). The results of this analysis were consistent with the activations observed in the contrast between the familiar-tight and the unfamiliar-tight conditions.

The waveforms and scalp distribution of the ERPs obtained in the four experimental conditions are illustrated in Figure 7c. ERP analyses revealed that the amplitude of the P3a was significantly larger when familiar-tight chunks had to be decomposed than in all other conditions as indicated by a significant interaction across the nine anterior electrodes that were analyzed [$F(1,13) = 6.403$, $P < 0.05$]. There were no other significant effects in this analysis. There were also no significant differences involving familiarity in any other ERP components.

DISCUSSION

The results of this study confirmed our general prediction that chunk tightness and chunk familiarity are separable difficulty sources in problem solving that recruit different brain networks. Converging evidence from fMRI and ERPs showed that, in order to overcome chunk tightness, frontal and parietal areas needed to work together to provide a spatial updating of an existing perceptual representation. Converging evidence from fMRI and ERPs also supported the hypothesis that chunk familiarity was particularly difficult to overcome if meaning was expressed in tight perceptual configurations. Inhibitory frontal circuits as well as brain regions that have been associated with conflict resolution needed to work in concert to suppress familiar meanings in the service of connecting new meanings to new perceptual configurations. Below we will discuss these two main results in more detail and link them to earlier research on the brain bases of insight.

Chunk Tightness

Activation in the bilateral parietal lobe (BA7/40), including the superior and inferior parietal gyrus, was more pronounced when chunk tightness was tight (familiar-tight vs. familiar-loose). This result was in accordance with the ERP finding of a centro-parietally distributed LPC. Increased parietal activation and an increased parietal LPC are markers that characterize a variety of visual-spatial tasks, such as visual grouping and object representation [Shannon and Buckner, 2004; Xu and Chun, 2007], spatial working memory [Curtis, 2006], and mental rotation [Harris et al., 2000; Zacks et al., 2002]. Interestingly, an enhanced LPC was observed in the ERP that has been previously found to reflect perceptual categorization [Pitts et al., 2009]. Accordingly, previous studies have also emphasized that the parietal cortex plays an important role in changing problem representations [Anderson et al., 2008], representing an initial item in a new perspective

[Dehaene et al., 1999], or in manipulating symbols [Sohn et al., 2004].

Given these previous results, the parietal cortex activation in this study likely reflects a process in which participants mentally manipulated a previously encoded spatial representation. More specifically, to successfully decompose a tight chunk, participants needed to mentally remove particular strokes from the original character and to recombine the remaining parts in an alternative way. The activity of the parietal cortex likely reflects this process. In addition, prefrontal areas, including inferior and superior frontal gyrus, showed a stronger fMRI signal for tight chunk decomposition than for loose chunk decomposition. As in previous fMRI studies of insight problem solving, the frontal activations likely reflect cognitive control processes that are needed to overcome an old problem representation to generate a new one in order to achieve a particular goal [Luo et al., 2004, 2006; Mai et al., 2004].

Interaction Between Chunk Familiarity and Chunk Tightness

A significant interaction between chunk familiarity and chunk tightness in the behavioral result suggested that familiar-tight chunks posed particular difficulties for chunk decomposition. The fMRI analysis located the interaction effect between chunk familiarity and chunk tightness in the ACC. Simple effects at different tightness levels also suggested that the chunk familiarity effect was scaled by chunk tightness. When compared with the decomposition of unfamiliar chunks, decomposition of familiar chunks elicited greater activation in ACC, in particular when chunk tightness was high. Our preferred interpretation of this finding is that interference from familiar meaning is high in tight chunks because the components of the chunk do not constitute meaningful units [Knoblich et al., 1999; Luo et al., 2006]. In contrast, interference is lower in loose chunks because their meaningful components enable semantic access to new characters [Tan et al., 2001]. Thus, the ACC would be selectively involved in simultaneously addressing different obstacles to chunk decomposition, chunk familiarity, and chunk tightness. This interpretation is in line with theories postulating that ACC is an important brain region for conflict detection and performance monitoring when multiple potential responses or processes are activated [Botvinick et al., 1999; MacDonald et al., 2000]. ACC has also been shown to be involved in cognitive control and, in particular, in coordinating different cognitive processes so as to minimize the conflict between different responses [Botvinick et al., 2001; Dreher and Grafman, 2003].

It was further predicted that an inhibition mechanism was necessary to overcome chunk familiarity. The brain imaging results confirmed this prediction. Bilateral inferior frontal gyrus was more active during the decomposition of highly familiar chunks. Activation in this region has

previously been associated with preventing inappropriate responses [Aron and Poldrack, 2006; Aron et al., 2003; Brown et al., 2008; Picton et al., 2007]. The left inferior frontal gyrus is believed to play a critical role in mediating inhibitory process [Jonides et al., 1998]. The ERP results further supported the prediction that decomposing familiar chunks would involve inhibition of the familiar meaning. An increased P3a was observed during the decomposition of familiar chunks, especially if they were tightly grouped. Several previous studies found that, in wide variety of tasks, the P3a reflects the suppression of improper response that is not in accordance with task requirements [Dimoska et al., 2006; Goldstein et al., 2002; Kok et al., 2004; Smith et al., 2006].

Relation to Previous Brain Imaging Research on Insight

Although the current research addressed insight problem solving by studying how perceptual and conceptual processes work together in chunk decomposition, previous studies have focused on tasks that required participants to retrieve remote associates test (RAT; Jung-Beeman et al., 2004; Kounios et al., 2006, 2008) or to establish meaningful words by rearranging letters solving anagrams such as “oxmia = axiom” [Aziz-Zadeh et al., 2009]. The comparison of the current results with the results of previous studies provides us with an opportunity to discuss which brain activations are likely to generally characterize the solution of insight tasks and which brain activations are more likely to reflect specific processes of restructuring [Luo and Knoblich, 2007; Ohlsson, 1992].

The work on remote associations showed that insight solutions were preceded by diffuse attention and a right hemispheric asymmetry during the resting state [Kounios et al., 2008]. They were also preceded by increased activities in medial frontal cortex and in temporal cortex [Kounios et al., 2006]. Furthermore, it was proposed that two distinct cognitive components contribute to the insight solution in RAT items. The first process supposedly inhibits visual input and is reflected in an increased electrophysiological alpha activity over the parieto-occipital cortex. This process may serve to protect a fragile internal solution generation process from perceptual distracters. The second process is an intensive search for remote semantic associations and is reflected by an increased neural activity in the right anterior superior temporal gyrus (aSTG; Jung-Beeman et al., 2004). A recent work on anagrams conducted by Aziz-Zadeh et al. [2009] contrasted brain activations between insightful solutions and search solutions. The contrasts showed that using both hemispheres to conduct task-specific processing facilitated insight solutions during the initial moments of problem solving as reflected by a strong activation in Broca’s area and the right insula. Furthermore, it was found that meta-cognitive components such as focusing attention, monitoring, and executive control were essen-

tial to insight solutions, as reflected in extensive activation in the right PFC and the anterior cingulate.

Several specific brain activations reported in these previous studies are distinct from those we observed in the current study. It is important to note that in the studies described above, semantic retrieval or letter processing was crucial for the problem solution. This was likely reflected in a higher activation of language-related regions, such as the right aSTG or Broca’s area, bilaterally. In contrast, the crucial step required in this study was to restructure, which means to follow a perceptual change that involves a higher activation of parietal cortex. The differences suggest that there are indeed different perceptual and memory processes that can lead to a restructuring of a problem representation, which is the core claim of the representational change theory of insight problem solving by Ohlsson [1992, 2011].

However, there was also overlap between previous findings and the current study. First, effective cognitive control as reflected by increased activation of prefrontal cortex and anterior cingulate seems to generally pave the way for insight solutions [Aziz-Zadeh et al., 2009; Kounios et al., 2006; Luo and Knoblich, 2007]. Second, in all studies, there were task-specific control processes that were crucial for the solution of a particular insight problem. These included using both hemispheres to process incoming information [Aziz-Zadeh et al., 2009], inhibiting perceptual information [Jung-Beeman et al., 2004], or inhibiting semantic information that is inconsistent with task requirements (the current study).

This study used the decomposition of Chinese characters as a proxy for processes that occur when people experience sudden insights during problem solving. Previous behavioral evidence suggests that chunk decomposition may generally play an important role in reinterpreting the meaning of familiar perceptual configurations [Knoblich et al., 1999]. Therefore, it seems likely that similar brain networks as in the current study would be active whenever a problem requires the solver to perform spatial transformation in order to attribute a new meaning to an observed configuration, be it in geometry [Wertheimer, 1959], chess [Gobet et al., 2001], or in physical and biological models [Ohlsson, 2011].

CONCLUSION

In summary, this study adopted a Chinese character chunk decomposition task to investigate how two different difficulty factors, chunk tightness and chunk familiarity, affect the difficulty of chunk decomposition, a process that plays an important role for changing problem representations during insight problem solving. The results demonstrated that distinct brain networks are required to overcome chunk tightness and to overcome chunk familiarity. Perhaps the most important finding was that chunk decomposition was particularly challenging when tight perceptual groupings with a stable meaningful interpretation

had to be rearranged in order to generate a new perceptual pattern with a meaningful interpretation. It should be noted that many important scientific discoveries required scientists to overcome challenges of this type, be it the discovery of the benzene ring by Kekule [1872] or the discovery of the structure of DNA by Watson and Crick [1953].

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