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Research Report

How perceptual processes help to generate new meaning: An EEG study of chunk decomposition in Chinese characters

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ABSTRACT

Chunk decomposition has been regarded as an important process in problem solving that helps problem solvers to generate new solution paths through changing inappropriate problem representations. We studied the neural bases of chunk decomposition in Chinese characters using the electroencephalogram (EEG). Participants decomposed Chinese characters either at the level of radicals or at the level of strokes to generate new target characters with a different meaning. We hypothesized that decomposition at the stroke level would require a more fundamental change in the problem representation that should involve differences in basic visual processing. To test this hypothesis, we compared the alpha rhythm (8–13 Hz) over parietal–occipital regions between the two different conditions. The regrouping of tight chunks (stroke level) exhibited a stronger alpha activation than the regrouping of loose chunks approximately 500 ms prior to response. Thus visual areas were less active during the decomposition of tight chunks. Together with a previous fMRI study the results provide convincing evidence that attenuation of early visual information is required to generate new meaning.

1. Introduction

Problems can be difficult for different reasons. Some problems are difficult because one needs to find the correct solution in a large space of possible solutions. However, problems can also be difficult because problem solvers have a perception or conception of the problem situation that does not allow them to solve the problem or because they conceive of the goal in a way that does not lead to the solution (Ohlsson, 1992; Schooler et al., 1993). Problems of the latter kind have been called insight problems (e.g., Metcalfe, 1986), because the solution appears suddenly in the problem solver's mind, leading to an AHA experience. In fact, in such problems solvers can often not predict whether they will solve a problem even if they are already very close to the solution (Metcalfe, 1986).

Recently, researchers have started to unravel the neural processes underlying the AHA experience (see Bowden et al. (2005) and Luo and Knoblich (2007), for two recent overviews). The results of these studies suggest that it is unlikely that there is a unitary brain process or a unitary brain area that triggers insight in problem solving. Rather, insights (defined as sudden solutions to a problem) seem to occur when unconscious perceptual (Luo et al., 2006) and semantic (Jung-Beeman et al., 2004; Mai et al., 2004) processes lead to a reconfiguration

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or new integration (Luo et al., 2004; Wagner et al., 2004) in the problem solver's representation of the problem that opens up a new solution path (Knoblich et al., 2001).

The aim of the present study was to investigate the neural processes that occur when perceptual processes are involved in reinterpreting a problem and changing its meaning. Previous studies on the role of semantic processes in restructuring found that the 'Aha' feeling response involved the activation of the right hemisphere (Bowden and Jung-Beeman, 2003). Brain imaging result indicated that when problem solvers reported to have had an insight, areas in the parietal–occipital cortex showed stronger alpha activity than when they reported no insight. The increased alpha activity was interpreted as idling or inhibition of cortical areas that serves to protect easily perturbed central processes from bottom-up stimulation (Jung-Beeman et al., 2004). In the present study we asked whether a similar neural process occurs when the problem requires a perceptual regrouping of problem elements in order to be solved.

This can be investigated with tasks that require chunk decomposition (Knoblich et al., 1999; Knoblich et al., 2001). Previous behavioral research demonstrated that some problems are difficult because they require the solver to decompose familiar chunks into their components and to regroup them in a different manner. The "tightness" of such familiar chunks varies depending on what the components of a chunk are. To illustrate the tightness of chunks consider the following two matchstick problems:

a) IV=III+III
b) XI=III+III

The task in these problems is to move only one stick to generate a correct arithmetic statement and the solution to the two above problems is the same: VI=III+III. Knoblich et al. (1999) found that it was more difficult to decompose the tight chunk 'X' into its perceptual components '/' and '\' than to decompose the loose chunk 'IV' into its meaningful components 'I' and 'V'. In contrast to loose chunks where meaningful components are regrouped, the regrouping of a tight chunk requires a decomposition of the chunk into meaningless components before a new meaningful component can be created. Unfortunately, the task domain for the above tasks is not flexible enough to provide a sufficient number of trials required by brain studies (Luo and Knoblich, 2007).

However, Luo et al. (2006) have recently developed a new chunk decomposition task using Chinese characters. Chinese characters are ideal examples for perceptual chunks that implement particular meanings through groupings on different levels (Tan et al., 2001; Tan et al., 2005a,b; Fu et al., 2002). The decomposition of Chinese characters can occur at different levels. Chinese characters are formed by radicals, which in turn, are formed by strokes (Fig. 1). The radicals always carry some phonetic or semantic meaning, and they have independent visual patterns so they can be regarded as chunks themselves. In contrast, strokes are basic perceptual components that do not carry meaning and tightly embedded in the character. Therefore, a Chinese character can be separated into its radicals and the radicals can be separated into strokes. Because radicals are meaningful and strokes are not meaningful it should be easier to decompose a character at the radical level than at the stroke level according to the chunk decomposition hypothesis. As is shown in Fig. 2, the character "旧" is a loose chunk because it is composed of two independent visual components "一" and "日", just like "I" and "V" in the Roman numeral "IV". This should make chunk decomposition easy. In contrast, the strokes in the character "四" form a holistic visual pattern, or a tight chunk. Accordingly, it should be difficult to decompose "四" into "一" and "匹", just like it was hard to decompose the Roman numeral "X" into "\" and "/".

Luo et al. (2006) performed an event-related fMRI study that compared brain activation for character decomposition at the radical level and at the stroke level. This study showed that the activation in parts of the visual cortex was reduced as chunk decomposition became harder. This result suggests the following mechanism for chunk decomposition: individual features of a chunk are processed in early visual cortex (Uchida et al., 1999). During problem encoding these individual features are automatically grouped together to form a holistic chunk. If the need to decompose a tight chunk arises these individual chunk components need to be rearranged into a different chunk. Accordingly, the representation of these features is suppressed and altered and this explains the inhibition of visual information about chunk's features in occipital brain areas, including the primary visual cortex (Luo et al., 2006).

However, there are also some problems that Luo et al.'s (2006) chunk decomposition study could not answer. First, the chunk decomposition process was induced by an external hint. This highlighted the parts to be moved out (radicals or strokes) from the character chunk in red color. Providing an external hint aimed at catalyzing the participants' solution process after they had failed to solve a puzzle on their own. Although this hint-catalyzing method allowed the accurate recording of neural activity correlated with cognitive insight to a problem that participants had previously regarded as unsolvable within a particular time window, this comes at a cost. It is not certain that the external hints trigger similar processes as internally generated solution attempts. The present study investigated internal restructuring processes relative to the point in time at which participants indicated that they had found the solution.

A second issue with Luo et al.'s (2006) previous study is that the negative BOLD signals in visual cortex may have been caused by a blood stealing effect (Smith et al., 2004). There may have been less blood flow in early visual cortex because more blood was shunted to other areas. Accordingly, it is not fully clear whether the deactivation in visual cortex observed in Luo et al.'s study was really related to changes in the firing patterns and synaptic activity of neurons or not. Therefore, a direct observation of the activity in parietal occipital would benefit to clarify whether the previously observed deactivation in the visual cortex is caused by cognitive processes or a blood stealing effect. Finally, Luo et al.'s (2006) experiment, like all fMRI studies, had low temporal resolution. Although the results suggest that the deactivation of visual cortex makes special contribution to the perceptual restructuring, the exact time course of chunk decomposition remains unclear.

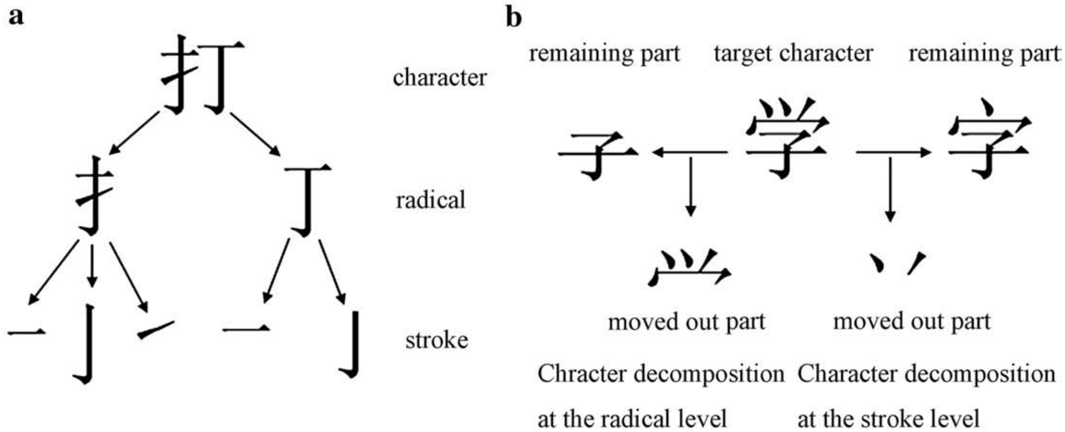

Fig. 1 – The anatomy of Chinese characters. (a) Hierarchical organization of radicals and strokes in a character. (b) Examples for character decomposition at the radical level and the stroke level.

In the present research, the basic experimental design and method were the same as that in Luo et al.'s (2006) study. However, a number of aspects were modified. Whereas Luo et al.'s (2006) study used Japanese Kanji (Chinese characters) as materials and native Japanese speakers as participants the present study used Chinese characters and native Chinese speakers as participants. The Chinese participants were more familiar with writing and restructuring Chinese characters, and thus more likely to solve chunk decomposition problems without help or hints. In addition, the present study focused on spontaneous problem solving without the use of external hints. In order to make the participants solve as many puzzles as possible by themselves, they were allowed 10s to work on each puzzle — our pilot study indicated that participants were able to solve 70% of the items in the more difficult tight chunk decomposition condition. Thus we expected enough successful solution attempts in order to be able to derive EEG parameters.

Considering the blood stealing effect and low temporal resolution of fMRI scanning, in the present study, we used continuous EEG recording to investigate the spontaneous brain activity associated with chunk decomposition. EEG provides higher temporal resolution and can therefore better elucidate the time course of chunk decomposition. As the main dependent variable in the current study, the event-related spectral perturbation (ERSP) was computed by time–frequency analysis. It describes the average brain dynamic changes in the form of EEG frequency spectrum amplitude (Makeig, 1993). The advantage of this measure is that it offers information about changes in frequency spectrum as well as temporal information. It could illustrate the EEG oscillation change of a particular frequency band during a predefined time window. Previous research has shown that EEG oscillations within different special frequency bands are related to particular patterns of neural activity and particular cognitive functions (Basar et al., 2001 #54). Besides, the temporal information could reveal the time course during which special cognitive process happened in the perceptual restructuring process.

The experimental task was as follows. Two meaningful Chinese characters were presented on the computer screen, one on the left side and the other on the right side. The participants were instructed to decompose the right character and to move certain parts of it to the left character so that two meaningful characters would result (Fig. 3). There were two experimental conditions, the tight-chunk decomposition

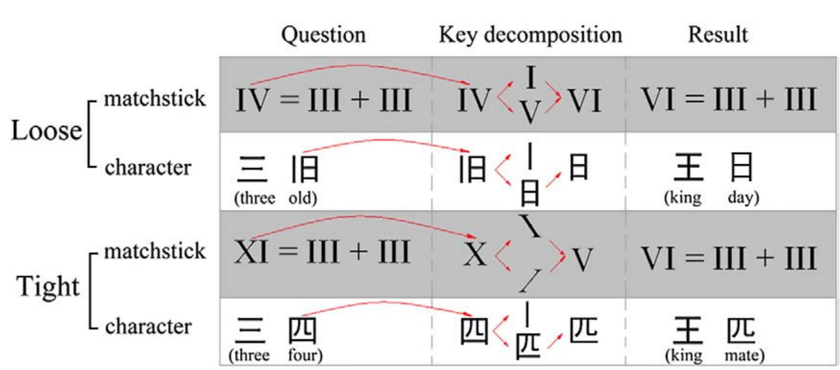

Fig. 2 – Comparison between the Chinese character chunk decomposition task and the matchstick arithmetic task. Words in the brackets indicated the meaning of the above Chinese character.

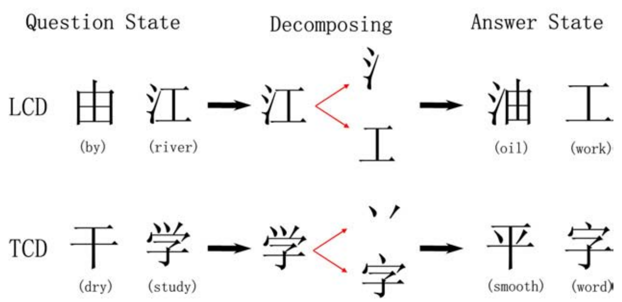

Fig. 3 – Examples for the question state, the decomposition process, and the answer state of a LCD problem and a TCD problem. The characters presented in the question state (left) needed to be rearranged to form the characters to answer state (right). During the chunk decomposition, some strokes were decomposed from the original character, left the remaining parts to be a valid character as well. English words in bracket indicated the meaning of the above characters.

(TCD) condition and the loose-chunk decomposition (LCD) condition. In the TCD condition, participants were required to decompose the right character into its component strokes and to move some of them out to the left character; in the LCD condition, the participants were required to decompose the right character into its component radicals and to move one of them over to the left one.

In Luo et al.'s (2006) experiment, the parietal–occipital visual area, including the primary visual cortex, showed reduced activation when tight chunks had to be decomposed in order to rearrange them. This indicated that the visual cortex of the parietal–occipital area was less activated during tight chunk decomposition than during loose chunk decomposition. If this interpretation is correct the alpha rhythm over parietal–occipital areas should also be modulated by the requirements of chunk decomposition. The research on spontaneous rhythms in the EEG signal and fMRI signal revealed an inverse relationship between the alpha activity and the BOLD signal in the occipital area (Moosmann et al., 2003; Petra Ritter, 2006). Thus based on Luo et al.'s (2006) result, we anticipated that during the chunk decomposition process, the visual cortex of the parietal–occipital area would show a stronger alpha rhythm activity in the TCD condition than that in the LCD condition.

A further hypothesis that we examined was based on Reverberi et al.'s (2005) finding that patients with prefrontal cortex damage were more successful than healthy participants in overcoming the goal constraints posed by insight problems (Reverberi et al., 2005). The prefrontal and frontal cortices, especially the left dorsolateral prefrontal cortex (DLPFC), are critical for defining a proper response space (Nathaniel-James and Frith, 2002). Insight problems often require that this response space be extended, relaxing overly narrow goal constraints (Knoblich et al., 2001; Ohlsson, 1992). Reverberi et al. (2005) showed that lesions in these areas increase the chances of success in solving insight problems because these areas are responsible for imposing goal constraints in healthy subjects. If the decomposition of tight chunks also requires reducing frontal control the decomposition of tight chunks should involve less frontal activity than the decomposition of loose chunks.

2. Results

2.1. Behavioral results

Mean response time and standard errors were shown in Fig. 4a. The mean response time for successfully solving the dechunking problem was 4539 (SE = 130) ms and 2465 (SE = 116) ms in TCD and LCD conditions, respectively. Paired T test result showed high significance in response time between TCD and LCD stimuli (t (16) = 14.51, p < .001). Mean solution rate and standard error were shown in Fig. 4b. About 71 (SE = 12) of the 112 TCD problems (63.55%) were successfully solved during the problem presentation phase. In contrast, about 77 (SE = 3) of the 80 LCD problems (96.68%) were successfully solved during the same phase. The difference between the solution rate between TCD and LCD problems reached significance (t (16) = −13.21, p < .001).

2.2. Brain imaging results

The alpha rhythm at frontal sites showed no significant differences between the two conditions. However, the alpha activity increased more over parietal–occipital sites in the TCD condition than in the LCD condition about 0.5 s prior to the response (Fig. 5). The comparison of the ERSPs for the alpha rhythm (10.14 Hz) in the TCD condition and the LCD

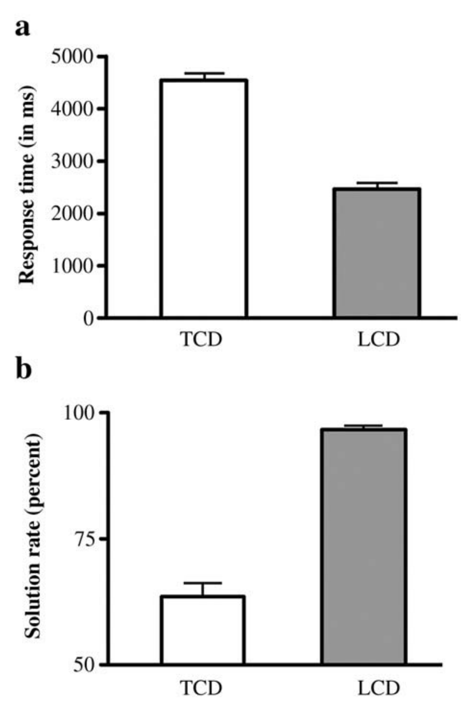

Fig. 4 – Mean response times (in ms, a) and solution rate (b) that influenced by perceptual tightness during the chunk decomposition process; N = 17. Error bars indicated SEM.

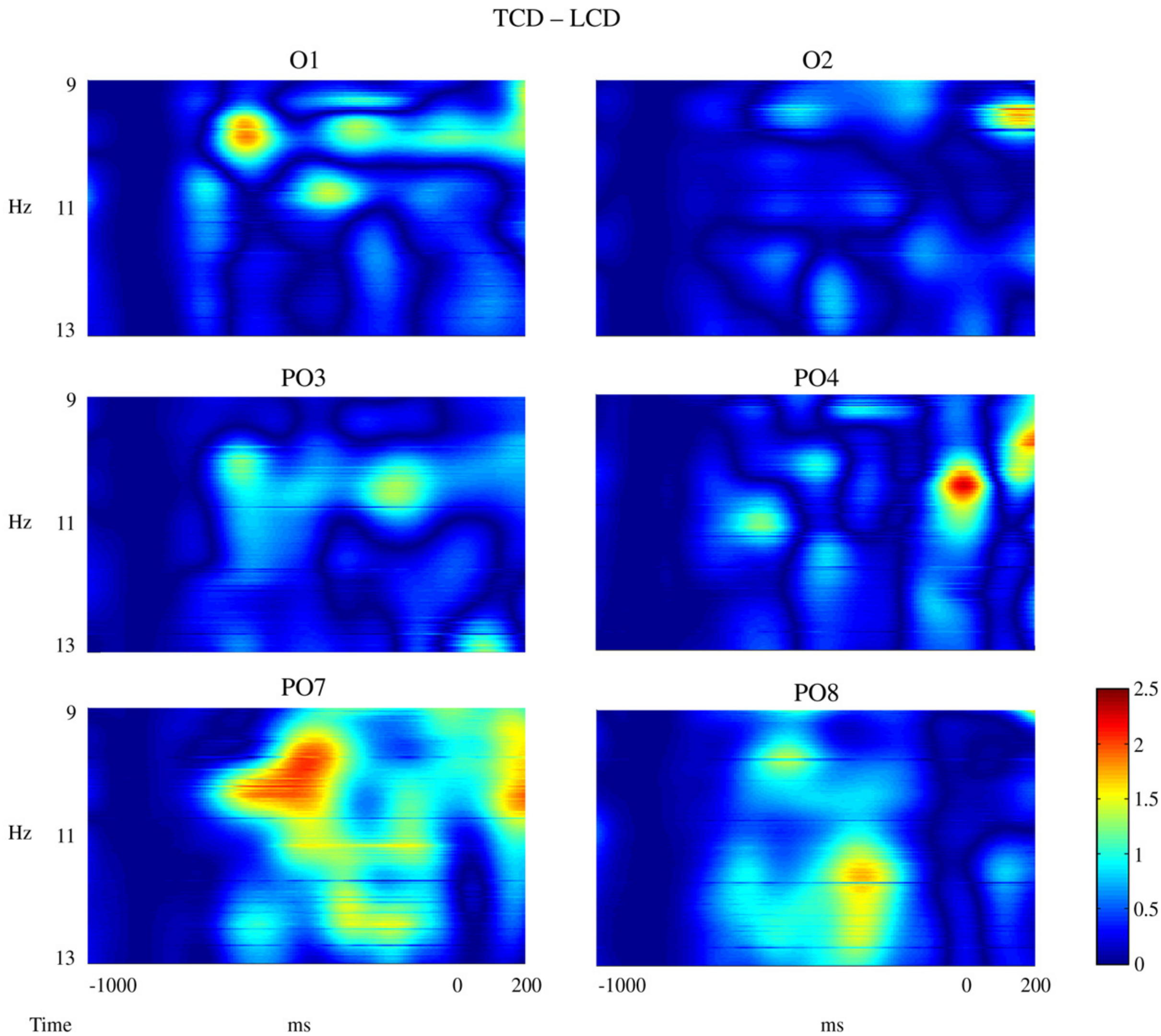

Fig. 5 – The evoked spectral perturbation (ERSP) difference (TCD minus LCD) in alpha band activity (9–13 Hz) at parietal–occipital electrodes. The *x*-axis represents time course in milliseconds and the *y*-axis represents the frequency band of the alpha rhythm. The alpha activity around 10 Hz was greater for TCD condition than LCD condition in the parietal–occipital area about 500 ms prior to correct key-press response.

condition is depicted (Fig. 6). The ERSP of the 17 participants was computed in the time window from −660 ms to −260 ms before the response. A paired *T* test revealed that during this time window, alpha activity was significantly higher in the TCD condition than in the LCD condition (t (16) = −2.203, p = 0.043).

3. Discussion

This research explored the brain mechanism underlying chunk decomposition, a process frequently required to solve (insight) problems. The behavioral data showed the predicted results. Response times were longer and solution rates were lower in the TCD condition than in the LCD condition. These differences cannot be explained by differences in visual stimulus complexity such as the number of strokes in a character or differences in the parts that needed to be moved out. Although the visual stimuli complexity was higher in the LCD condition than in the TCD condition, the behavioral results showed longer response times and lower solution rates in the TCD condition. The tight chunk was more difficult to decompose than the loose chunk for their perceptual tightness, confirming the results of past insight research (Knoblich et al., 1999). Prior to the response which indicated that a solution had been found, there was also a difference in the brain activity between TCD and LCD conditions. The analysis of EEG parameters showed stronger alpha (10.14 Hz) rhythm activity in the parietal–occipital cortex in the TCD condition compared to the LCD condition.

Whereas a reduction in the alpha (10–12 Hz) component likely reflects a state of cortical activation related to such processes as feature extraction and stimulus identification (Pfurtscheller et al., 1994), an increase in alpha band activity implies that a cortical area is at rest or in an idling state (Pfurtscheller, 1992). For example, a previous study showed

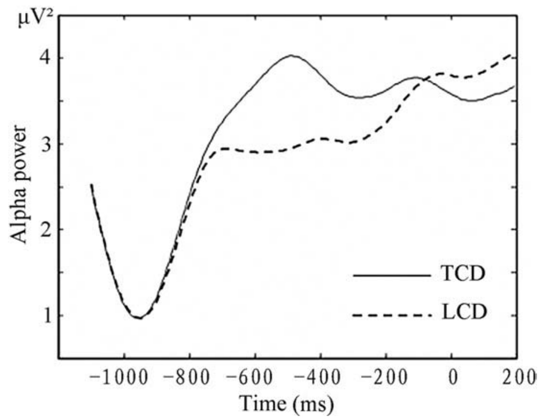

Fig. 6 – The mean alpha band (10.14 Hz) power comparison between TCD and LCD conditions and its time course at the right parietal–occipital electrode (PO8). The *x*-axis represents time course in milliseonds and the y-axis represents the alpha rhythm power in μv^2.

the induced alpha band rhythm appears to be related to the deactivation in cortical neuronal networks (Neuper and Pfurtscheller, 2001). The alpha band activity had also been observed in the visual cortex when participants actively suppressed their attention to the distracters in order to focus on particular targets (Ward, 2003).

Accordingly, the elevated alpha band activity in the TCD relative to the LCD implies that during the decomposition of tight chunks, parietal–occipital areas were less active than during the decomposition of loose chunks. This decrease likely reflects inactivity or inhibition of a visual area that establishes perceptual groupings based on familiar patterns. In order to be able to rearrange such a grouping, the visual areas that establish it need to be less active, at least if the component parts cannot be dealt with on a higher level (remember that the components of loose chunks are meaningful themselves). This interpretation of the current result is in line with the inhibition of visual areas observed in Luo et al.'s (2006) fMRI study and with Beeman et al.'s (2004) suggestion that the "alpha band activation in parietal–occipital visual cortex gates visual inputs through attenuating bottom-up activation that could potentially reduce the signal-to-noise ratio for the actual solution". There was also a difference in the time course for the alpha band activity between the current study and Beeman et al.'s (2004) earlier research, which likely reflects the difference between semantic restructuring and perceptual restructuring. During semantic restructuring, the visual input inhibition, indicated by the posterior alpha band activity, preceded activation in right anterior superior temporal gyrus (aSTG). Only after a semantic restructuring had occurred in this area a response could be made. The character decomposition process, however, requires a restructuring process that can be completed in the visual area. The inhibition of visual input, indicated by increased alpha activity, was critical to this perceptual restructuring and sufficient for generating the solution. Immediately after the visual restructuring process, the response could be made. Despite the time shift difference in alpha band activities, semantic restructuring and perceptual restructuring process were similar that suppression of visual input was necessary. This suppression, indicated by the increased alpha band activity in the parietal occipital area, seems to be a necesarry component of restructuring.

Previous research has shown that enhanced alpha band activity can also occur as a result of withdrawing attention from the visual system in order to facilitate selective attention to a motor response (Pfurtscheller et al., 2000). However, the activity observed in the present experiment cannot be due to such a process because participants carried out exactly the same key-press responses in both experimental conditions.

Another potential concern for our interpretation of the higher alpha activity in the TCD condition is that the RTs in the TCD condition were significantly longer than in the LCD condition (4539 ms vs 2465 ms). Could the elevated alpha activation be a result of differences in encoding? This seems very unlikely. The semantic encoding of a word occurs during a time interval of 300–500 ms after stimulus presentation (Pfurtscheller et al., 1994). Because the materials were simple characters and because the participants were native Chinese speakers, it was very easy for them to recognize the stimuli. Only trials where the RT was longer than 1000 ms were analyzed and therefore it is likely that the participants had finished visual encoding in all trials at the point in time when the critical difference in alpha activity occurred. In order to further ensure that the observed effect was not due to encoding average, ERPs locked to the stimuli onset of the question phase were also analyzed. There were no significant differences between the TCD condition and the LCD condition 600 ms after stimulus onset.

We did not observe differences in frontal activity that were reported in previous studies of insight problem solving (Bowden et al., 2005; Luo and Knoblich, 2007; Reverberi et al., 2005). This suggests that the difficulty of decomposing tight chunks does not imply the need to extend to relax goal constraints or to extend the space of mental actions that are considered. This is another indication that the main difficulty of decomposing tight chunks is related to perceptual processing.

The present results are in line with a negative activation in early visual brain areas that was observed during tight chunk decomposition in an earlier fMRI study that used the same character decomposition task (Luo et al., 2006). However, this study also showed increased activity in the higher visual cortex. There was no corresponding finding in the present study. There are at least two possible reasons for this. First, the EEG method may have not been sensitive enough to pick up the activation revealed by the fMRI study. Second the difference may be due to the difference in the two experimental procedures. In the fMRI study (Luo et al., 2006), participants' brain activity was measured while they observed the solutions to problems and participants may have focused more strongly on the external hints in the tight chunk decomposition condition. Such voluntary control would induce an increased activity in the higher visual cortex. In the current study, the participants solved the problems without such hints.

In conclusion, the present study provides further evidence for the claim that perceptual processes can make a difference in problem solving, which was originally proposed by the Gestalt psychologists (Duncker, 1945; Wertheimer, 1959). In order to decompose tight visual chunks the brain areas that support grouping need to be inactive or inhibited. Thus a certain pattern of activation in the visual system can be a necessary condition to generate new meaningful patterns that are required to solve difficult problems. Of course, the present study had to rely on relatively simple problems that Chinese speakers could solve within a relatively short time spans. More studies and methods are needed to fully understand the interplay of perceptual and semantic processes during problem solving, especially in more difficult problems. However, there is hardly any doubt that this should be an interesting field for further study. If one believes Watson and Crick's autobiographical statements the discovery of the DNA structure is one famous example where the tight interplay between perceptual and semantic processing revealed a groundbreaking scientific result.

4. Experimental procedures

4.1. Participants

Seventeen young adults (8 females, age range 19–24 years) were recruited from China Agricultural University and paid for their participation. None of them had a history of neurological or psychiatric disorders. All participants were healthy, right-handed, and had normal or corrected-to-normal vision. They were accustomed to using pronunciation rather than strokes to input Chinese characters when using a computer (for people who use strokes to input characters the distinction between tight chunks and loose chunks is blurred).

4.2. Stimulus and paradigm

We used 384 valid Chinese characters as materials, combined into 192 pairs. Every pair included two characters. Eighty pairs belonged to the loose-chunk condition where regrouping of radicals was sufficient to generate a new target character. The remaining 112 pairs belonged to the tight-chunk condition, where regrouping of strokes was required to generate a new target character. Because items in the tight-chunk decomposition condition were harder to solve, we used more items in this condition. This guaranteed that each participant solved a sufficient number of items in this condition. Therefore, two conditions were used. In the loose-chunk decomposition (LCD) participants needed to decompose characters at radical level and in the tight-chunk decomposition (TCD) condition participants needed to decompose characters at stroke level.

The number of strokes in each character and in the parts to be removed (radicals or strokes) in TCD and LCD conditions is summarized in Table 1.

Table 1 – Comparison of the character stroke numbers between LCD and TCD conditions.

	Left character	Moved-out parts	Right character
LCD (mean stroke numbers)	5.24	3.65	9.15
TCD (mean stroke numbers)	4.19	2.09	5.95
T test results between LCD and TCD	t (190) = −3.671	t (190) = −8.026	t (156.125) = −10.721
p value (significance)	$p < .001$	$p < .001$	$p < .001$

The mean stroke numbers of the right character (character required to decompose), the left character (character that needs to combine with the moved-out radical or strokes to generate a new character), the parts that decomposed from the right original character and T test results between TCD and LCD conditions were summarized.

In each trial two characters were presented on the screen, one on the left side and the other on the right side. The participants were instructed to decompose the right character, to move some parts from it and to join them to the left character so that two meaningful characters would result. They were instructed that any part (radicals or strokes) of the right-side characters could be moved.

The time course of each trial was shown below (Fig. 7). Each trial started with the problem presentation, followed by the hint presentation, and the answer presentation. During the problem presentation phase, two characters were presented on the screen for 10 s followed by a 3-s interval. Participants were instructed to immediately press a left key with their left index finger if they thought that they had found a solution. They also had the opportunity to indicate that they had given up by pressing a right key with their right index finger.

During the following hint phase (4 s) the same characters were displayed but the color of the parts that needed to be moved were highlighted in red followed by a 3-s interval in which the fixation cross was displayed. Again, participants pressed the left or right key to indicate whether they had found a solution or they gave up. They were required to give a response even if they had already successfully solved the problem. In the final stage, the answer was presented for 3 s. The participants pressed the left or right key in order to indicate whether they could make sense of the answer.

4.3. Data recording and data analysis

The brain electrical activity was continuously recorded from 64 scalp sites using Ag/AgCl electrodes mounted in an elastic cap (NeuroScan Inc.), with reference to linked mastoids. The vertical electro-oculogram (VEOG) and horizontal electro-oculogram (HEOG) were recorded by electrodes placed on the outer canthus of both eyes and above and below the left eye. All interelectrode impedance was maintained below 5 kΩ. Signals were amplified using a 0.05–40 Hz bandpass and continuously sampled at 500 Hz/channel. Ocular artifacts (blinks and eye movements) were removed offline.

Two conditions were defined in the analysis: the loose-chunk decomposition (LCD) condition and the tight-chunk decomposition (TCD) condition. The continuous EEG data was epoched into 1400 ms segments with 1200-ms pre-response. Only the trials in which the participants had successfully

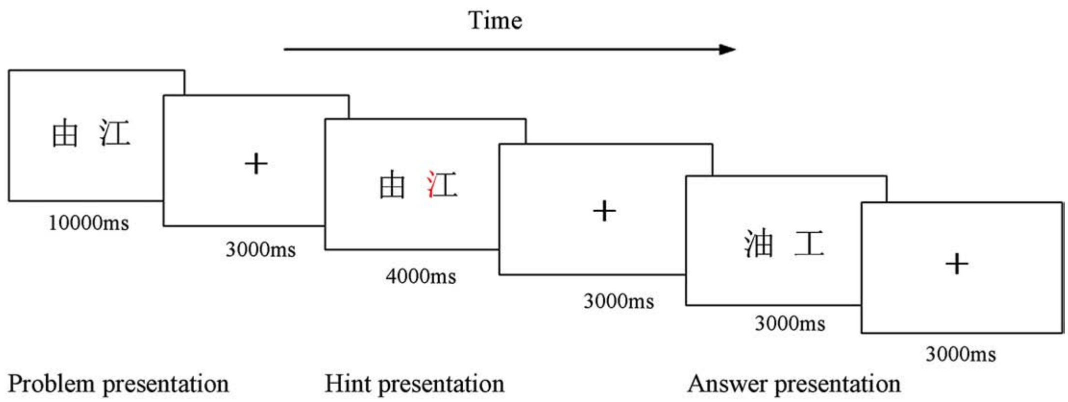

Fig. 7 – Illustration of the character decomposition task. During the problem presentation phase, the participants were required to solve the problems as fast as possible and to press a key once they found a solution.

decomposed the target character during the question phase (i.e. the first stage) were analyzed. Prior to analysis, trials containing artifacts due to amplifier clipping or bursts of electromyography (EMG) activity were rejected manually. The response time of the trials during the question phase was taken into consideration, and those shorter than 1000 ms were excluded from later analysis in order to eliminate effects of early chunk encoding.

Because we could not a priori define the time at which chunk decomposition occurred we relied on Beeman et al.'s (2004) assumption that, most likely, insight occurs about half a second or less before the participants provide a response. Furthermore, there is no reason to assume that the time between finding a solution and indicating with a button press that a solution has been found would differ between the LCD and TCD conditions. Therefore, we focused on the brain activity approximately 500 ms before the response. Brain activity prior to this period was used as a baseline to analyze the alpha rhythm of the frontal and parietal–occipital areas. In order to get a full analysis, we used response-locked EEG to contrast the brain activities associated with LCD and TCD in a time window that started 1100 ms before the key press.

To assess the brain activation related to chunk decomposition, the phases of brain activity were analyzed computing the evoked spectral perturbation (ERSP) around 500 ms before the response in the two conditions. For the ERSP analysis, the segmented epochs were imported into the EEGLAB software (Delorme and Makeig, 2004), and the evoked spectral perturbation (ERSP) was computed with ERPWAVELAB (Morup et al., 2007). We chose 10 parietal–occipital electrode sites (PO3, PO4, PO5, PO6, PO7, PO8, POz, O1, O2, and Oz) and 9 frontal sites (Fz, F1, F2, F3, F4, F5, F6, F7, and F8) to compute the ERSP. Time–frequency transforms were analyzed with ERPWAVELAB by applying the complex Morlet wavelets (Morup et al., 2007) (Fig. 8):

$$\varphi\,(t) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-i2\pi t} e^{-t^2/2\sigma^2}$$

Fig. 8.

σ was set to be 1 and the width of the Morlet wavelets was 2π. The ERSP values of the alpha rhythm of the frontal and parietal–occipital area are displayed as a function of time (−1100–200 ms) and frequency (5–25 Hz).

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