Perceptual contributions to problem solving: Chunk decomposition of Chinese characters

Jing Luo [a,b,d,*], Kazuhisa Niki [c,d], Guenther Knoblich [e]

[a] *Key Laboratory of Mental Health, Institute of Psychology, Chinese Academy of Sciences, Da-tun Road 10#, Chao-Yang District, Beijing 100101, PR China*
[b] *Learning & Cognition Laboratory, Capital Normal University, Beijing, PR China*
[c] *Neuroscience Research Institute, National Institute of Advanced Industrial Science and Technology (AIST), Japan*
[d] *Brainscience and Education, RISTEX, JST, Japan*
[e] *Psychology Department, Rutgers University, USA*

Abstract

Chunk decomposition is the decomposing of familiar patterns into their component elements so that they can be regrouped in another meaningful manner. Such a regrouping is sometimes critically required in problem solving because during initial encoding the problem elements become automatically grouped into familiar chunks and this may prohibit finding a novel or efficient solution to problems [G. Knoblich, S. Ohlsson, H. Haider, D. Rhenius, Constraint relaxation and chunk decomposition in insight problem solving, J. Exp. Psychol. Learn. Mem. Cogn. 25 (1999) 1534–1556]. In order to elucidate the brain mechanisms underlying the process of chunk decomposition, we developed a task that uses Chinese character as materials. Chinese characters are ideal examples of perceptual chunks. They are composed of radicals, which in turn, are composed of strokes. Because radicals are meaningful chunks themselves but strokes are not meaningful in isolation, it is much easier to separate a character by its radicals than to separate a character by its strokes. By comparing the stroke-level decomposition and the radical-level decomposition, we observed activities in occipital, frontal, and parietal lobes. Most importantly, during the moment of chunk decomposition, we found the early visual cortex showed a tendency of negative activation whereas the higher visual cortex showed a tendency of positive activation. This suggests that in order to successfully decompose a chunk, the higher visual areas must at least partly be 'disconnected' from the input provided by early visual processing in order to allow simple features to be rearranged into a different perceptual chunk. We conclude that early perceptual processes can crucially affect thinking and problem solving.
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1. Introduction

Traditionally, problem solving has been conceived of as the stepwise application of mental operators [32]. In this framework the initial problem situation is transformed into the desired goal state through a sequence of inferences and this framework has been successful in explaining how people solve analytic problems. However, earlier work in the Gestalt tradition [8,19,53] suggests that problem solving does not always advance step by step. Rather, the phenomenon of sudden insight during problem solving suggests that changing the perceptual structure of a problem situation can also be crucial to successfully solve problems.

Newer cognitive theories of problem solving have extended Newell and Simon's problem space theory to also account for such phenomena (e.g., [37,29–31,34–36]). For instance Ohlsson [36] postulates that in some problems solvers have to change their representation of the problem in order to be successful. He proposed several processes for representational change. So far, experimental studies have mainly focused on constraint relaxation [13,16–18,37,11]. According to Ohlsson [36], past experience can lead to a biased goal representation of the problem that is overly constrained, thus preventing solution of the problem. In order to solve the problem one needs to relax these constraints, thereby extending the space of possible solutions. Take one of [15] famous problems as an example: How can

* Corresponding author. Tel.: +86 10 6487 0650; fax: +86 10 6487 6979.
  E-mail address: luoj@psych.ac.cn (J. Luo).

four equilateral triangles be formed using only six matchsticks? Most problem solvers unknowingly impose the constraint that the solution can be achieved in two-dimensional space. However, the problem can only be solved if solvers also consider solutions in three-dimensional space (the solution is to form a pyramid). According to Ohlsson [36] in order to overcome constraints, the problem solver needs to change the problem representation, more precisely the goal representation that defines the space of possible solutions.

1.1. Chunk decomposition

In this article, we will focus on "chunk decomposition", an equally important process of changing problem representations [17]. This process describes the decomposition of familiar patterns into their component elements so that they can be regrouped in another meaningful manner. Such a regrouping is required because during problem encoding problem elements become automatically grouped into familiar chunks. For instance, we perceive letters as a whole and not as being composed of single strokes. This can prevent the solution of a problem if the single elements that are part of a chunk need to be re-arranged in order to solve the problem.

So far, only few studies have addressed chunk decomposition. This is surprising because chunk decomposition allows one to study an important issue in problem solving that has already been raised by the Gestalt psychologist [8]: How can perceptual processes that encode and recode the elements of a problem situation help to find new meanings that lead to the solution of problems? The difficulty of chunk decomposition largely depends on how tight the elements of a chunk are grouped together. Chunks can be considered as "loose" if the components that form the chunk are meaningful in themselves. For instance it easy to decompose the loose perceptual chunk that forms the word "BIT" into its component letters and remove one letter to form the word "IT". The reason is that the letters "B", "I", and "T" remain meaningful chunks after the decomposition. In contrast, the components that make up the letters are not meaningful themselves. Thus letters are tight chunks and should be more difficult to decompose, e.g., transforming the word BIT to form the word "PIT" by removing the lower part of the letter "B". In the matchsticks arithmetic task of [17], problem solvers were given a false arithmetic statement, written using roman numerals (e.g., 'I', 'II' and 'IV'), operations ('+' and '−') and an equal sign ('=') and were required to transform the statement into true equation by moving only one stick from one position to another within the pattern. Researchers found it was easy for the participants to transform the equation 'VI = VII + I' to 'VII = VI + I', whereas it was difficult for them to transform the equation 'XI = III + III' to 'VI = III + III'. Because the 'VII' is a relative loose chunk that is composed of meaningful small chunks ('V' and 'I'), in contrast, 'X' and 'V' are much more tight chunks. Chunk decomposition not only means to simply break a chunk into components, but also means to efficiently separate, recognize, and regroup these essential components to meet the specific requirement of problem situation. For example, to efficiently transform the inequation of 'XI = III + III', not only should the 'X' be decomposed into '\'

and '/', but also should these component elements be regrouped as 'V'. Therefore, regrouping or reorganization is also the essential aspect of chunk decomposition.

1.2. Chunk decomposition in Chinese characters

Yet, the brain mechanisms underlying the process of chunk-decomposition are still unknown. In order to elucidate these processes we conducted a brain imaging study for which we developed a novel chunk-decomposition task that uses Japanese Kanji (Chinese character) as materials. The task requires rearranging parts of characters to create new characters.

As a logographic language system, Chinese characters are ideal examples of perceptual chunks [38,48,46,47,9,44]. They are composed of radicals, which in turn, are composed of strokes. Strokes are the most simple and basic components of a Chinese character. Usually, they do not carry meaning on their own. In contrast, radicals convey information about the meaning and pronunciation of the character. They usually consist of several strokes and can be thought of as sub-chunks of a character (Fig. 1a). Thus, radicals are meaningful chunks whereas strokes are not meaningful in isolation. According to the chunk decomposition hypothesis it should be much easier to separate a character by its radicals than to separate a character by its strokes, because particular strokes are tightly embedded in a perceptual chunk (Fig. 1b). In other words, the decomposition of characters into strokes will require a specific process that breaks the tight bond among strokes created by the perceptual chunk.

Participants were given tasks that always involved two valid characters, one on the left side of the display and the other on the right. They were asked remove a part of the right character and add it to the left character so that two new valid characters resulted after the move (Fig. 1c). This task arrangement, through restricting participants' way to separate and combine characters, forms a reasonable problem situation and contains well-defined initial states and goal states.

There were two conditions. In the tight chunk decomposition (TCD) condition, the problem could be solved only if participants decomposed the character into separate strokes and moved some of the resulting strokes from the right to the left character. In the loose chunk decomposition (LCD) condition it was sufficient to decompose the character into separate radicals and to move one of the resulting radicals to the left character. Pilot studies showed that problems requiring the decomposition of a tight chunk were much more difficult than problems requiring the decomposition of a loose chunk. The former were often not solved or took several minutes to solve whereas the latter were usually solved within 2–4 s.

The large differences in problem difficulty make it generally difficult to address the brain processes related to problem solving. In this study we used Luo and Niki's [25] methodology (see also [26,27]). This methodology provided the problem solvers a trigger (or a hint) to catalyze the puzzle solving process, after they had failed to solve the puzzle by themselves and got into a impasse state (but see [14], for a different methodology to study insight problem solving). This allowed us to accurately record neural activity correlated with cognitive insight within a time-
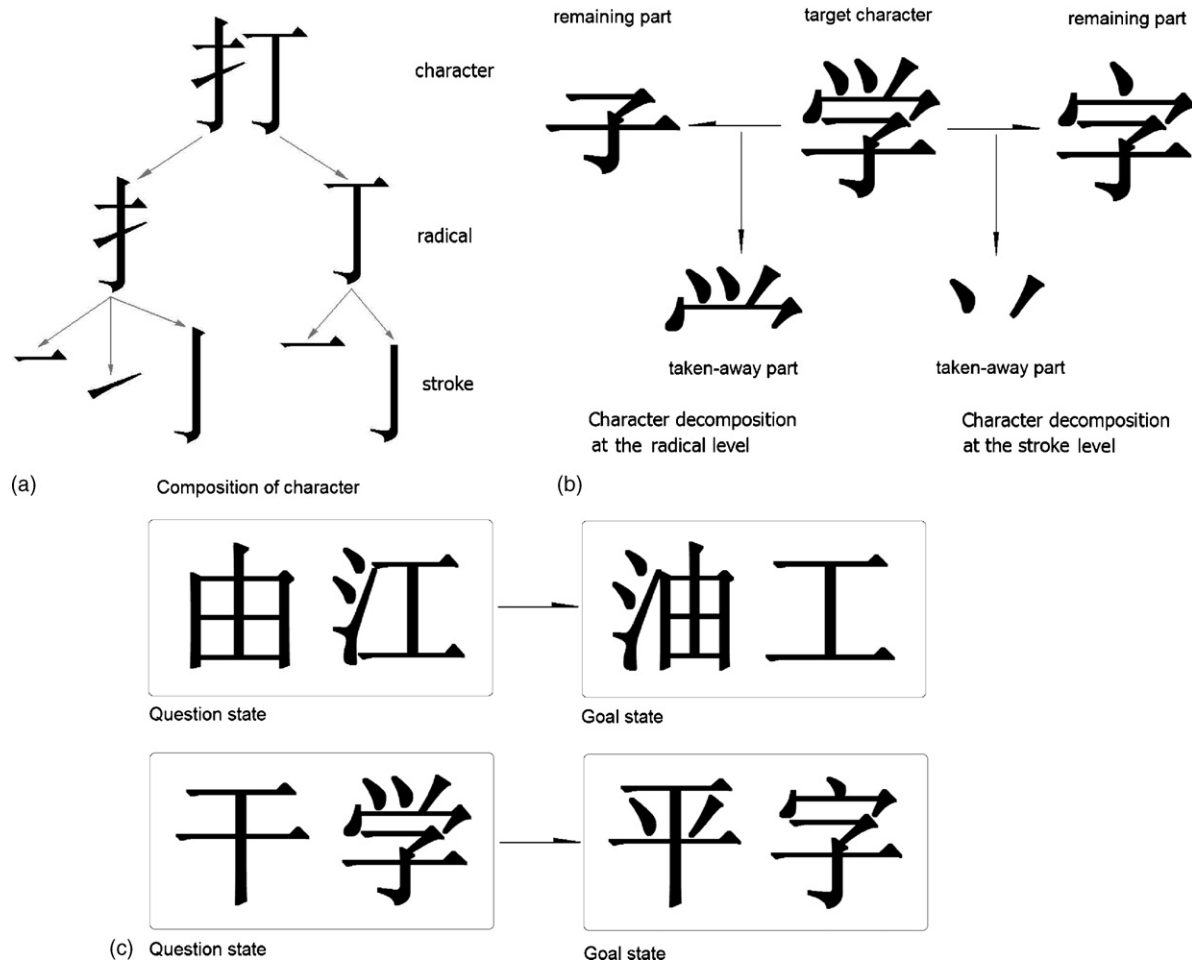
Fig. 1. (a) The composition of Chinese character. (b) Example of two kinds of character decomposition. If subjects are required to take something away from the target character with the remaining part to be a legal/real character, then to take the top radical away (left) will be easier than to take some strokes away (right) for the native readers. (c) The cognitive task of this study.

limited window for a large variety of puzzles or riddles that the subjects previously regarded as unsolved. Although it has the advantage that it provides very accurate onset times for the mental processes in question, this comes at a cost. Because one needs to make the assumption that solution hints trigger similar processes as internally generated solution attempts. Note, however, that many behavioral experiments addressing problem solving are based on exactly this assumption [16,37,52].

To summarize, we will address the neural correlates of chunk decomposition by comparing brain activities in the TCD and LCD condition that occur in response to a solution hint. LCD problems were usually solved before a solution hint is provided. Thus the solution hint simply confirmed an existing solution. Hardly any of the problems in the TCD condition were solved before the solution hint was provided. Rather, for most of them the solution hint provided the critical decomposition information needed to solve the problem. Comparing brain activations that occurred during the LCD hint phase and brain activation that occurred during the TCD hint phase allowed us to identify brain areas that are involved in chunk decomposition. In addition, the question presentation phases of the TCD and LCD conditions were also compared. It was predicted that, before the crucial hint

is given, the TCD and LCD conditions evoke comparable problem encoding and initial thinking process, but TCD trials might involve more attempts in vain to separate the target character.

1.3. Predictions

As stated above, we assume that chunk decomposition leads to changes in an existing problem representation. Presumably, these changes involve perceptual processes that recode the elements of a problem situation. Nevertheless, it is unlikely that perceptual processes alone can lead to the solution of a problem that requires tight chunks to be decomposed. Rather, additional executive processes are needed to guide the goal-directed regrouping of the elements. Thus, we hypothesize that perceptual processes in visual cortex as well as executive processes in prefrontal cortex are needed to solve chunk decomposition problems.

More specifically, we predict that brain activations in visual cortex should differ depending on the type of chunk that needs to be decomposed. Early visual processing is mainly concerned with the processing of basic visual features that are not necessarily meaningful (bottom of Fig. 2). However, as visual processing proceeds, these features are grouped into more and more com-
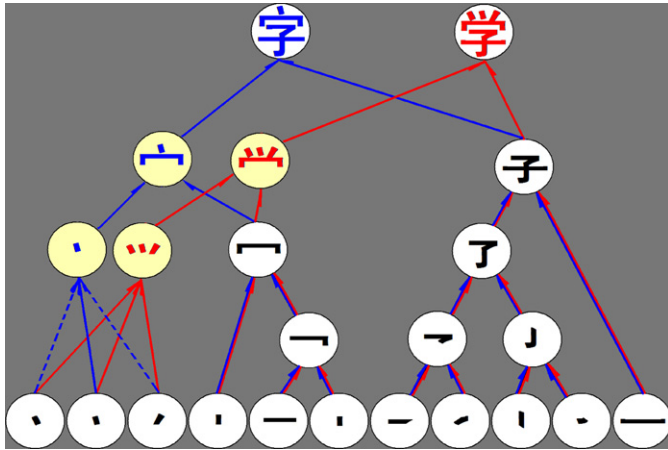
Fig. 2. The assumed hierarchical processing of a Chinese character.

plex patterns that are related to certain meanings (top of Fig. 2). Such functional differences have been firmly established in previous research [3–5,7,39–41,49,50]. In particular, Uchida et al. [51] compared the processing of valid characters and scrambled characters that had the same luminance, contrast, and retinotopical size. Early visual areas were involved in the processing of scrambled as well as valid Kanji characters. However, higher visual areas (left inferior occipital gyrus) were only active when valid characters were observed. What are the implications for chunk decomposition? When native speakers perceive a character the processing of basic components leads to an automatic activation of a perceptual chunk representing that character on a higher level of visual processing (red arrows and character in Fig. 2). However, in order to successfully decompose a chunk the higher visual areas must at least partly be 'disconnected' from the input provided by early visual processing in order to allow simple features to be rearranged into a different perceptual chunk (blue arrows and character in Fig. 2). In other words, the exact original features embedded in a character might be temporally neglected to get ride of the restriction of perceptual chunk, this process might be accompanied by the negative activation in early visual cortex and positive ones in higher visual cortex.

Regarding the executive processes contributing to chunk decomposition, we predict stronger activations in prefrontal cortex (PFC) for the TCD condition. The rationale for this prediction is that executive functions seem to be generally involved in the restructuring of problem representations. Previous studies have demonstrated anterior cingulate cortex (ACC) and left lateral PFC activation during restructuring [26,27]. Generally, these areas are related to detecting and resolving cognitive conflicts. In the domain of problem solving ACC activation seems to reflect the detection of a conflict between an existing interpretation of a problem and new evidence provided by a solution hint or a new idea. The PFC activation is likely to reflect resolution of this conflict by inhibiting problem elements that interfered with the solution so far. During chunk decomposition a cognitive conflict might arise when one encounters new information that conflicts with an existing interpretation of a visual pattern. Detection of this conflict, in turn, might lead to inhibition of the existing interpretation.

2. Methods

2.1. Participants

Fourteen healthy, right-handed undergraduate volunteers (aged from 20 to 27) recruited from University of Tsukuba participated in this experiment. All of the subjects gave their informed consent in accordance with the MRI ethics committee guidelines of the Neuroscience Research Institute, AIST.

2.2. Materials and procedure

The task was to separate and to recombine characters. Subjects were given two valid characters, one on the left side the other on the right, and they were required to move certain parts from the right character and to join them with the left character to produce two new valid characters (Fig. 1c). Character parts could not be dropped. Subjects were explicitly instructed that any part of the right-side character could be moved (radicals, strokes, or parts of strokes). Each trial started with a question presentation phase, followed by a hint presentation phase, and a solution presentation phase (Fig. 3). In the question (Q) phase, subjects were shown the two characters and they tried to solve the problem. They were asked to press the left key of the button box (which was attached to their right leg) with the right index finger, if they thought they had solved the problem and to press the right key with the right middle finger if they thought they could not solve the problem. During the hint (H) stage, the to-be-moved part of the right side character was highlighted in red and participants were asked to retry to solve the problem with the help of hint. They were required to respond even if they had already successfully solved the problem during the Q stage and the hint just confirmed their previous solution. As in the Q phase, they pressed the left or right key to indicate whether or not they had found the solution. During the final solution (S) stage, the solution was provided and subjects indicated whether they could comprehend the solution (left key: yes; right key: no). In the LCD condition, the problem could be solved moving a radical from the right to the left character. In the TCD condition, however, subjects had to move strokes between the two characters (see Fig. 4, for examples). There were 30 trials in each condition. All of the characters used in the study were highly familiar to the participants who are native Japanese speakers. All of the trials in two conditions were randomized in the whole experimental session. The resting interval between trials was 12 s. After the MRI scanning, participants went out of the MRI machine and were interviewed on how they solved each problem, how they thought about the hint and answer. Based on the reported information, together with participants' online yes/no key pressing, we identified the LCD items that were correctly solved in the Q phase and the TCD items correctly solved in the H phase as the critical trails to be focused on.

2.3. FMRI data acquisition

All scanning was performed on a 3.0-T MRI Scanner (GE 3T Signa) equipped with EPI capability. Eighteen axial slices (5.3 mm thick, interleaved) were prescribed to cover the whole brain. A T2* weighted gradient echo EPI was employed. The imaging parameters were TR = 2 s, TE = 30 ms, FA = 70°, FOV = 20 cm × 20 cm (64 × 64 mesh). To avoid head movement, participants wore a neck brace and were asked not to talk or move during scanning. Motion correction was also performed in a standard realign process in SPM2.

2.4. FMRI data analysis

The image data were analyzed using SPM2. Each subject's data were individually pre-processed (timeslice adjusted, realigned, normalized and smoothed), and the spatially pre-processed data were then estimated to establish a random-effects model. The TCD event was time-locked at the onset of hint presentation of the TCD condition trials in which subjects had not successfully solved the problem in the Q stage and successfully solved the problem with the help of the hint. The LCD event was time-locked at the onset of hint presentation of the LCD condition trials in which subjects had already successfully solved the problem during the Q stage. Although we focused on the TCD and LCD events in this study, other mental events evoked in the Q, H, or S phases were also defined in the model (through time-locking on the onset of these phases) to
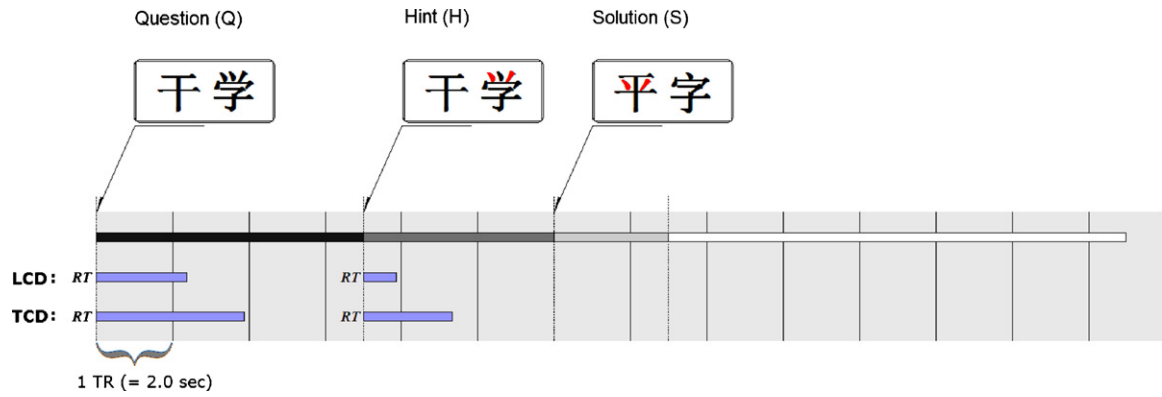
Fig. 3. The sequence of stimulus. The blue bars show the average response time (RT) of LCD and TCD trials in the Q and H phases.

prevent the brain responses corresponding to these mental events being falsely attributed to the key mental events we want to discuss. One participant's data were not included in the random effects model because he did not solve enough items in the TCD condition (less than ten). The 13 subjects included in the model had more than 10 trials of LCD items that were solved in the Q phase and 10 trials of TCD items that were solved in the H phase (number of trials in LCD event: mean = 26.92 trials, S.D. = 2.43; number of trials in TCD event: mean = 13.53 trials, S.D. = 3.09). The relatively low numbers of trials in TCD event were sufficient to detect the neural correlates of chunk decomposition, because the effect of insightful problem solving tends to be very robust in individual and group-level analyses. The correction threshold was set at $p < 0.05$ FEW- or FDR-corrected. Clusters of activations that involved less than 50 con-

tiguous voxels were discarded. Locations reported by SPM2 were converted into Talairach coordinates [45] by the transform specified in the mni2tal.m program [2]. These coordinates were used to determine the nearest gray matter (region and corresponding Brodmann area) using the Talairach Daemon program version 1.1 [21] with the maximum range of 7 mm. We used a masking method to distinguish between different patterns of activations observed in the contrast of TCD > LCD. First, the image that exhibited the common activation in both TCD and LCD and the image that exhibited unique activation in TCD but not in LCD were converted into masks, then these masks were applied in the one-sample t-contrast of TCD > LCD, respectively. This allowed us to sort the activations observed in TCD > LCD into two categories: (1) areas that were both positively activated in TCD and LCD and (2) areas positively activated in TCD but not in
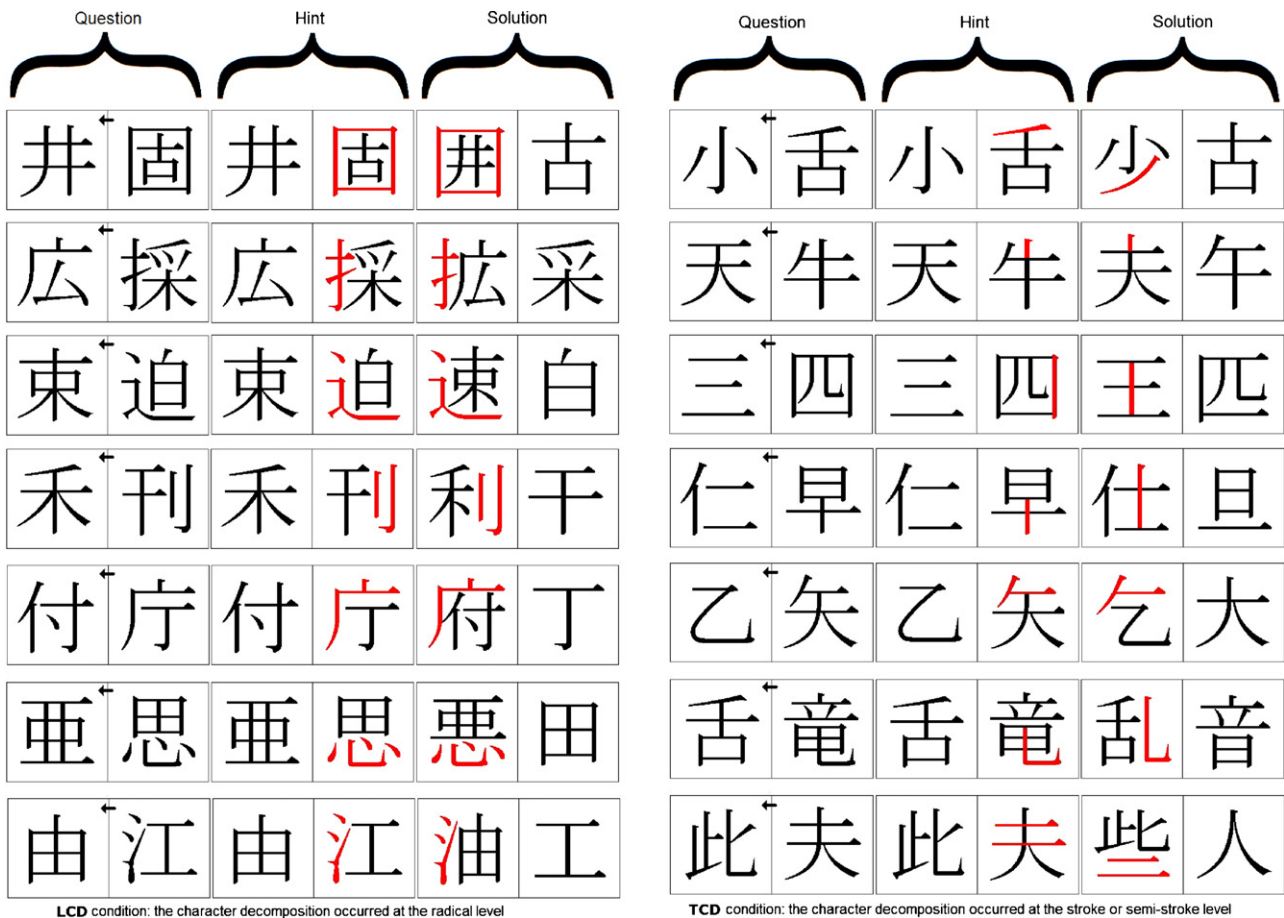

Fig. 4. Examples of the LCD and TCD items.

LCD. We also used similar masking method for the contrast of TCD < LCD to define (1) areas that were both negatively activated in TCD and LCD and (2), areas that were only negatively activated in TCD but not in LCD. The masks were thresholded at $p < 0.001$ (uncorrected).

3. Results

3.1. Behavioral results

In the LCD condition 89.76% of the items were solved during the question (Q) phase, 8.57% were solved during the hint (H) phase, and 1.67% were solved after the solution (S) was displayed. In the TCD condition only 26.67% of the items were solved during the Q phase, 45.12% of the items were solved with the help during the hint (H) phase and 28.23% were solved after the solution was displayed.

For the analysis of brain data, we only considered the LCD items that were successfully solved during the question phase (Q) and the TCD items solved during the hint phase (H). For the LCD items successfully solved during the question stage (Q), the average response time (RT) was 2.37 s (S.D. = 0.57). Confirming the solution during the hint stage took 0.86 s (S.D. = 0.16). For the TCD items it took participants 3.88 s (S.D. = 1.18) on average during the question phase (Q), to indicate that they could not immediately solve the problem. After the presentation of the solution hint it took them 2.32 s (S.D. = 0.48) to solve the problem. Solving the problem after receiving hint in the TCD condition took significantly longer than confirming the hint in the LCD condition, $t(12) = 11.07$; $p < 0.001$).

3.2. Imaging results

We compared the brain activations in the TCD condition and the LCD condition during the question presentation (Q) phase and hint presentation (H) phase respectively. As mentioned earlier, from the LCD condition we included only items that were successfully solved during the question stage (Q) and from the TCD condition we only included items that were successfully solved during the hint phase (H) and had not been solved during the question phase (Q). The contrasting of TCD and LCD condition in the Q phase showed that, relative to the Q phase of LCD, that of TCD was associated with activation located in: (1) right cingulate gyrus ($x, y, z = 8, -18, 27$; BA 23; $T = 8.38$; $Z = 4.72$) and left posterior cingulate ($x, y, z = 0, -26, 22$; BA 23; $T = 5.44$; $Z = 3.79$) (cluster level = 92); (2) right superior frontal gyrus ($x, y, z = 12, 22, 49$; BA 6; $T = 7.47$; $Z = 4.48$), left medial frontal gyrus ($x, y, z = -4, 18, 45$; BA 8; $T = 7.28$; $Z = 4.42$), and right cingulate gyrus ($x, y, z = 12, 30, 24$; BA 32; $T = 7.2$; $Z = 4.4$) (cluster level = 267); (3) left sub-gyral ($x, y, z = -28, -3, 55$; BA 6; $T = 6.94$; $Z = 4.32$) and left superior frontal gyrus ($x, y, z = -22, 14, 47$; BA 6; $T = 6.25$; $Z = 4.09$) (cluster level = 358) ($N = 13$, $p < 0.05$, FRD-corrected, random-effect analysis). Relative to the Q phase of TCD, the Q phase of LCD showed no super-threshold activation. Following, we focused on the comparison between TCD and LCD in the crucial hint (H) phase. We examined the activation in visual areas, prefrontal cortex, and parietal areas respectively.
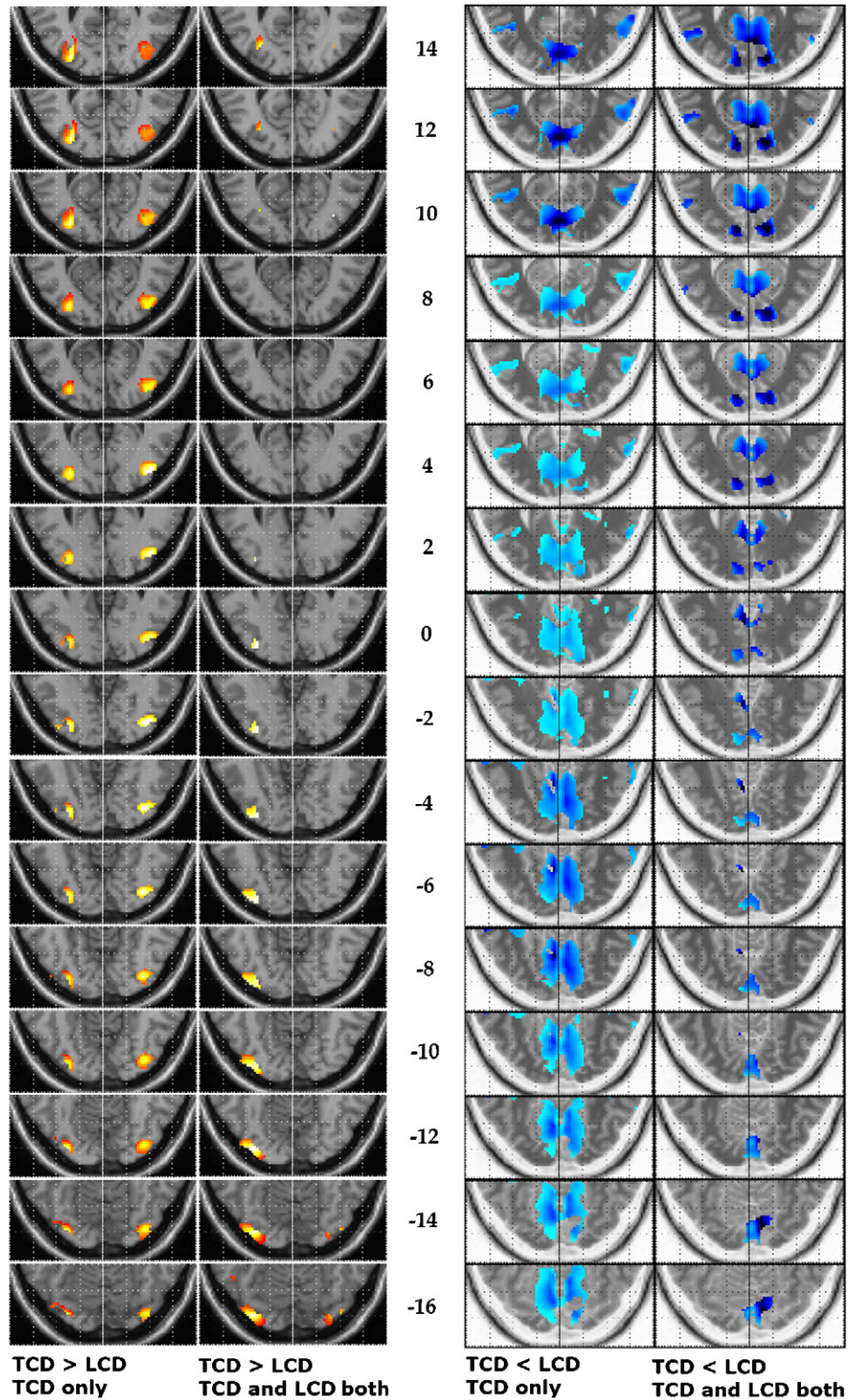
3.3. Activation in visual areas

First, we determined which visual areas showed stronger positive activation in the TCD condition than in the LCD condition. These areas included the left inferior occipital gyrus (BA 18) and the middle occipital gyrus bilaterally (BA 18 and 19, Fig. 5, the two left-side columns; Tables 1 and 2). Next we determined which areas showed positive activations in both TCD and LCD conditions. This was true for the activation observed in left inferior occipital gyrus (BA 18), but not for the activation observed in the relative superior location, i.e., the bilateral middle occipital gyrus (BA 18 and 19). Thus bilateral middle occipital gyri were selectively activated in the TCD condition but the left inferior occipital gyrus was not.

Furthermore, we determined which visual areas showed stronger negative activation in the TCD condition than in the LCD condition. These areas included the left and right medial cuneus (BA 18). In the next step we determined which areas showed negative activation in both of the TCD and LCD condition. In this contrast, we observed another medial cuneus (BA 18) area that was different from the one that was observed earlier (Tables 3 and 4). The above-mentioned results were obtained at the threshold of $p < 0.05$, FEW-corrected. A more detailed list of negative visual activities in TCD was obtained using a threshold of $p < 0.05$, FDR-corrected. This threshold is (generally speaking) more lenient than the threshold of $p < 0.05$, FEW-corrected, but still strict enough. The list of peak voxels within the cluster is given in Table 5 and the territories of negative activations were shown in the two right-side columns in Fig. 5. Bilateral cuneus (BA 18, 17) and lingual gyrus (BA 18, 17) were negatively activated in the moment of character decomposition.

3.4. Activation in prefrontal cortex

We determined which PFC areas showed stronger positive activation in the TCD condition than in the LCD condition. These areas included bilateral middle frontal gyrus, bilateral inferior frontal gyrus, and bilateral superior frontal gyrus (Fig. 6, Tables 1 and 2). Next we determined which areas showed common activations in the TCD and the LCD conditions. The majority of the PFC areas that were observed in the contrast of TCD minus LCD were also positively activated in the LCD condition (Fig. 6). For example, around the locations of left inferior frontal gyrus ($x, y, z = -48, 28, 20$) and the right middle frontal gyrus ($x, y, z = 46, 32, 20$) the territories of activation that were uniquely activated in TCD surround the common activations (Fig. 6b and e). Similarly, the common activation in medial PFC (around the location of $x, y, z = -2, 18, 54$) was extended to the more anterior part of superior frontal gyrus in the TCD condition (Fig. 6g). We also found two relatively small right inferior frontal locations that were only positively activated in TCD but not in LCD (Fig. 6h and i). We also try to determine which PFC areas showed stronger negative activation in the TCD condition than in the LCD condition, but were hardly any differences between them in this contrast.

Fig. 5. The transient visual activation in the moment chunk decomposition. "TCD only" means these areas were only positively (the two left-side columns) or negatively (the two right-side columns) activated in TCD trials. The "TCD and LCD both" means these areas were positively (the two left-side columns) or negatively (the two right-side columns) activated in both TCD and LCD trials.

Table 1
List of areas that showed stronger activation in TCD than in LCD, all of the reported areas were positively activated in both LCD and TCD

Cluster, K_E	Voxel					MNI coordinates			Talairach coordinates			Area	Range
	p(FEW-cor)	p(FDR-cor)	T	$\equiv Z$	p(unc)	x	y	z	x	y	z		
171	0.000	0.000	14.6	5.84	0.000	−28	−88	14	−28	−85	17	Left middle occipital gyrus, BA 19	3
	0.000	0.000	11.96	5.45	0.000	−26	−80	14	−26	−77	17	Left middle occipital gyrus, BA 19	5
167	0.000	0.000	11.33	5.34	0.000	46	32	20	46	32	17	Right middle frontal gyrus, BA 46	3
176	0.001	0.000	10.16	5.12	0.000	38	−86	6	38	−83	10	Right middle occipital gyrus, BA 19	1
	0.011	0.000	7.81	4.57	0.000	34	−86	−6	34	−84	−1	Right middle occipital gyrus, BA 18	3
80	0.003	0.000	9.30	4.94	0.000	−48	28	20	−48	28	17	Left inferior frontal gyrus, BA 46	1
	0.011	0.000	7.79	4.57	0.000	−42	28	26	−42	28	23	Left middle frontal gyrus, BA 46	5
483	0.003	0.000	9.04	4.88	0.000	−6	−26	−34	−6	−27	−27	Brain stem	
	0.003	0.000	9.04	4.88	0.000	−8	−14	−24	−8	−15	−19	Brain stem	
	0.006	0.000	8.38	4.72	0.000	4	−24	−32	4	−25	−26	Brain stem	
110	0.004	0.000	8.91	4.85	0.000	−46	40	6	−46	39	4	Left inferior frontal gyrus, BA 46	5
84	0.004	0.000	8.85	4.84	0.000	36	28	−12	36	27	−11	Right inferior frontal gyrus, BA 47	3
	0.029	0.000	6.87	4.30	0.000	38	34	−20	38	32	−18	Right inferior frontal gyrus, BA 47	7
62	0.004	0.000	8.72	4.81	0.000	−46	8	40	−46	10	36	Left middle frontal gyrus, BA 9	3
	0.009	0.000	7.99	4.62	0.000	−50	16	34	−50	17	30	Left middle frontal gyrus, BA 9	3
	0.025	0.000	7.03	4.35	0.000	−58	16	26	−57	17	23	Left inferior frontal gyrus, BA 9	3
56	0.011	0.000	7.83	4.58	0.000	−26	−2	50	−26	0	46	Left middle frontal gyrus, BA 6	1
183	0.011	0.000	7.79	4.57	0.000	−2	18	54	−2	20	49	Left superior frontal gyrus, BA 8	1
	0.026	0.000	6.98	4.33	0.000	8	28	40	8	29	35	Right medial frontal gyrus, BA 6	1

$N = 13$; $p < 0.05$ (FEW-corrected); $K_E > 50$. No GM means no gray matter is found in the $7 \times 7 \times 7$ mm cube range.

Table 2
List of areas that showed stronger activation in TCD than in LCD, these areas were positively activated in TCD but not in LCD

Cluster, K_E	Voxel					MNI coordinates			Talairach coordinates			Area	Range
	p(FEW-cor)	p(FDR-cor)	T	$\equiv Z$	p(unc)	x	y	z	x	y	z		
171	0.000	0.000	14.6	5.84	0.000	−28	−88	14	−28	−85	17	Left middle occipital gyrus, BA 19	3
	0.000	0.000	11.96	5.45	0.000	−26	−80	14	−26	−77	17	Left middle occipital gyrus, BA 19	5
167	0.000	0.000	11.33	5.34	0.000	46	32	20	46	32	17	Right middle frontal gyrus, BA 46	3
176	0.001	0.000	10.16	5.12	0.000	38	−86	6	38	−83	10	Right middle occipital gyrus, BA 19	1
	0.011	0.000	7.81	4.57	0.000	34	−86	−6	34	−84	−1	Right middle occipital gyrus, BA 18	3
80	0.003	0.000	9.30	4.94	0.000	−48	28	20	−48	28	17	Left inferior frontal gyrus, BA 46	1
	0.011	0.000	7.79	4.57	0.000	−42	28	26	−42	28	23	Left middle frontal gyrus, BA 46	5
483	0.003	0.000	9.04	4.88	0.000	−6	−26	−34	−6	−27	−27	Brain stem	
	0.003	0.000	9.04	4.88	0.000	−8	−14	−24	−8	−15	−19	Brain stem	
	0.006	0.000	8.38	4.72	0.000	4	−24	−32	4	−25	−26	Brain stem	
110	0.004	0.000	8.91	4.85	0.000	−46	40	6	−46	39	4	Left inferior frontal gyrus, BA 46	5
84	0.004	0.000	8.85	4.84	0.000	36	28	−12	36	27	−11	Right inferior frontal gyrus, BA 47	3
	0.029	0.000	6.87	4.30	0.000	38	34	−20	38	32	−18	Right inferior frontal gyrus, BA 47	7
62	0.004	0.000	8.72	4.81	0.000	−46	8	40	−46	10	36	Left middle frontal gyrus, BA 9	3
	0.009	0.000	7.99	4.62	0.000	−50	16	34	−50	17	30	Left middle frontal gyrus, BA 9	3
	0.025	0.000	7.03	4.35	0.000	−58	16	26	−57	17	23	Left inferior frontal gyrus, BA 9	3
56	0.011	0.000	7.83	4.58	0.000	−26	−2	50	−26	0	46	Left middle frontal gyrus, BA 6	1
183	0.011	0.000	7.79	4.57	0.000	−2	18	54	−2	20	49	Left superior frontal gyrus, BA 8	1
	0.026	0.000	6.98	4.33	0.000	8	28	40	8	29	35	Right medial frontal gyrus, BA 6	1

$N = 13$; $p < 0.05$ (FEW-corrected); $K_E > 50$.

Table 3
List of areas that showed stronger activation in LCD than in TCD, all of the areas were negatively activated in both LCD and TCD

Cluster, K_E	Voxel					MNI coordinates			Talairach coordinates			Area	Range
	p(FEW-cor)	p(FDR-cor)	T	$\equiv Z$	p(unc)	x	y	z	x	y	z		
	0.000	0.000	10.3	5.15	0.000	44	−18	40	44	−16	38	Right precentral gyrus, BA 4	1
77	0.010	0.001	6.89	4.30	0.000	38	−22	44	38	−19	41	Right precentral gyrus, BA 4	1
	0.022	0.001	6.19	4.07	0.000	46	−14	28	46	−12	26	No GM	
	0.007	0.001	7.18	4.39	0.000	52	−12	−4	51	−12	−3	Right superior temporal gyrus, BA 22	5
98	0.013	0.001	6.67	4.24	0.000	40	−16	12	40	−15	12	Right insula, BA 13	3
	0.045	0.001	5.60	3.86	0.000	56	−6	8	55	−5	8	Right precentral gyrus, BA 6	3
61	0.011	0.001	6.82	4.28	0.000	10	−22	44	10	−19	41	Right cingulate gyrus, BA 24	5
	0.036	0.001	5.79	3.93	0.000	12	−30	44	12	−27	42	Right cingulate gyrus, BA 31	3
70	0.011	0.001	6.82	4.28	0.000	16	−88	12	16	−85	15	Right cuneus, BA 18	1
57	0.015	0.001	6.56	4.20	0.000	2	−76	12	2	−73	15	Right cuneus, BA 18	3

$N = 13$; $p < 0.05$ (FEW-corrected); $K_E > 50$. No GM means no gray matter is found in the $7 \times 7 \times 7$ mm cube range.

Table 4
List of areas that showed stronger activation in LCD than in TCD, these areas were negatively activated in TCD but not in LCD

Cluster, K_E	Voxel					MNI coordinates			Talairach coordinates			Area	Range
	p(FEW-cor)	p(FDR-cor)	T	$\equiv Z$	p(unc)	x	y	z	x	y	z		
	0.000	0.000	14.35	5.8	0.000	64	−14	4	63	−13	4	Right superior temporal gyrus, BA 22	3
647	0.000	0.000	12.75	5.58	0.000	54	4	−14	53	3	−12	Right middle temporal gyrus, BA 21	1
	0.003	0.000	9.62	5.01	0.000	62	−6	8	61	−5	8	Right superior temporal gyrus, BA 22	1
70	0.001	0.000	11.2	5.32	0.000	46	−16	46	46	−13	43	Right precentral gyrus, BA 4	1
	0.005	0.000	9.14	4.90	0.000	−62	−10	0	−61	−10	0	Left superior temporal gyrus, BA 22	1
317	0.006	0.000	8.94	4.86	0.000	−60	−26	8	−59	−25	9	Left superior temporal gyrus, BA 41	5
	0.008	0.000	8.62	4.78	0.000	−60	−8	10	−59	−7	10	Left precentral gyrus, BA 43	1
	0.008	0.000	8.63	4.79	0.000	−48	−14	12	−48	−13	12	Left precentral gyrus, BA 13	1
95	0.019	0.000	7.70	4.54	0.000	−46	−14	26	−46	−12	25	No GM	
	0.027	0.000	7.34	4.44	0.000	−38	−18	34	−38	−16	32	No GM	
84	0.011	0.000	8.27	4.69	0.000	0	−84	12	0	−81	15	Left cuneus, BA 18	3
63	0.012	0.000	8.14	4.66	0.000	48	−12	24	48	−11	23	No GM	

$N = 13$; $p < 0.05$ (FEW-corrected); $K_E > 50$. No GM means no gray matter is found in the $7 \times 7 \times 7$ mm cube range.

Table 5
The list of negative visual activities in chunk decomposition

| p(FEW-cor)	p(FDR-cor)	T	$\equiv Z$	p(unc)	MNI coordinates			Talairach coordinates			Area	Range
LCD > TCD, negatively activated in both LCD and TCD												
0.011	0.001	6.82	4.28	0.000	16	−88	12	16	−85	15	Right cuneus, BA 18	1
0.015	0.001	6.56	4.20	0.000	2	−76	12	2	−73	15	Right cuneus, BA 18	3
0.027	0.001	6.02	4.01	0.000	12	−82	−18	12	−80	−11	Right lingual gyrus, BA 18	3
0.193	0.001	4.44	3.35	0.000	6	−84	−10	6	−82	−4	Right lingual gyrus, BA 18	1
0.298	0.002	4.08	3.17	0.001	4	−88	−2	4	−85	2	Right lingual gyrus, BA 17	3
0.34	0.002	3.96	3.11	0.001	10	−94	−2	10	−91	3	Right cuneus, BA 17	1
LCD > TCD, only negatively activated in TCD but not LCD												
0.011	0.000	8.27	4.69	0.000	0	−84	12	0	−81	15	Left cuneus, BA 18	3
0.077	0.000	6.36	4.13	0.000	12	−84	−18	12	−82	−11	Right lingual gyrus, BA 18	3
0.115	0.000	5.99	4.00	0.000	−6	−70	0	−6	−68	3	Left lingual gyrus, BA 18	3
0.149	0.000	5.76	3.91	0.000	10	−82	−12	10	−80	−6	Right lingual gyrus, BA 18	3
0.47	0.001	4.65	3.45	0.000	−12	−94	16	−12	−90	19	Left cuneus, BA 18	3
0.521	0.001	4.53	3.39	0.000	12	−96	12	12	−92	16	Right middle occipital gyrus, BA 18	1
0.596	0.001	4.37	3.32	0.000	10	−100	−4	10	−97	1	Right cuneus, BA 17	1
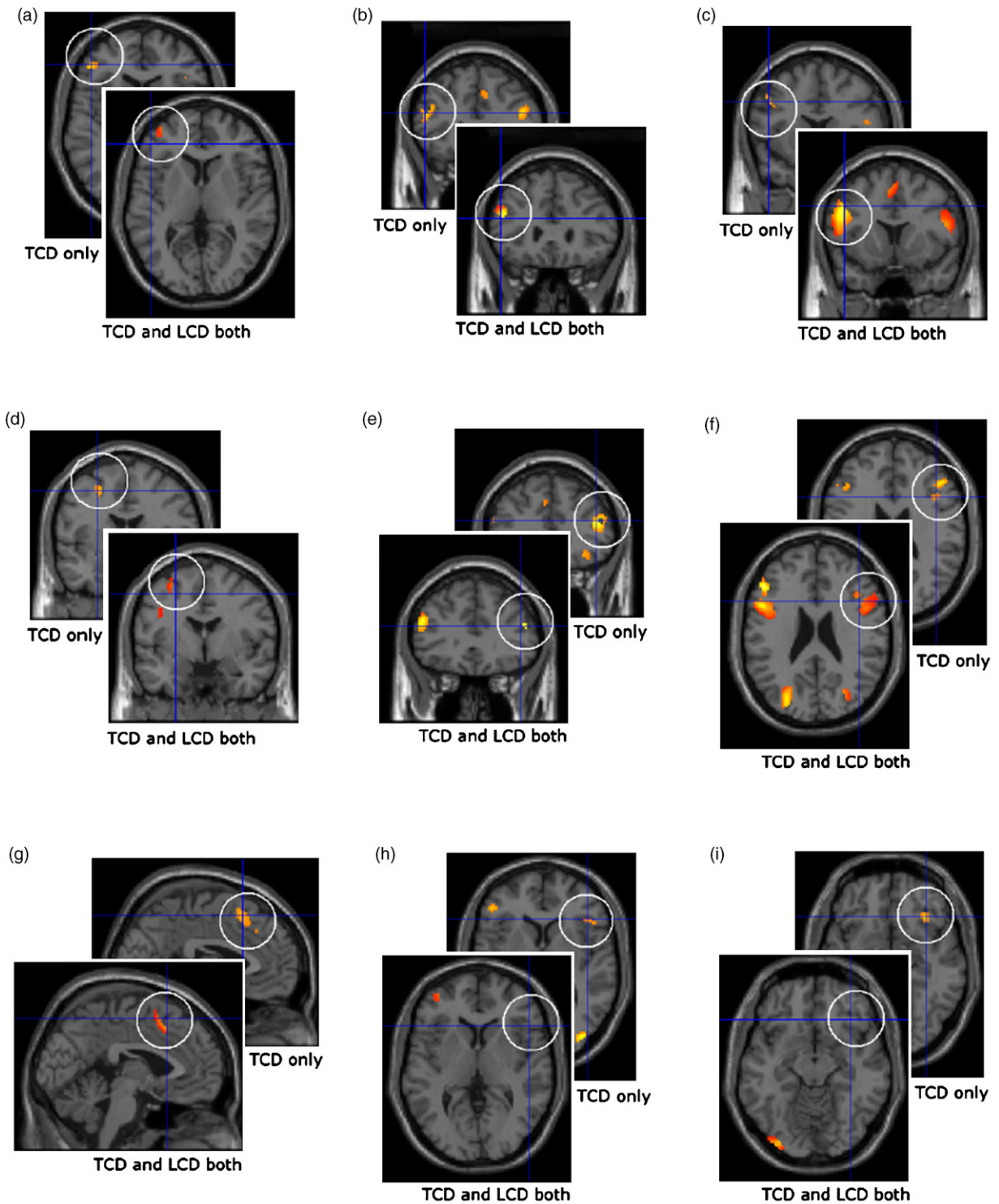
Fig. 6. The frontal activation in chunk decomposition. "TCD only" means these areas were only positively activated in TCD trials. The "TCD and LCD both" means these areas were positively activated in both TCD and LCD trials. The blue cross marks the exact location of the peak voxel in cluster. (a) Left inferior frontal gyrus (x, y, $z = -46$, 40, 6); (b) left inferior frontal gyrus (x, y, $z = -48$, 28, 20); (c) left middle frontal gyrus (x, y, $z = -46$, 12, 36); (d) left middle frontal gyrus (x, y, $z = -26$, -2, 50); (e) right middle frontal gyrus (x, y, $z = -46$, 32, 20); (f) right middle frontal gyrus (x, y, $z = 42$, 16, 24); (g) left superior frontal gyrus (x, y, $z = -2$, 18, 54); (h) right inferior frontal gyrus (x, y, $z = 44$, 28, 4); (i) right inferior frontal gyrus (x, y, $z = 36$, 28, -12).
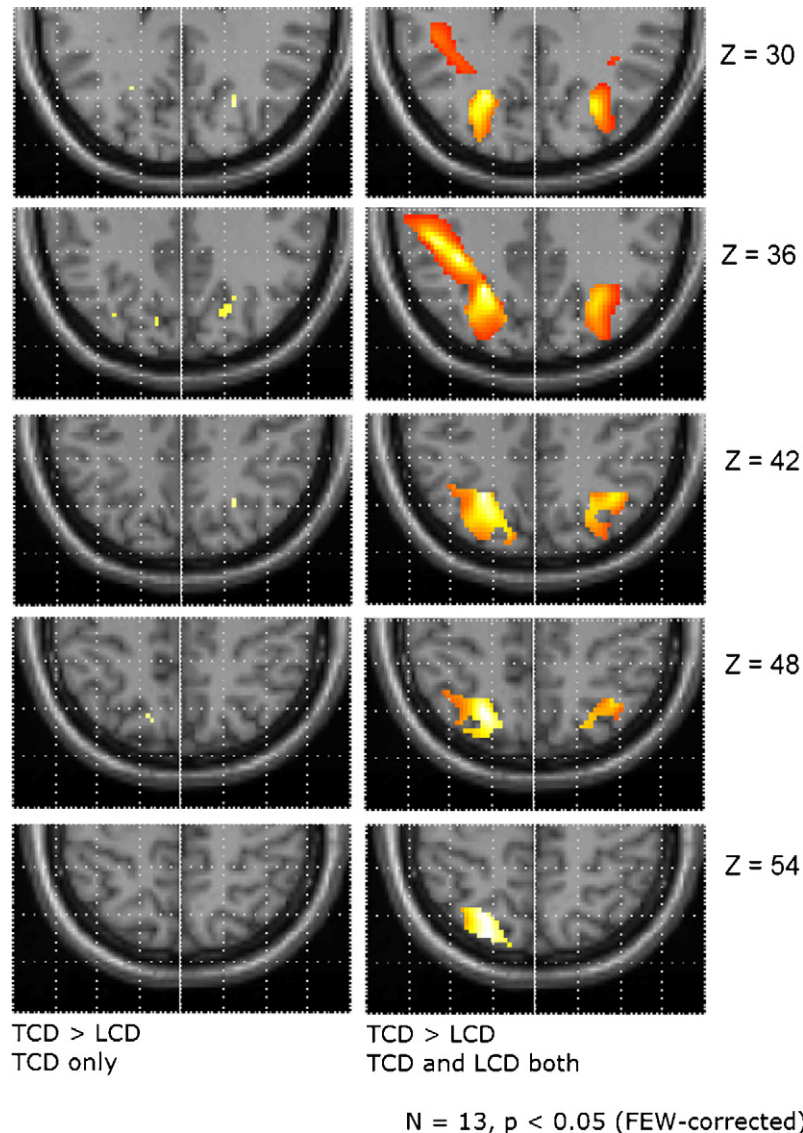
Fig. 7. The parietal activation in chunk decomposition. "TCD only" means these areas were only positively activated in TCD trials. The "TCD and LCD both" means these areas were positively activated in both TCD and LCD trials.

3.5. Activation in parietal areas

There were also differences in parietal activation in the contrast of TCD minus LCD. Those areas included the right precuneus (BA 7), right inferior parietal lobule (BA 7), right sub-gyral (BA 40), left supramarginal gyrus (BA 40), and left precuneus (BA 31). Most of these areas were also positively activated in LCD (Fig. 7, Tables 1 and 2). Only small activities in bilateral precuneus (BA 7) and right superior parietal lobule (BA 7) were found to be only positively activated in TCD but not in LCD (Fig. 7).

4. Discussion

This study explored the cognitive and brain mechanisms underlying chunk decomposition. For the behavioral results we predicted that it would be more difficult to decompose tight chunks than to decompose loose chunks. In terms of the brain

mechanisms involved we predicted that perceptual as well as executive functions contribute to chunk decomposition. The results supported the predictions.

The behavioral results showed that subjects were able to solve the majority of problems that required decomposing a character into radicals within a few seconds without being given an external hint. At the same time, most of the problems that required the decomposition of the character into basic strokes could not be solved without a hint. This confirmed the prediction that decomposing a character into basic strokes is much more difficult than decomposing it into radicals. This result is consistent with the results of previous behavioral experiments and further supports the notion of chunk decomposition [17].

The imaging data showed, in the question presentation (Q) phase, the contrast of TCD and LCD revealed TCD was associated with activation in left superior frontal gyrus and medial frontal gyrus (including anterior cingulate gyrus) relative LCD, these activities might be related to the attempts in vain to separate

the target character in the Q phase of TCD. In the hint presentation (H) phase, however, the contrast of TCD and LCD showed widely distributed activation in visual, prefrontal, and parietal areas. These activities embodied different cognitive aspects of chunk decomposition.

4.1. Visual contributions to chunk decomposition

We hypothesized that visual processes contribute to chunk decomposition in a particular manner. The tighter the chunk the needs to be decomposed, the more we should see involvement of areas in higher visual cortex that are concerned with the generation of meaningful patterns. At the same time we hypothesized that early visual cortex should show lower activation. Presumably, this pattern reflects a disconnection of higher visual areas from the early visual input. Both predictions were supported by the data.

Several locations in higher visual cortex were more positively activated in the TCD condition, including the left inferior occipital gyrus (BA 18) and the bilateral middle occipital gyrus (BA 18 and 19). However, the bilateral cuneus (BA 18, 17) and lingual gyrus (BA 18, 17) were more negatively activated in the TCD condition indicating that activations in early visual cortex decreased during the moment of chunk decomposition. We will discuss each of these activations in turn.

The activation in left inferior occipital gyrus (BA 18) (which located in x, y, $z = -32$, -88, -16 of MNI coordinates) was quite close to the one observed in Uchida et al.'s [51] experiment in which the perception of real characters was contrasted with the perception of scrambled characters (x, y, $z = -35$, -80, -14). Although Uchida et al. [51] proposed the function of this area was related to orthographic processing of real characters, their hypothesis could not be firmly supported by their evidence given the nature of their contrast. The contrast of the real character versus the scrambled one can simply mean the areas that were sensitive to the basic visual processing of character-like stimulus. To further discuss the exact function of the left inferior occipital gyrus. We compared the hint (H) and the solution (S) phase of LCD condition. Relative to the S phase of LCD condition, the H phase of this condition involved additional process for alternative characters perception and re-arrangement. However, the components of characters perception and attentive control contained in these events were comparable. Therefore, if the function of left inferior occipital gyrus was related to the basic visual processing of character-like stimulus and allocation of attention, then the H phase of LCD will not show more left inferior occipital activation than the S phase. However, the result showed more left inferior occipital activation in H phase of LCD (Fig. 8). Thus we infer the function of left inferior occipital in chunk decomposition might be related to alternative characters perception and re-arrangement of visual stimulus.

Whereas activation of left inferior occipital gyrus was present in both in the TCD and LCD conditions, the left middle occipital gyrus (BA 19) and the right middle occipital gyrus (BA 19 and 18) were only positively activated in the TCD condition. Kuo and colleagues observed similar activations in a same–different judgment task [20]. Participants were presented with two famil-

Hint Stage of LCD > Solution Stage of LCD
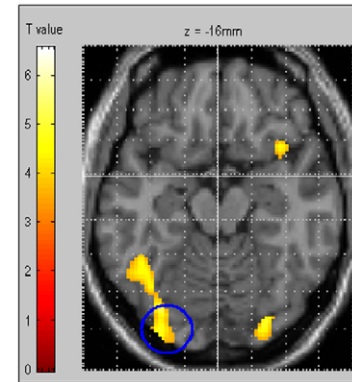
N = 14, p <0.05 (FDR-corrected, random-effect analysis)

Fig. 8. The activation in inferior occipital gyri shown in the contrast of LCD in H phase minus LCD in S phase. The blue circle marked the activation located in left inferior occipital gyrus.

iar Chinese characters or with two visual patterns that were similar to the Chinese characters (Korean-like nonsense figures participants could not recognize). Left and right middle occipital gyrus were selectively activated for nonsense patterns. Thus, the function of this visual area might be related to the detailed analysis of visual patterns. It is likely that the processing of familiar Chinese character involved holistic processing of a perceptual chunk, whereas the processing of the meaningless visual patterns occurred on a more basic stroke level. Consistent with this interpretation no activation in bilateral middle occipital gyrus occurred in a contrast of pseudo-characters composed of regular radicals with Chinese characters [20]. This suggests that pseudo-characters are processed using perceptual chunks of radicals and do not require more detailed analysis on the stroke level. In our study, stroke level decomposition of a character might also require this type of analytical processing supported by bilateral middle occipital gyrus.

As mentioned earlier bilateral cuneus (BA 18, 17) and lingual gyrus (BA 18, 17) were more negatively activated in the TCD condition indicating that activations in early visual cortex decreased during the moment of chunk decomposition. Negative BOLD signal were previously detected in the "default brain" during the goal-directed cognitive operations (e.g., [12]), in the sensory-specific cortex during cross-model stimulating [23] or during visual imagery [1]. There are more and more evidences indicate that the negative BOLD signals is not a pure artifact due to image analysis or the shunting of blood flow, rather, it is a process that is related to less neural processing [22,1,43]. In this study, we predicted a negative activation in early visual cortex and proposed it was related to the process in which the visual patterns need to be re-interpreted and the higher visual areas become "disconnected" from early visual processing. In our event-related analysis, the negative activation reflects a significant decrease of the BOLD signal just after the moment of hint presentation. What we can infer from this observation is that the activation in early visual cortex generally decreased when subjects were presented with a hint and that the decrease was larger when a hint provided the crucial information to solve a TCD problem.

The negative activation in early visual cortex and positive activation in higher visual cortex during the moment of chunk decomposition cannot be interpreted as an attention effect, because the attention account may predict positive activation for both earlier and higher visual cortex [28]. Second potential alternative explanation for the pattern of activations observed in visual cortex is the so-called blood stealing effect, which supposes more blood is shunted to higher visual areas and so there is less blood flow available to earlier visual cortex. However, further analysis results did not support this interpretation. We contrasted the successful hints and unsuccessful hints in the TCD condition (the presentation of a TCD hint failed to evoke a successful problem solving) and found that the unsuccessful TCD hints were associated with a longer RT and more positive activation in higher visual cortex (left middle and inferior occipital gyrus, BA 19). However, no more negative activation in early visual cortex was observed in this contrast. These observations did not support blood-stealing hypothesis, rather, they are consistent with Amedi et al.'s [1] suggestion that the deactivation (in auditory cortex during visual imagery) is related to changes in the firing patterns and synaptic activity of neurons. The third alternative explanation, which attributed the observed positive/negative activation pattern in visual cortex to the "attention plus blood stealing" effects, may also not be true. Although it is already known that attention effect is stronger for higher visual cortex relative to earlier visual cortex [33], it does not imply the activation in earlier visual cortex will be weaker in the highly attentive condition than in the lower one. Rather, it is more reasonable to predict stronger earlier visual cortex activation in highly attentive condition.

4.2. Executive contributions to chunk decomposition

A further prediction was that a prefrontal network generally involved in the restructuring of problem representations would also be involved in chunk decomposition. Consistent with this prediction a PFC network including bilateral middle, inferior frontal gyrus, and superior frontal gyrus showed stronger activation in the TCD condition. Although the medial PFC activation in this study was located more superior and anterior than the cingulate cortex activation observed in previous insight studies using ambiguous sentences [26], it is likely that this activation reflects the detection of a conflict between an existing interpretation of a problem and new evidence provided by a solution hint or a new idea.

The predicted left lateral PFC activations were also observed. They were located more superior, anterior, and more widely distributed than in previous studies [26]. Functionally, this activation can be interpreted as the resolution of a conflict (detected by medial PFC) that leads to inhibition of problem elements that interfered with the solution so far. Unfortunately, the present data do not allow us to draw firm conclusions about interactions between frontal and visual areas. However, it is tempting to speculate that the medial and lateral PFC activation shifted the mode of processing in visual cortex from grouping perceptual input to form familiar chunks to separating and re-interpreting basic perceptual elements into a new meaningful configuration.

4.3. Other contributions to chunk decomposition

In contrast to previous studies on insight problem solving that highlighted a left-hemisphere network (e.g., [26]), we found robust right hemisphere activation in character decomposition. In particular, the right lateral PFC activation together with the bilateral parietal activation (BA 7) is often observed in studies of problem solving requiring visuo-spatial processing [10,6]. It is likely that these activations are due to the visuo-spatial character of the character decomposition task. In addition to the finding that visual areas play an important role in chunk decomposition this result seems to further support previous claims that representational change is often non-sentential, that is, not language-based (see [42], for a review).

Furthermore, we observed robust activation in the left supramarginal gyrus during character decomposition. This region is part of a left temporoparietal network that also includes the superior and inferior parietal lobules and superior temporal gyrus. Previous studies have demonstrated that this network plays an important role in the orthography-to-phonology transformation (OPT) of Chinese characters ([24]; but also see [46]). Thus the higher activation of supramarginal gyrus during character decomposition might suggest that phonological knowledge was accessed in order to determine which new characters could be formed. Alternatively, this activation could reflect a "pronouncability" check for visual patterns that are considered a solution thereby helping to determine whether a correct solution has been found.

5. Conclusion

The major challenge for brain imaging studies addressing representational change in problem solving is to separate brain areas generally involved in representational change and brain areas that reflect different types of representational change. The present study extends previous evidence obtained in the domain of verbal problem solving that medial and lateral prefrontal brain areas are involved in changing or restructuring problem representations [26,27]. In addition, the present study provides the first demonstration that visual processes can provide the crucial information for representational change. Thus it seems that executive control processes are generally involved in representational change whereas, depending on the nature of the task, different perceptual and memory processes can provide the specific information leading to the change.

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