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Identification and transformation difficulty in problem solving: Electrophysiological evidence from chunk decomposition

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Abstract: A wealth of studies have investigated how to overcome experience-based constraints in creative problem solving. One such experience-based constraint is the tendency for people to view tightly organized visual stimuli as single, unified percepts, even when decomposition of those stimuli into component parts (termed chunk decomposition) would facilitate problem solving. The current study investigates the neural underpinnings of chunk decomposition in creative problem solving by analyzing event-related potentials. In two experiments, participants decomposed Chinese characters into the character’s component elements and then used the base elements to form a new valid character. The action could require decomposing a “tight” chunk, meaning that the component elements intersected spatially, or a “loose” chunk, in which the component elements did not overlap in space. Behaviorally, individuals made more errors and responded slower to trials involving tight chunks relative to loose-chunks. Analysis of the ERPs revealed that relative to loose chunks, the electrophysiological response to tight chunks contained an increased N2, an increased N400, and a decreased late positive complex. Taken together, these results suggest that chunk tightness is a principle determinant of the difficulty of chunk decomposition, and that chunk tightness provokes neural conflict and semantic violations, factors known to influence the N2 and N400 ERP components.

Keywords: Chunk tightness; Chunk decomposition; insight problem solving; Chinese character; ERPs

1. Introduction

Insight-based problem solving involves an "impasse-overcoming" sequence, in which people encounter a difficulty that temporarily slows progress to a halt despite all efforts, until suddenly the difficulty is overcome by the act of restructuring an ineffective mental representation (Cranford & Moss, 2012; Knoblich, Ohlsson, Haider, & Rhenius, 1999; Kounios & Beeman, 2014; Ohlsson, 1984). One typical cause of an impasse in creative problem solving is an experience-based constraint, such as having a mental set or exhibiting functional fixedness, whereby the subject cannot "think outside the box." (Knoblich et al., 1999; Storm & Angello, 2010; Storm & Patel, 2014; Luchins, 1942; Smith, 1995; Duncker, 1945). To solve the problem, one has to discard the ineffective mental representation.

Chunk decomposition is a variant of insight-based problem solving whereby subjects must mentally deconstruct a stimulus into simpler components in the service of solving the problem (Knoblich et al., 1999; Knoblich, Ohlsson, & Raney, 2001; Luo, Niki, & Knoblich, 2006; Wu, Knoblich, Wei, & Luo, 2009; Tang et al., 2016; Zhang et al., 2015). During chunk decomposition, particular kinds of experienced-based constraints can interfere with a subject's ability to partition the stimulus appropriately (Knoblich et al., 1999; Wu, Knoblich, & Luo, 2013). The past decades have witnessed a wealth of studies on problem solving associated with experience-based fixations/constraints (e.g., Chi & Snyder, 2011; Duncker, 1945; Knoblich et al., 1999, 2001; Luchins, 1942; Mai et al. 2004; Ollinger, Jones, & Knoblich, 2008; Smith, 1995; Qiu et al. 2006; Storm & Angello, 2010; Zhao et al., 2011). However, relatively little research has focused specifically on chunk decomposition.

Chunk decomposition is a reciprocal process to “chunking”. The term “chunking” refers to grouping strongly or weakly associated information components into a meaningful pattern (Chase & Simon, 1973; De Groot, 1978; Gobet et al., 2001; Gobet & Lane, 2012; Miller, 1956). Chunking has wide application in human cognition (Gobet et al., 2001), affecting a diverse set of mental tasks including the learning of action repertoires (Graybiel, 1998) speech (Gilbert, Boucher, & Jemel, 2015), memory (Miller, 1956), and problem solving (Chase & Simon, 1973; De Groot, 1978). Reversing the process, chunk decomposition refers to decomposing a unified chunk into smaller components, paving the way either for regrouping (Knoblich, et al., 1999; Knoblich, Ohlsson, & Raney, 2001; Luo, Niki, & Knoblich, 2006; Wu, Knoblich, Wei, & Luo, 2009; Zhang et al., 2015), or for generating a new representation (Huang, Fan, & Luo, 2015; Tang et al., 2016; Wu, Knoblich, & Luo, 2013).

Chunk tightness is a critical factor that determines the difficulty of chunk decomposition (Knoblich, et al., 1999; Luo, et al., 2006). Chunk tightness can be conceptual or perceptual in nature. Conceptually, a chunk is tight if the component elements of the chunk have no independent meaning, and a chunk is loose if the component elements of the chunk carry independent meaning (Huang et al., 2015; Knoblich, et al., 1999, 2001; Luo, et al., 2006; Wu, et al., 2009, 2013). When the individual elements of the chunk have no independent meaning, the elements are more difficult to extract from the larger chunk. For example, in the matchstick problem, “XI = III + III”, people decompose the chunk “X” into two relatively independent components (“/” and “\”) so that the two components can be reorganized into another chunk “V”, to generate a valid equation, “VI = III + III”. Here “X” is a tight chunk, because the to-be-removed parts (“/” and “\”) are not meaningful chunks. In contrast, in another matchstick problem, “VII = II + III”, people decompose the chunk “VII” into two components, “VI” and “I”, so that “I” can be combined with “II” to generate a valid equation, “VI = III + III”. In this case, “VII” is a loose chunk, because the to-be-removed component “I” is itself a meaningful chunk.

Recently, Zhang and colleagues (2015) challenged the conceptual definition of chunk tightness, by investigating the effects of both conceptual chunk tightness and perceptual chunk tightness. A chunk is perceptually tight when the component elements of the chunk overlap in space. Perceptual chunk tightness is a type of perceptual bias that has been thoroughly researched by Gestalt psychologists (Wagemans, Elder, Kubovy, Palmer, Peterson, Singh, & von der Heydt, 2012). Zhang and colleagues hypothesized that in the above example the chunk “X” is tight because the elements (“/” and “\”) intersect each other, not because “/” and “\” have no independent meaning. By contrast, “VII” is a loose chunk, because the to-be-removed component “I” and the to-be-left “VI” are spatially separated, not because “I” and “VI” each carry meaning of their own. Zhang and colleagues tested the claim with a task in which participants had to move some part of a character on the right side to another character on the left side, to get two new characters (e.g., “巾亢——市几”).

The to-be-removed part of each chunk could be conceptually tight (a set of strokes with no meaning), conceptually loose (a character with its own meaning), perceptually tight (intersecting with other elements of the chunk), or perceptually loose (not overlapping in space with the other elements). Though both conceptual and perceptual manipulations of tightness affected performance, perceptual manipulations had a larger impact.

Previous studies investigated the neurocognitive mechanisms of chunk decomposition in problem solving have only studied manipulations of conceptual chunk tightness (Huang et al., 2015; Luo et al., 2006; Tang et al., 2016; Wu et al., 2009; 2010; 2013). Past work has revealed three major findings. First, chunk decomposition requires the suppression of irrelevant visual information (Luo et al., 2006; Tang et al., 2016; Wu et al., 2009). Alpha oscillations over parietal–occipital regions are associated with the successful suppression of visual information (Sauseng et al., 2009), and alpha activity is greater when subjects decompose tight chunks versus loose chunks (Wu et al., 2009). In addition, successful chunk decomposition is associated with reduced activity in neural regions relating to attention and visual processing, including the inferior parietal lobe, the bilateral cuneus, and the lingual gyrus (Luo et al., 2006; Tang et al., 2016). Second, chunk decomposition involves visuo-spatial processing (Huang et al., 2015; Wu et al., 2010; Wu et al., 2013). Chunk decomposition is associated with effective connectivity between the dorsal and ventral visual pathways (Wu et al., 2010), and elicits both greater activity in visuo-spatial brain regions (Huang et al., 2015), and increased amplitude of the late positive complex (LPC), an ERP component sensitive to visuo-spatial processing (Wu et al., 2013). Third, chunk decomposition, activates the cognitive control network, including the right lateral prefrontal cortex, the pre-supplementary motor area, the inferior frontal junction, and the anterior cingulate cortex (Huang et al., 2015; Luo et al., 2006; Tang et al., 2016; Wu et al., 2013).

The current work examines the underlying neuro-cognitive mechanisms at play when decomposing a tightly-organized percept in the service of insight problem solving. Previous neuroimaging research has neglected the impact of spatial intersection in defining chunk tightness (e.g., Knoblich, et al., 1999, 2001; Luo et al., 2006; Tang et al., 2016; Wu et al., 2009, 2013). The current work uses an adapted Chinese character decomposition task (Tang et al., 2016; Wu et al., 2013). Chinese characters are used as materials because Chinese characters are perceptual chunks composed of sub-components that can be meaningful or not-meaningful, and that can intersect or be spatially independent (Fu, Chen, Smith, Iversen, & Matthews, 2002; Siok, Perfetti, Jin, & Tan, 2004; Tan et al., 2001; Tan, Laird, Li, & Fox, 2005; Zhang et al., 2015). Chinese characters are frequently-used materials in research on chunk decomposition (e.g., Huang et al., 2015; Luo et al., 2006; Tang et al., 2016; Wu et al., 2009, 2013; Zhang et al., 2015). In the current task, there is a source character (the to-be-decomposed chunk) and a probe (the to-be-removed part). The task is to remove the probe from the source character to get a valid character. The experiment includes two levels of chunk tightness in the decomposition task: tight chunk decomposition (TCD) or loose chunk decomposition (LCD). The current version of the task diverges from previous research in two main ways. First, in Tang et al. (2016) and Wu et al. (2013), the researchers presented the source character and the probe simultaneously whereas the current study presents the probe first and the source character afterward. The change reduces horizontal eye-movements between stimuli, but should also engage working memory to a greater degree than in the task used by Tang and colleagues (2016), and by Wu and colleagues (2013). Second and more importantly, Wu and colleagues (2013) manipulated chunk tightness according to the conceptual view of chunk tightness, whereby a chunk was tight if the to-be-removed part had meaning on its own, and loose if the to-be-removed part had no individual meaning. In contrast, the current study manipulated chunk tightness according to the spatial relationship between the parts of the source character. Specifically, according to the hypothesis that chunk tightness varies according to the degree of intersection between elements, the to-be-removed part and the to-be-left part intersect each other in the TCD condition, and spatially separate from each other in the LCD condition.

The current work includes the recording and analysis of event-related potentials (ERPs) in order to elucidate the neural mechanisms involved in chunk decomposition, and to examine how the neural mechanisms unfold over a millisecond timescale. Previous studies have indicated that conflict detection—a critical component of cognitive control—plays an important role in breaking impasses at a moment of insight (Aziz‑Zadeh, Kaplan, & Iacoboni, 2009; Dietrich & Kanso, 2010; Mai, Luo, Wu, & Luo, 2004; Qiu et al., 2006; Subramaniam, Kounios, Parrish, & Jung-Beeman, 2009; Zhao, Li, Shang, Zhou, & Han, 2014). Some work has suggested that the process of conflict detection is reflected by the N2 ERP component when solving an insight-requiring task, such as Chinese riddle comprehension (Mai et al., 2004; Qiu et al., 2006; Zhao et al., 2014). In addition, functional magnetic resonance imaging (fMRI) studies have provided converging support for the importance of conflict detection in overcoming chunk decomposition difficulty (Huang et al, 2015; Luo et al., 2006; Wu et al., 2013). Also of note is that the N2 wave is sensitive to visual discrimination difficulty, exhibiting larger amplitude to greater difficulty in a discrimination task (Senkowski & Herrmann, 2002). Thus, two lines of research suggest that increasing chunk tightness should elicit a larger N2. In addition, Wu and colleagues (2013) observed a late positive complex (LPC) that is sensitive to manipulations of the difficulty of perceptual transformation. Wu and colleagues suggest that the LPC is an index of visual-spatial processing, thus the current work includes an analysis of the effect of chunk decomposition on the LPC.

FIGURE 1 ABOUT HERE

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2. Experiment 1

Experiment 1 made a preliminary exploration on the neural mechanism underlying chunk decomposition influenced by chunk tightness, by directly comparing ERPs between the tight and loose chunk decomposition conditions (TCD vs. LCD).

2.1. Methods

2.1.1. Participants

In accordance with the Declaration of Helsinki and with the approval of the local university ethics committee (Liaoning Normal University), 24 right-handed native speakers of Chinese gave written consent prior to participation in exchange for a small honorarium (¥ 30 Yuan). Two volunteers were excluded before data analysis because of high impedances (one recorded 20 kΩ in the ground electrode and the other recorded 13 kΩ in the EOG electrode), leaving 22 volunteers (10 males; mean age = 22.14, 95% confidence interval (CI) = [20.96, 23.32]) All volunteers reported normal or corrected-to-normal vision with no history of brain damage or psychiatric illness.

2.1.2. Stimuli

There were 92 normal Chinese source characters, which could be decomposed into two parts: a to-be-removed part/character and a to-be-left part/character. The to-be-removed part was the probe whereas the to-be-left part was the target. Half of the source characters comprised the TCD condition, in which the to-be-removed part and the to-be-left part intersected each other. For example, the source character “全” could be decomposed into two parts: “三” and “个”, which were in a spatially intersecting relationship with each other in the source character. The other half of the source characters comprised the LCD condition, in which the to-be-removed part and the to-be-left part were in a spatially non-intersecting relationship with each other. For example, the source character “夺” could be decomposed into two parts: “大” and “寸”, which were separated from each other in the source character. Three normal sub-types of spatially non-intersecting relationship were included in the LCD condition: 20 cases with horizontal offset (e.g., “女” and “少” in the source character “妙”) and 17 cases with vertical offset (e.g., “大” and “寸” in the source character “夺”) and 9 cases with half-surrounding relationship (e.g., “广” and “占” in the source character “店”). The average stroke number of the source characters, the to-be-removed parts, and the to-be-left parts between the two conditions (TCD vs. LCD) was 6.70 vs. 6.78, 2.78 vs. 2.78 and 3.96 vs. 4.00, respectively. There were no significant differences in the stroke number of the source character, the to-be-removed part, and the to-be-left part between the two conditions (TCD vs. LCD). Source character frequency was referenced from www.cncorpus.org to determine if frequency of use of the source characters was different between conditions. There was no significant source-character frequency difference between the TCD [$M \pm SD$: (.0900 ± .1653)%] and the LCD [$M \pm SD$: (.0653 ± .1236)%] conditions, F (1, 90) = .654, p = .42, η^2 = .007. Another 60 characters were collected to make up 20 filler trials, in which any of the three characters was not a part of another (e.g., the characters: “卫”——“农”——“县”). Like the presentation style of the critical trials in both TCD and LCD conditions, the three characters were assigned and respectively presented in the positions of the probe, the source character and the target, but participants were unable to complete the decomposition task (e.g., participants were unable to remove “卫” from “农” to get “县”, because “卫” and “县” were not the parts of “农”). The 20 fillers served to assess how often a participant was guessing when the participant did not actually know the answer. The stimuli were presented on a LCD monitor, subtending approximately 3.3 × 3.3° of visual angle.

2.1.3. Procedure and task

Participants were seated in a silent room, at a viewing distance of approximately 1.0 m from the computer screen, and were asked to put their right index finger on button “1” and the middle finger on button “2” of the keypad. Three stimuli per trial (the probe, source character, and target character) were presented one by one (see Figure 1). A fixation was followed by a probe (e.g., “个”) lasting for 1 s, then a source character (e.g., “全”) was presented for 4 s, during which time participants were asked to remove the previously presented probe from the source character to get a new valid character. Participants pressed “1” if they came up with the answer within 4 s or made no response if they did not think up the answer. Afterwards, one character (e.g., “三”) was presented for 4 s, participants were asked to respond whether the character was their answer. Participants pressed “1” if the presented character was consistent with their answer or pressed “2” if not. Participants made no response if they had no answer. A blank screen was presented for a random interval between 0.6~0.8 s after the first and second stimulus. The source character and the probe were presented separately to reduce horizontal eye movements. The 112 trials (46 trials in TCD condition, 46 trials in LCD condition and 20 fillers) were equally distributed into two blocks and order was randomized within each block. There were 10 practice trials before the formal experiment.

2.1.4. ERP recordings and analysis

Electroencephalography (EEG) was recorded from 64 scalp sites using tin electrodes mounted in an elastic cap (Brain Products). The electrodes were placed according to the international 10-20 system, and referenced to FCz during recording. The ground electrode was positioned at the medial frontal aspect. The vertical electrooculograms (EOG) was recorded infra-orbitally at the right eye. Impedances were kept below 10 kΩ for all electrodes across all 22 participants included in the analysis: the actual average was 3.21 kΩ, within the range 0-8 kΩ. The EEG and EOG were amplified by using a band-pass of 0.01-100Hz and continuously sampled at 500Hz/Channel.

The EEG data was re-referenced offline to the average of left and right mastoids (TP9/TP10). Eye movements were corrected offline. The infinite impulse response (IIR) Butterworth Zero Phase Filters were used for low-pass filtering on the continuous data, with a cut-off frequency of 30 Hz and 24 dB/octave roll-off. The EEG data were then notch-filtered at 50Hz. Trials contaminated by large artifacts (with deflections outside the range of ±80μV) were excluded before averaging. ERP epochs were extracted with a 200 msec baseline and included 800 msec of post-stimulus onset activity. ERPs were time-locked to the onset of the source character (the to-be-decomposed character, e.g., the character "夺" in the task of "大——夺——寸"). ERPs on trials with correct answers were averaged separately for each condition.

Similar to N2 observed by Mai and colleagues (2004) and by Qiu and colleagues (2006) in the insightful riddle task (the so-called N380 or N320), the pattern and distribution of the N2 deflection exhibited a central midline distribution peaking between 240 msec and 460 msec (see Figure 2). The authors therefore analyzed N2 mean amplitude between 240 and 460 msec at the following 25 electrode sites (F1, F2, F3, F4, Fz, FC1, FC2, FC3, FC4, FCz, C1, C2, C3, C4, Cz, CP1, CP2, CP3, CP4, CPz, P1, P2, P3, P4, Pz). In addition, following Wu and colleagues (2013), the authors analyzed mean amplitude of the LPC between 460-800 msec at the 13 posterior electrodes (CP1, CP2, CP3, CP4, CPz, P1, P2, P3, P4, Pz, PO3, PO4, POz). There was no evidence of a distinct N400 component occurring in Experiment 1, and therefore no analysis dedicated specifically to that component.

All these ERPs were analyzed using two-way repeated measures analysis of variance (ANOVA) with chunk tightness (two levels: TCD vs. LCD) and electrode site (25 sites for N2, 13 sites for LPC) as within-subject factors. Effects with $p < .05$ were reported to be significant. For any effect with $df > 1$, Greenhouse-Geisser correction was used and the value of Epsilon (ε) was reported if sphericity assumption was violated ($p < .05$). Bonferroni corrections were used for each of the multiple comparisons. Two types of effect size estimates were given: Classical eta squared (η^2) for results of two-level ANOVA and partial eta squared (η_p^2) for ANOVA results of more than two levels. Effect size was reported according to Cohen's rule of thumb: Cohen (1988) defined small, medium and large effects as η^2 (or η_p^2) values of 02, .13 and .26, respectively. Accordingly, in the current work, effects <= .02 were labeled as small, effects between .02 and .26 as medium, and effects >= .26 as large.

FIGURE 2 ABOUT HERE

2.2. Results

2.2.1. Behavioral results

For the filler trials, an accurate response was no response because there was no solution. Filler trial accuracy was 97% (95% CI = [95%, 100%]), indicating that participants did not press the button habitual, and did not often guess when there was no solution.

A repeated measures analysis of variance (ANOVA) on accuracy in the critical trials showed that participants had significantly lower accuracy in the TCD condition, *M* = 0.86, 95% CI = [.83, .90], than the LCD condition, *M* = 0.98, 95% CI = [.97, .99], *F* (1, 21) = 60.48, *p* < .001, 95% CI for difference = [-.15, -.09], with a large effect size, η^2 = 0.74. In addition, participants took more time to complete the task in the TCD condition, *M* = 1568.46 msec, 95% CI = [1454.20, 1682.72], than in the LCD condition, *M* = 899.47 msec, 95% CI = [826.85, 972.08], *F* (1, 21) = 259.16, *p* < .001, 95% CI for difference = [582.57, 755.42], with a large effect size, η^2 = 0.93. These results indicate that the tight vs. loose chunk manipulation was successful.

To determine if character frequency influenced the difficulty of chunk decomposition, the authors computed a Pearson correlation between the frequency of the source character and both reaction time data, and accuracy data. There was no significant correlation between frequency and reaction times: *r* (92) = .019, *p* = .854, nor between frequency and accuracy: *r* (92) = -.137, *p* = .192.

2.2.2. ERPs results

N2 (240-460 msec): The mean amplitude of the N2 in the TCD condition, *M* = 2.08 μV, 95% CI = [.93, 3.23], was higher than the mean amplitude of N2 in the LCD condition, *M* = 3.66 µV, 95% CI = [2.26, 5.07], *F* (1, 21) = 9.86, *p* = .005, 95% CI for difference = [-2.63, -.53], with a large effect size, η^2 = .32. There was no interaction between chunk type and electrode, *F* < 1.

LPC (460-800 msec): The mean amplitude of the LPC in the TCD condition, *M* = 1.79 µV, 95% CI = [.76, 2.82], was lower than the mean amplitude of LPC in the LCD condition, *M* = 5.29 µV, 95% CI = [3.97, 6.60], *F* (1, 21) = 23.58, *p* < .001, 95% CI for difference = [-4.99, -2.00], with a large effect size, η^2 = .53. No interaction between chunk and electrode was found, *F* <1.

FIGURE 3 ABOUT HERE

Evidence for distinct effects: Inspection of the grand average waveforms could provoke the concern that the N2 and LPC effects were not distinct. That is, the effects appear to overlap in space and in time. This could occur for several reasons (see Luck, 2014 for several discussions of this issue). First, event-related mental processes unfold over time such that later processing is influenced by earlier processing. Second, distinct mental processes can generate ERP components that have similar topological distributions. Third, it is an intrinsic property of the EEG that data points across either space or time will be correlated dependent on proximity. In an attempt to disentangle the significant N2 effect from the LPC effect, the authors did the following work.

The authors calculated *p*-values from a paired *t*-test of the difference between the TCD and LCD conditions at frontal/central (F1, F2, F3, F4, Fz, FC1, FC2, FC3, FC4, FCz), central/parietal (C1, C2, C3, C4, Cz, CP1, CP2, CP3, CP4, CPz), and parietal/occipital regions (P1, P2, P3, P4, Pz, PO3, PO4, POz, O1, O2), comparing mean amplitude within a 20 msec sliding window at each time point in the epoch from -190 msec to 790 msec. Figure 3 shows the *p*-values plotted across time. Between 200 msec and 300 msec, the difference between TCD and LCD conditions was significant at frontal/central electrodes but not at parietal/occipital electrodes. Further, the later LPC effects were consistently significant at parietal/occipital electrodes, but fell away from significance at frontal/central electrodes beginning at approximately 500 msec. Finally, there was a gap in significant effects between approximately 300 msec and 360 msec indicating that the N2 and LPC effects did not overlap in time.

Though there were strong *a priori* reasons based on previous work (Mai et al., 2004; Qiu et al., 2006) for selecting the electrode groups and time windows for analysis reported above, the *p*-value plot indicated *post hoc* that the N2 and LPC were maximally distinct at narrower time windows and more focal topologies. That is, the N2 effect was significant at frontal/central electrodes but not parietal/occipital electrodes between 200 msec and 300 msec and the LPC effect was significant at parietal/occipital electrodes but not at frontal/central electrodes between 700 msec and 800 msec. The relevant statistics for these *post hoc* time-window and electrode groupings are as follows: The *post hoc* N2 was more negative in the TCD condition, M = 2.31 µV, 95% CI = [.71, 3.90], than in the LCD condition, M = 3.51 µV, 95% CI = [1.70, 5.32], F (1, 21) = 4.72, p = .04, 95% CI for difference = [-2.36, -.05], with a medium effect size, η^2 = .18. The *post hoc* LPC was less positive in the TCD condition, *M* = -1.77 µV, 95% CI = [-2.99, -.54], than in the LCD condition, *M* = 1.91 µV, 95% CI = [.70, 3.12], *F* (1, 21) = 19.39, *p* < .001, 95% CI for difference = [-5.41, -1.94], with a large effect size, η^2 = .48.

To further examine the relationship between these two effects, the authors tested for a correlation between the *post hoc* N2 and LPC effects. The authors quantified the N2 effect by subtracting the mean amplitude of the LCD N2 from the mean amplitude of the TCD N2 between 200 msec and 300 msec across frontal/central electrodes, and the LPC effect by subtracting the mean amplitude of the LCD LPC from the mean amplitude of the TCD LPC between 700 msec and 800 msec across parietal/occipital electrodes. The correlation between effects was not significant, *r* (22) = .394, *p* = .069, but the *p* value was close to threshold. Thus, the *p*-value plot suggests the N2 and LPC effects are distinct, but the correlation does not bolster this interpretation. Taken together, these secondary analyses suggest the authors can tentatively discuss the N2 and LPC effects as distinct, but further work is warranted. Experiment 2 returns to this issue.

2.3. Discussion for Experiment 1.

The behavioral results show that participants took longer to decompose tight chunks than loose chunks, and made more errors on tight chunks. These results support the hypothesis that perceptual chunk tightness is an important determinant of the difficulty of chunk decomposition. In addition, when compared to loose chunk decomposition, tight chunk decomposition elicits an enhanced N2 (240-460 msec) as well as a decreased LPC (460-800 msec).

Consistent with the predicted effect, the N2 in the TCD condition was larger than in the LCD condition. Previous studies have shown that the fronto-central N2 is sensitive to conflict, with higher amplitude in conflict-inducing tasks, such as in the incongruent condition of an Eriksen flanker task (Bartholow et al., 2005; Kopp, Rist, & Mattler, 1996; Van Veen & Carter, 2002a). The fronto-central N2 is generated in the anterior cingulate cortex (ACC), as indicated through source modeling of the N2 (Bocquillon et al., 2014; Van Veen & Carter, 2002a, 2002b), and fMRI studies of the flanker task (Botvinick, Nystrom, Fissell, Carter, & Cohen, 1999). A major theory of the N2 is that N2 reflects conflict detection by the ACC (Botvinick et al., 1999; Folstein & Van Petten, 2008). However, the N2 wave is also sensitive to difficulty in visual discrimination tasks (Senkowski & Herrmann, 2002). In the current task, the authors speculate that the N2 reflects the process of recognizing/discriminating the probe inside the source character. The larger N2 amplitude in the TCD condition might indicate high conflict in the process of probe identification, due to interference from the spatially intersecting relationship. The effect would be similar to the increased interference observed in the attentional blink task when distracters appear closer in time to the targets (Warren, Breuer, Kantner, Fiset, Blais, & Masson, 2009), or when distracters overlap in time with targets (Nieuwenhuis, Gilzenrat, Holmes & Cohen, 2005). Warren and colleagues (2009) interpret the interference as neural conflict.

Additionally, there was a decreased LPC in the TCD condition relative to the LCD condition. The LPC is sensitive to mental workload (Kok, 2001). Specifically, the amplitude of the LPC decreases as memory load or task demand increases (Johnson, 1986; Kok, 2001). In a chunk decomposition task, once individuals identify the probe, a process of perceptual transformation from one percept (e.g., the to-be-removed part) to another (e.g., the to-be-left part) should occur. Thus, the elicited LPC deflection might index the transformation between perceptual representations, a type of visuo-spatial processing (Wu et al., 2013). The decrease in LPC amplitude observed here might reflect difficulty in perceptual transformation caused by chunk tightness (specifically the spatially intersecting relationship), which imposes a greater memory load and requires allocation of more cognitive resources.

There are several potentially confounding factors in Experiment 1. First, the to-be-removed part appears as a probe in a standard form in the first exposure and in a non-standard form (as part of the source character) in the second exposure. Thus, sometimes changes in the precise shape of a part between the first and the second exposure occurred. To eliminate such noise in Experiment 2, the shape of the to-be-removed part held constant across the two exposures (see the examples in Figure 4). Second, among the possible types of non-intersecting relationships (vertical offset, horizontal offset, or half-surrounding), the probability of each individual type is lower than the probability of the spatially intersecting relationship. Again, Experiment 2 eliminates the source of noise, by controlling differences in the frequencies of the various types of spatial relationships and by using only a vertical offset relationship in the LCD condition. Third, the effect on the elicited N2 in Experiment 1 could overlap with an effect of the classic N400 wave. Generally, semantic violations in linguistic processing provoke a N400 component (Hagoort, Hald, Bastiaansen, & Petersson, 2004; Holcomb, 1993; Kutas, & Hillyard, 1980). The N400 is also sensitive to conceptual fluency (Wolk, Schacter, Berman, Holcomb, Daffner, & Budson, 2004). Chinese characters contain semantic information, and thus can elicit N400 deflections (e.g., Liu, Perfetti, & Hart, 2003). The time window analyzed for N2 (240-460 msec) in Experiment 1 largely overlaps with the time window of the classic N400 (300-500 msec). Further, the well-known repetition priming effect for N400 implies that the second presentation of a word should induce a decreased N400 amplitude (Kutas & Federmeier, 2000; Van Petten, Kutas, Kluender, & Mitchiner, 1991). In the current chunk decomposition task, the participants view a probe, and then must find that probe in the source character. This means the probe repeats and thus could elicit a repetition priming, N400 response. To distinguish the N2 from a potential N400, Experiment 2 introduces a third condition, in which the to-be-removed part is not actually present in the source character, making it impossible for the participants to obtain a new character (The third condition serves as a “filler” condition relative to TCD and LCD). Previous research indicates that unrepeated characters (relative to repeated characters) elicit larger N400 deflections in a Chinese character matching task (Wang, Huang, & Mao, 2009). Considering that a matching or identification process is needed when looking for the to-be-removed part in the current character decomposition task, the third (filler) condition should elicit a standard N400, serving as a reference for differentiating between the N2 effect and a potential subsequent N400 effect.

The authors conducted the primary ERP analysis in Experiment 1 using *a priori* time windows based on previous work (Mai et al., 2004; Qiu et al., 2006). However, these time windows did not appear to capture distinct effects. A secondary analysis characterizing the effects across time and space indicated that the significant effect of chunk tightness was separated across both space (frontal-central vs. parietal-occipital) and time (no significant effects between ~300 msec and 360 msec) (see Figure 3). However, a correlational analysis using *post hoc* time windows guided by the data suggested that the frontal/central N2 effect between 200 msec and 300 msec and the LPC effect between 700 msec and 800 msec were closely, if not significantly, related. The authors performed the same set of analyses in Experiment 2 to address this issue further.

3. Experiment 2

The aim and task of Experiment 2 were the same as Experiment 1 with the main difference that the fillers serve not only to reduce and assess rates of guessing, but also as a control condition for the comparison with the critical conditions (TCD and LCD). The amount of trials was equivalent across three decomposition conditions or levels (TCD vs. LCD vs. fillers/ “not”) for final ERP analysis and comparisons.

3.1. Methods

3.1.1. Participants

Selection and consent procedures for a new group of 24 participants (12 males; mean age = 23.6, 95% CI = [22.53, 24.72]), were identical to Experiment 1, as was the compensation with a small honorarium (¥ 30 Yuan). No volunteer from

Experiment 1 participated in Experiment 2.

3.1.2. Stimuli

Stimuli were the same as those in Experiment 1 with the following exceptions. First, there were forty trials in the TCD and LCD conditions, respectively. Second, the to-be-removed parts and the to-be-left parts were always in a relationship of vertical offset in the source character for the LCD condition (see the examples in Figure 4). Third, 40 new source characters, each composed of a to-be-removed part and the to-be-left part, were collected for the filler condition. These characters were separated in order to be randomly regrouped with other characters in any given trial. For example, the character “禾” from “秀”, the character “正” from “歪” and the character “舍” can make up a catch trial, in which participants cannot find “禾” within the source character “舍”, and thus cannot remove “禾” to get the target character “正”. Fourth, the average stroke number was computed among the three conditions (the filler/control condition, the TCD condition, the LCD condition) in an attempt to limit variability in stroke number across conditions. The average stroke number of the probes were 2.85, 3.05, 3.05, which did not differ significantly, F (2, 117) = .28, p = .76. The average stroke number of the source character was 6.075, 6.65, 6.65, which also did not differ significantly, F (2, 117) = 1.23, p = .30. The average stroke number of the target also did not differ, (3.35, 3.6, 3.6), F (2, 117) = .38, p = .68. Fifth, the new characters exhibited a significant difference in frequency of use in the Chinese language between the TCD (M±SD: (.0779 ±.1204)%) and the LCD (M±SD: (.0206 ± .0227)%), F (1, 78) = 8.77, p = .004, η^2 = .101 conditions (character frequency was statistically referenced by www.cncorpus.org). This difference in character frequency was unintentional, but as reported in the behavioral results, character frequency differences did not appear to produce any behavioral differences across conditions. No other changes were made to the stimuli, and the size of the stimuli was the same as in Experiment 1 (subtending 3.3 × 3.3° of visual angle).

FIGURE 4 ABOUT HERE

3.1.3. Procedure and task

The procedure and task in Experiment 2 were the same as the procedure and task in Experiment 1 except that the durations of the source character and the left character were adjusted to 3 seconds and 2 seconds, respectively, in light of the average response times in Experiment 1. The 120 trials (40 trials in the TCD condition, 40 trials in the LCD condition and 40 filler trials) were presented in a randomized order in each block. Participants were given a break every 40 trials. There were 12 practice trials before the formal experiment.

3.1.4. ERP recordings and analysis

The ERP recordings and the pre-processing steps of ERP data from re-referencing to grand averaging was the same as Experiment 1. The impedances of all electrodes were kept below 10 kΩ: the actual average was 2.86 kΩ, (range 0-7 kΩ).

The time ranges analyzed were different between Experiment 1 and 2, to allow for independent analysis of the N400. The N2 was analyzed between 260-360 msec, the N400 in a 360-460 msec time window, and the LPC was analyzed during the same time window as Experiment 1, 460 to 800 msec (see Figure 5 and 6). The mean amplitude of N2 was measured at the same 25 electrodes as in Experiment 1, and the N400 was analyzed at the same electrodes as the N2. The mean amplitude of LPC was measured at the same 13 electrodes as in Experiment 1. One final difference in analysis between Experiment 1 and 2 was that in Experiment 2, the ERPs to the filler condition were included as third level of the chunk tightness factor in the omnibus ANOVA.

3.2. Results

3.2.1. Behavioral results

The percentage of correct no-responses in the filler condition was 96% (95% CI = [94%, 97%]), indicating again that participants did not guess when there was not an apparent solution. Participants had lower accuracy in the TCD condition, $M = .89$, 95% CI = [.85, .92], than the LCD condition, $M = .98$, 95% CI = [.97, .99], $F(1, 23) = 34.76$, $p < .001$, 95% CI for difference = [-.13, -.09], with a large effect size, $\eta^2 = .62$. In addition, participants took more time to complete the task in the TCD condition, $M = 1436.43$ msec, 95% CI = [1355.20, 1517.66] than in the LCD condition, $M = 916.95$ msec, 95% CI = [858.68, 975.21], $F(1, 23) = 421.34$, $p < .001$, 95% CI for difference = [467.13, 571.83], with a large effect size, $\eta^2 = .95$.

Character frequency did not appear to influence chunk decomposition difficulty. Pearson correlations indicated no significant correlation between frequency and reaction times: *r* (80) = .038, *p* = .738, nor between frequency and accuracy: *r* (80) = -.006, *p* = .961.

3.2.2. ERPs results

N2 (260-360 msec): There was a medium significant main effect of decomposition level, Greenhouse-Geisser correction: ε = .79, *F* (2, 46) = 6.83, *p* = .005, η_p^2 = .23; Huynh-Feldt correction: *F* (2, 46) = 6.83, *p* = .005. The pairwise comparison (**Bonferroni corrections**) showed that mean amplitude between N260-360 in the TCD condition, *M* = 2.96, 95% CI = [1.44, 4.49], was higher than in the two other conditions (compared to the LCD condition, *M* = 4.81, 95% CI = [2.93, 6.68] *p* = .009, 95% CI for difference = [-3.27, -.42]; compared to the filler condition, *M* = 4.27, 95% CI = [2.89, 5.64], *p* = .004, 95% CI for difference = [-2.23, -.37]). There was no difference between the LCD condition and the filler condition (*p* = 1.0). There was no significant interaction of decomposition level * electrode, Greenhouse-Geisser correction: ε = .18, *F* (48, 1104) = 1.66, *p* = .11, with a small effect size, η_p^2 =.07; Huynh-Feldt correction: *F* (48, 1104) = 1.66, *p* = .11.

FIGURE 5 ABOUT HERE

N400 (360-460 msec): There was a large significant main effect of decomposition level, *F* (2, 46) = 8.69, *p* = .001, η_p^2 =.27. The pairwise comparison (**Bonferroni corrections**) showed that there was no difference between the TCD condition, *M* = 2.56, 95% CI = [.57, 4.55], and the filler condition, *M* = 2.87, 95% CI = [1.25, 4.48] (*p* = 1.0, 95% CI for difference = [-1.92, 1.30]), but both were higher than the mean amplitude of N360-460 in the LCD condition, *M* = 5.09, 95% CI = [3.13, 7.06] (for TCD vs. LCD, *p* = .001, 95% CI for difference = [-4.08, -.98]; for filler vs. LCD, *p* = .02, 95% CI for difference = [-4.18, -.27]). There was no significant interaction of decomposition level * electrode, Greenhouse-Geisser correction: ε = .19, *F* (48, 1104) = 1.48, *p* = .15, with a small effect size, $\eta_p{}^2$ = .06; Huynh-Feldt correction: *F* (48, 1104) = 1.48, *p* = .10.

FIGURE 6 ABOUT HERE

LPC (460-800 msec): There was a large significant main effect of decomposition level, *F* (2, 46) = 14.71, *p* < .001, $\eta_p{}^2$ =.39. The pairwise comparison (**Bonferroni corrections**) showed that there was a significant difference between each pairing of the three conditions: TCD (*M* = 2.00, 95% CI = [-.10, 4.11]) < LCD (*M* = 3.91, 95% CI = [1.76, 6.06]) < filler (*M* = 5.87, 95% CI = [3.75, 7.98]), [*p* (TCD vs. LCD) = .02, 95% CI for difference = [-3.61, -.21]; *p* (TCD vs. filler) < .001, 95% CI for difference = [-5.78, -1.95]; *p* (LCD vs. filler) = .04, 95% CI for difference = [-3.86, -.06]. There was no significant interaction between decomposition level and electrode. Greenhouse-Geisser correction: ε = .35, *F* (24, 552) = 1.33, *p* = .23, with a small effect size, $\eta_p{}^2$ = .06; Huynh-Feldt correction: *F* (24, 552) = 1.33, *p* = .19).

FIGURE 7 ABOUT HERE

Evidence for distinct effects: As was done for the data from Experiment 1, *p*-values were plotted across time for the difference between the LCD and TCD conditions at frontal/central, central/parietal, and parietal/occipital regions (Figure 7). Figure 7 indicates that the LPC effect observed after 500 msec was significant at parietal/occipital regions, but not at frontal/central nor central/parietal regions. In addition, the N2 effect began later in Experiment 2 (~300 msec) and extended for a longer period of time (approximately 200 msec). This may be the spatial and temporal overlap between the N2 and N400 effects, potentially provoked by including the filler condition in Experiment 2, or perhaps by other small differences, including the use of different participants.

The *p*-value plot for experiment 2 suggested the N2 did not begin until 300 msec. In addition, the LPC effect showed spatial specificity between 600 msec and 800 msec. To continue the examination of the relationship between the N2 and LPC effects begun in Experiment 1, the authors analyzed the *post hoc* N2 at frontal/central electrodes between 300msec and 400 msec, and the *post hoc* LPC at parietal/occipital electrodes between 600 msec and 800 msec. The *post hoc* N2 was more negative in the TCD condition, $M = 1.55$ µV, 95% CI = [-.57, 3.68], than in the LCD condition, $M = 4.00$ µV, 95% CI = [2.00, 6.01], F (1, 23) = 17.23, $p < .001$, 95% CI for difference = [-3.67, -1.23], with a large effect size, $\eta^2 = .43$. The *post hoc* LPC was less positive in the TCD condition, $M = -.41$ µV, 95% CI = [-2.53, 1.71], than in the LCD condition, $M = 1.62$ µV, 95% CI = [-.46, 3.70], F (1, 23) = 11.62, $p = .002$, 95% CI for difference = [-3.26, -.80], with a large effect size, $\eta^2 = .34$. As in Experiment 1, the authors quantified the *post hoc* N2 and LPC effects in these maximally distinct time-window/electrode-grouping combinations by subtracting the LCD values from the TCD values. The correlation between *post hoc* N2 and LPC effects was not significant, *r* (24) = .250, *p* = .239. This non-significant effect does not prove the effects are distinct, but continued, cautious interpretation along these lines seems appropriate.

3.3. Discussion for Experiment 2

Experiment 1 primarily investigated the role of chunk tightness in chunk decomposition, by comparing the TCD and LCD conditions. Experiment 2 added the filler condition to the statistical analysis, giving three decomposition levels (TCD vs. LCD vs. filler). In addition, the primary negative-going deflection in Experiment 1 was divided into an N2 (260-360 msec) and an N400 (360-460 msec) for measurement and analysis in Experiment 2.

The ERPs results of Experiment 2 show characteristic differences in the pattern of sensitivity across conditions, dissociating these components. The N2 was sensitive to the difference between tight and loose chunks, but not between loose chunks and the filler condition. The N400 was sensitive to the difficulty of finding the probe, but not to the difference between a difficult probe identification, and no probe identification in the filler condition. The LPC effect was distinctive from the N2 and N400 effects by virtue of being sensitive to the differences between all three conditions.

Experiment 2 replicated the N2 effect seen in Experiment 1, in that the TCD condition elicits a larger N2 than the LCD condition, even when the shape of the probe is kept rigorously constant and the spatial offset between the to-be-removed part and the target character is always vertical in the LCD condition.

In Experiment 2 the filler condition elicited an N400, representative of the N400 repetition effect, in which a non-repetition condition elicits a larger N400 than a repetition condition (Kutas & Federmeier, 2000; Van Petten et al., 1991; Wang et al., 2009). The observed N400 in the filler condition might reflect a semantic violation that occurs when participants cannot find the target character within the source character. With the N400 elicited in the filler condition taken as reference, there is an enhanced N400-like deflection (N360-460) in the TCD (vs. LCD) condition, following the N2 (N260-360). However, there is no significant difference in N400 amplitude between the TCD condition and the filler condition, suggesting that the neural activity associated with searching for the solution in the TCD condition is similar to activity associated with failing to find the probe stimulus within the source character, even though the accuracy data indicates that participants typically do find the solution.

As an interim summary, the N2 effect, the N400 effect, and the LPC effect together seem to index multiple stages of chunk decomposition. The N2 seems to reflect neural conflict or interference associated with identifying the probe in crossed-relation with the target. The N400 effect then reflects the ongoing difficulty of mentally extracting the probe when it is firmly embedded or not at all present in the source character, relative to the easier, LCD condition. Finally, the LPC effect seems to index the last stage of the mental task, when subjects have either realized there is no solution (largest LPC to the filler condition), are solving the solution easily (intermediate LPC), or are having greater difficulty performing the final visuo-spatial transformation associated with the solution (smallest LPC).

4. General discussion

This work investigated the temporal course of neural activity associated with insight-based problem solving in a chunk decomposition task, **revealing that the N2 and LPC (Experiment 1 and 2), and the N400 (Experiment 2) are all sensitive to the difficulty of chunk decomposition.** Each of these ERP components have a unique sensitivity to our manipulation, allowing speculation on the progress of problem solving in the task from early to late stages. In addition, what is already known about each of these components can be leveraged to suggest what cognitive process is occurring during each window of time.

4.1. Different roles of spatial intersection and element type in chunk decomposition

Interestingly, the pattern of LPC deflection in the current study is completely different from the pattern observed by Wu and colleagues (2013), in which the LPC deflection was larger during tight chunk decomposition than during loose chunk decomposition. The different results must be due to the different ways of manipulating chunk tightness between the current work, and the study of Wu and colleagues. Wu and colleagues used a conceptual manipulation of chunk tightness based on whether the to-be-removed component had independent meaning or not, Conceptual manipulations of chunk tightness have a smaller effect on chunk decomposition difficulty than perceptual manipulations (Zhang et al., 2015). In contrast, the current study uses a perceptual manipulation of chunk tightness whereby tight chunks have spatially overlapping components and loose chunks do not. It is reasonable to suggest that these two different manipulations of chunk tightness might influence chunk decomposition through different mechanisms. Such a proposal still needs to be tested, given that neither study compared the neural underpinnings of perceptual and conceptual manipulations of chunk tightness directly.

4.2. Two-phase difficulties of insight problem solving

The observed time course of ERP effects (N2, N400, and LPC) in the current work support a preliminary model of insight problem solving during Chinese character decomposition (see Figure 8). The model suggests two essential phases: an identification process and a transformation process. In the model, perceptual chunk tightness causes the difficulty of both probe identification and perceptual transformation.

FIGURE 8 ABOUT HERE

In the first phase, individuals have to recognize the key element of a perceptual chunk. The first step serves as an initiation probe for the decomposition of a perceptual chunk. The ERP data exhibit sensitivity to the difficulty of identification in the consecutive N2-N400 waves. The enhanced amplitude of N2 indicates greater conflict in the TCD condition. Subsequently, the enhanced N400 deflection indicates greater semantic violation in the TCD condition and the filler condition, compared to the LCD condition. The difficulty in identification causes both the conflict-related N2 effect and the semantic violation N400 effect.

The second phase involves the transformation of the perceptual representation. In the second phase, the hierarchical pattern of LPC amplitudes across the three conditions (TCD < LCD < filler) provides evidence for the difficulty of transformation hypothesis. The LPC reflects a process of perceptual transformation (Wu et al., 2013) from an old perceptual element to a new one (the target character). As the difficulty of transformation increases, associated demands such as memory load increase, which results in a decrease in LPC amplitude (Johnson, 1986; Kok, 2001). Further, the difficulty of perceptual transformation contributes to poor behavioral performance, as an additional correlation analysis (by combining data from both experiments) indicates that there was a significant negative correlation between LPC amplitude values and response times [r (92) = -.290, p = .005].

4.3. Conflict detection and resolution in creative insight: Implications of early ERP negativity (N2) and late ERP positivity (LPC) effects.

A leading theory of the N2 is that N2 reflects conflict detection by the ACC (e.g., Botvinick et al., 1999; Coderre, Conklin, & van Heuven, 2011; Folstein & Van Petten, 2008). The conflict is due to simultaneous activation of incompatible representations (Botvinick et al. 1999). The N2 effect observed here supports the view that conflict detection and resolution play essential roles in creative insight, particularly in breaking an impasse (Laukkonen & Tangen, 2017; Zhao et al., 2014). The cause of impasse is ineffective mental representations (experience-based constraints or constraints imposed by biases in the perceptual system). These mental representations interfere with the process of finding the solution (Zhao et al., 2014). The interference might provoke the neural conflict associated with the N2, and conflict detection may be the impetus for abandoning the ineffective mental representation. Such an interpretation is supported by studies of other insight problem solving tasks that also report a larger N2 and/or greater ACC activity in more difficult problems. For example, many studies of insight problem solving have found an increased N2 when the solution required the breaking of experience-based constraints (Luo et al., 2011; Mai et al., 2004; Qiu et al., 2006; Zhao et al., 2014; Wang et al., 2009; Xing, Zhang, & Zhang, 2012). Dipole source analysis in two of these studies suggested that the generator of the N2 was located in the ACC (Mai et al., 2004; Wang et al., 2009). In addition, fMRI studies have observed strong ACC activation in solving verbal problems of insight, such as Chinese riddles (Luo, Niki, & Phillips, 2004), the RAT task (Subramaniam et al., 2009), and the anagram task (Aziz-Zadeh et al., 2009). Finally, researchers have observed greater ACC activity in other chunk decomposition tasks for conceptually tight chunks versus conceptually loose chunks (Wu et al., 2013).

The LPC effect may reflect conflict resolution during the breaking of the impasse in these kinds of problems. LPC, has been associated with conflict resolution in the Stroop task (Appelbaum, Boehler, Davis, Won, & Woldorff, 2014; Coderre et al., 2011; Xiang, Wang, & Zhang, 2013; West, 2003). During insight problem solving, detecting conflict alone is not sufficient for breaking the impasse. As Qiu et al. (2006) show in a Chinese riddle task, both the unsolved condition and the insight condition elicited greater N2-like deflections than the non-insight condition. Thus, the N2 is not predictive of finding the solution, such that resolving the conflict is necessary as well (Zhao et al., 2014). Accumulating work has provided evidence that LPC might function as an index of conflict resolution when breaking the impasse caused by experience-based constraints. Several studies have observed LPC effects following N2 effects (Xing et al., 2012; Zhao et al., 2014), Wang and colleagues (2009) found additional positive deflections (P300-800 and P1200-1500) over parietal-occipital regions, together with additional negative deflections (N300-800 and N1200-1500) over fronto-central regions. Similarly, Luo et al. (2011) found a greater P900-1700 (insight vs. non-insight) accompanied by early negative deflections (N300-500 and N1100-1300). Concomitant with the conflict-detecting negativity, the LPC might reflect conflict resolution as an index of activation of the answer (Zhao et al., 2014), or as an index of the formation of new associations (Luo et al., 2011; Wang et al., 2009; Xing et al., 2012).

4.4. Limitations and future directions

The interpretation offered here of findings presented in the current work should be tempered by several considerations. First, though the N2 findings in the current and other work support the involvement of conflict detection in breaking an impasse during insight problem solving, there has been some inconsistent work. For example, Zhang et al. (2011) found a P400-600 effect associated with insight solutions (vs. search solution) in a Chinese anagram task and argued that the P400-600 reflected the breaking of mental set. Zhang and colleagues did not find an N2 effect in that study.

Similarly, Zhao et al. (2011) found a P500-700 deflection associated with breaking an impasse and no N2 effect. Second, in contrast to the many important papers linking the N2 to conflict detection, the link between conflict resolution and the LPC has not yet received abundant support (Appelbaum et al., 2014; Coderre et al., 2011). In fact, some have suggested that LPC might reflect semantic processing (e.g., Liotti et al., 2000). Thus, the account of conflict deflection and resolution on creative insight calls on more empirical examinations in the future.

There are some methodological limitations that should be noted here as well. First, though the authors carefully handled channel selection and time window definition according to the experimental observations and previous studies, more objective data-driven methods (e.g., principle components analysis) have been encouraged for ERP analysis (Dien, 2012; Dien, Beal, & Berg., 2005).

Second, the ANOVA analysis for Experiment 2 included the ERP results from the filler/control condition, which was important for testing specific claims, but raises the concern that the filler may not have been an appropriate control condition. The filler condition can be regarded as not requiring decomposition, in that the task only involves searching for the probe, not identification or perceptual transformation (i.e., transformation from the to-be-removed part to the to-be-left part). Thus, the LPC result for the filler condition may not be able to provide sufficient information to explain the difficulty of perceptual transformation. In this regard, future studies could examine a wider variety of control conditions. For example, for conditions not involving decomposition, researchers could use at least two types of control: a control condition in which the participants cannot find the probe (the to-be-removed part) within the source character, so that decomposition does not occur, coupled with a control condition in which participants can find the probe but cannot use it to create a valid character. In this way, researchers could isolate the ERP activity associated with specific task phases (probe identification or perceptual transformation). Another consideration is that future researchers could construct a three-level parametric design for chunk tightness: high vs. middle vs. low (loosest). In this way, researchers could get deeper insight into how the ERPs change incrementally with changes in chunk tightness.

Finally, though this study reveals consistent ERP effects across the two experiments, the ERP patterns are inconsistent to some degree. For instance, the slope of LPC is steep in Experiment 1 but not steep in Experiment 2, appearing more similar to a long-lasting P3b in Experiment 2. The LPC and P3b (as well as N400) overlap in time but might be functionally dissociable (Misra & Holcomb, 2003; Olichney, Yang, Taylor, & Kutas, 2011). Some factors differing between experiments might affect LPC as well as overlapping components (P3b or N400) making it difficult to attribute specific effects to the LPC alone.

One factor that differed between experiments was character frequency (character frequency of use in the Chinese language). Whereas Experiment 1 controlled character frequency across the two chunk tightness conditions, Experiment 2 did not control the character frequency. However, the concern that character frequency confounded effects in Experiment 2 can be mitigated by considering that high frequency (vs. low frequency) words induce a smaller N400 (Rugg, 1990), as well as larger P300 (Polich & Donchin, 1988), a pattern opposite to that observed in the current study.

The other two factors that differed between Experiment 1 and 2 were shape change and stimuli probability. Experiment 1 did not control either factor, but Experiment 2 controlled both. It is possible that the difference in experimental control exerted over shape change and stimulus probability between experiments caused some differences in the ERPs between experiments (e.g., the LPC amplitude). Nevertheless, the main findings concerning the N2 and LPC were replicated between experiments.

In conclusion, the current study found increased amplitude of the consecutive N2-N400 wave and decreased amplitude of the LPC for tight (vs. loose) chunk decomposition. The behavioral and ERP results support the hypothesis that chunk tightness associated with spatial intersection causes the difficulty in insight problem solving by increasing neural conflict and requiring greater mental resources for visuo-spatial transformation.

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Appendix

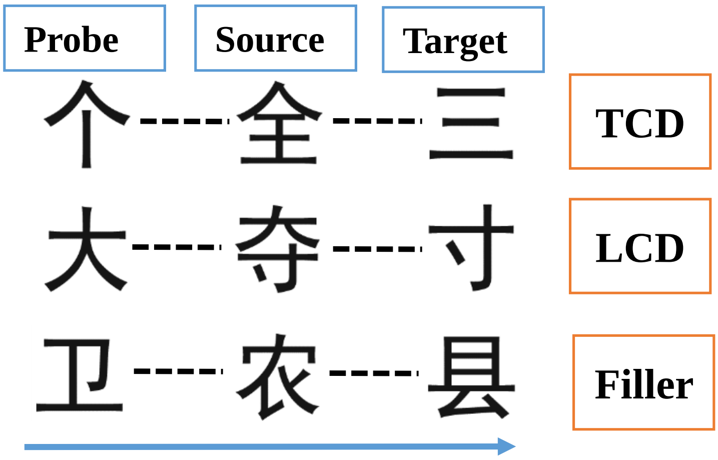

Figure 1. An example of a trial in each condition of Experiment 1. Participants were asked to remove a probe from the source character to get a target. TCD: tight chunk decomposition; LCD: loose chunk decomposition.

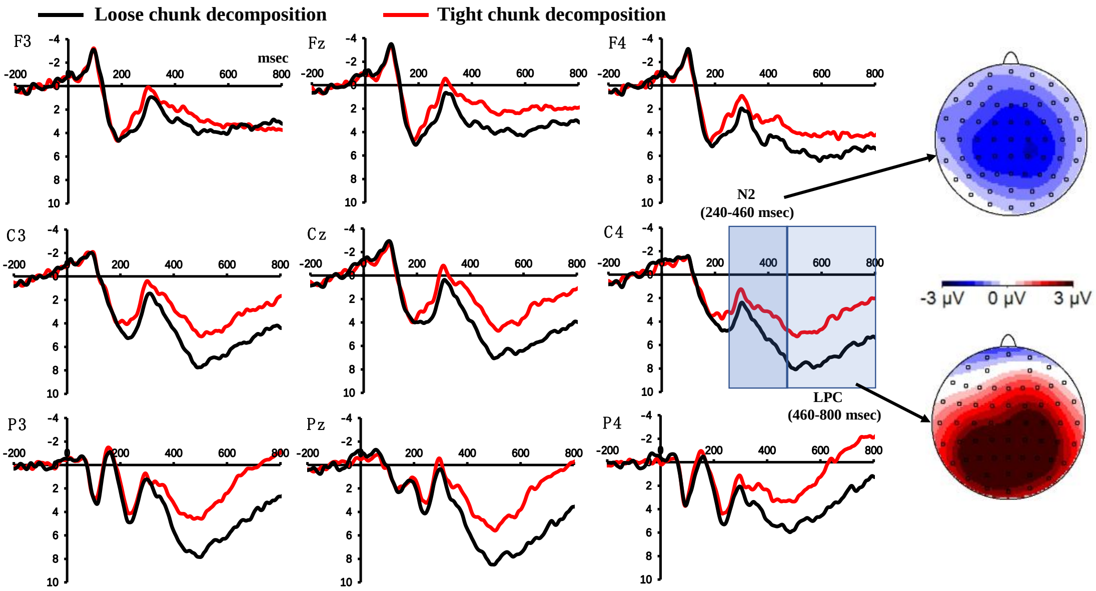

Figure 2. Grand-average ERPs and the scalp distributions of N2 and LPC in Experiment 1. Left: Grand-average ERP waveforms for the tight chunk decomposition (TCD) condition and the loose chunk decomposition (LCD) condition at 9 electrode sites. Right: topographical maps of voltage amplitudes for N2 during 240-460 msec (TCD minus LCD) and for LPC during 460-800 msec (LCD minus TCD).

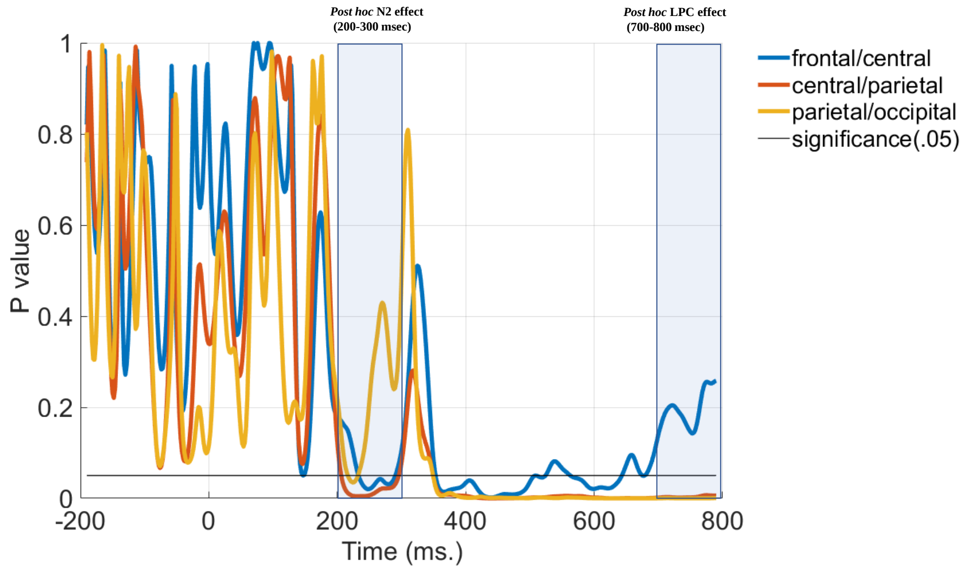

Figure 3. Significance of TCD vs. LCD difference across time for Experiment 1. There was no overlap in time of effects preceding 360 msec post-stimulus onset and effects following 360 msec post-stimulus onset. The pattern of effects also differed from frontal/central electrode sites to parietal/occipital sites. TCD: tight chunk decomposition; LCD: loose chunk decomposition.

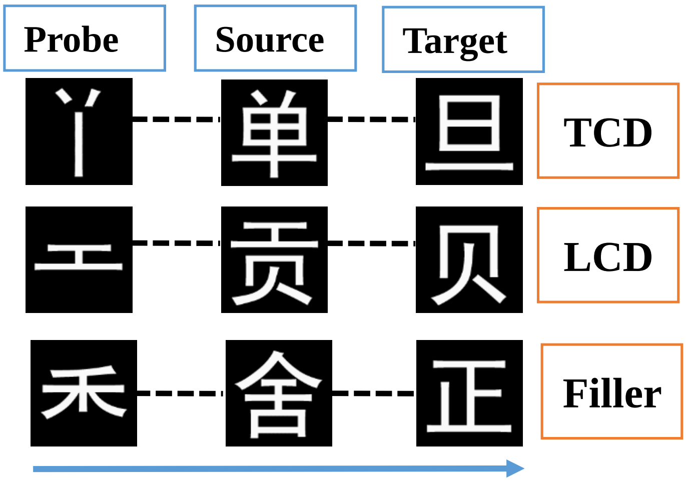

Figure 4. An example of a trial in each condition in Experiment 2. Participants were asked to remove a probe from the source character to get a target. TCD: tight chunk decomposition; LCD: loose chunk decomposition.

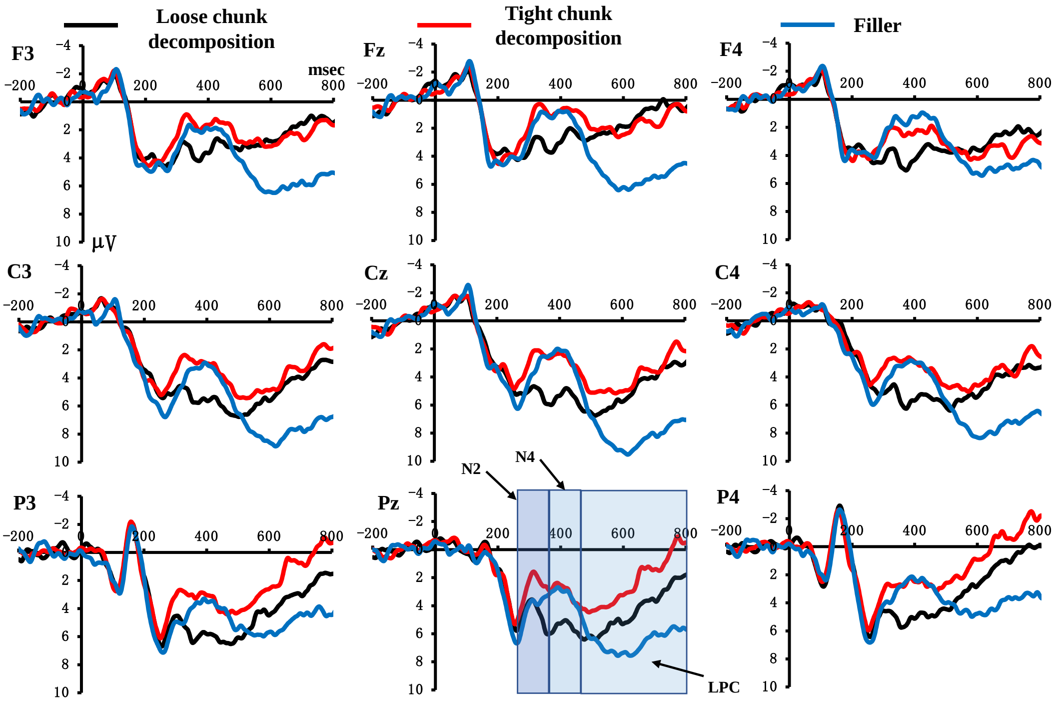

Figure 5. Grand-average ERPs in Experiment 2. Grand-average ERP waveforms for the TCD condition (red line) and the LCD condition (black line) as well as the filler condition (blue line) at the 9 electrode sites. TCD: tight chunk decomposition; LCD: loose chunk decomposition.

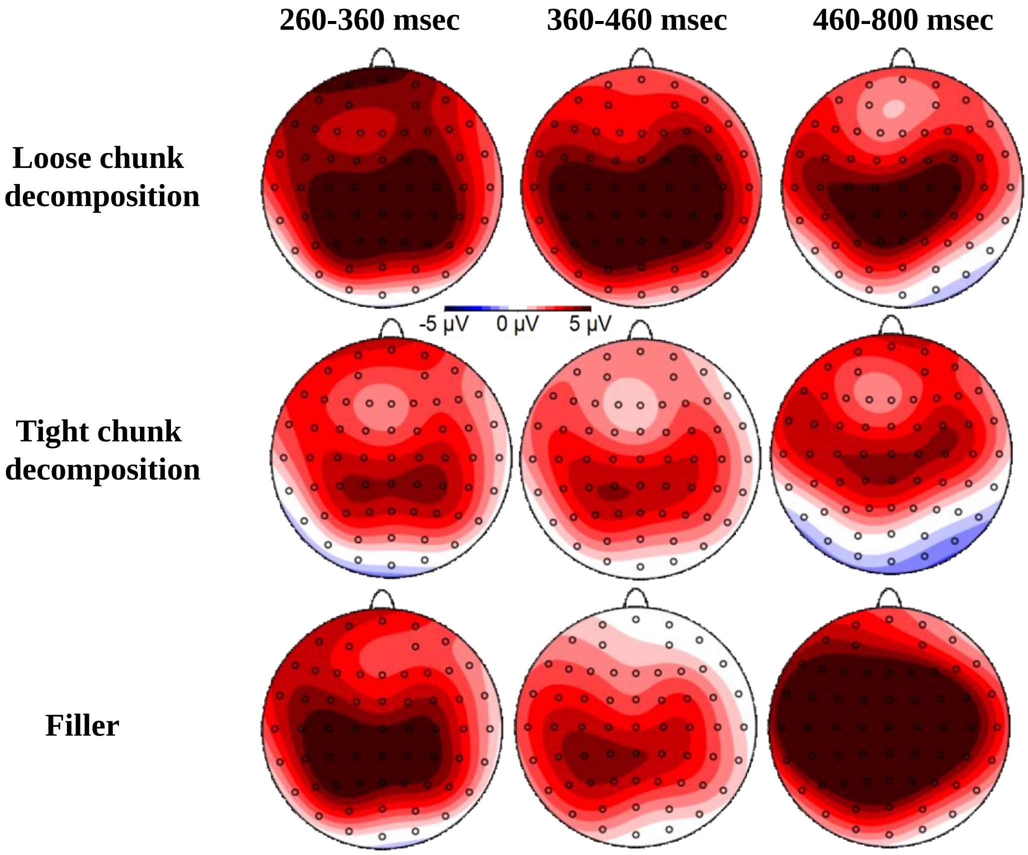

Figure 6. Topographical map of N2, N400 and LPC in three conditions from Experiment 2. Left column: Topographical map of N2 (260-360 msec); Middle column: Topographical map of N400 (360-460 msec); Right column: Topographical map of LPC (460-800 msec). (Three conditions from top to bottom: LCD vs. TCD vs. Filler). TCD: tight chunk decomposition; LCD: loose chunk decomposition.

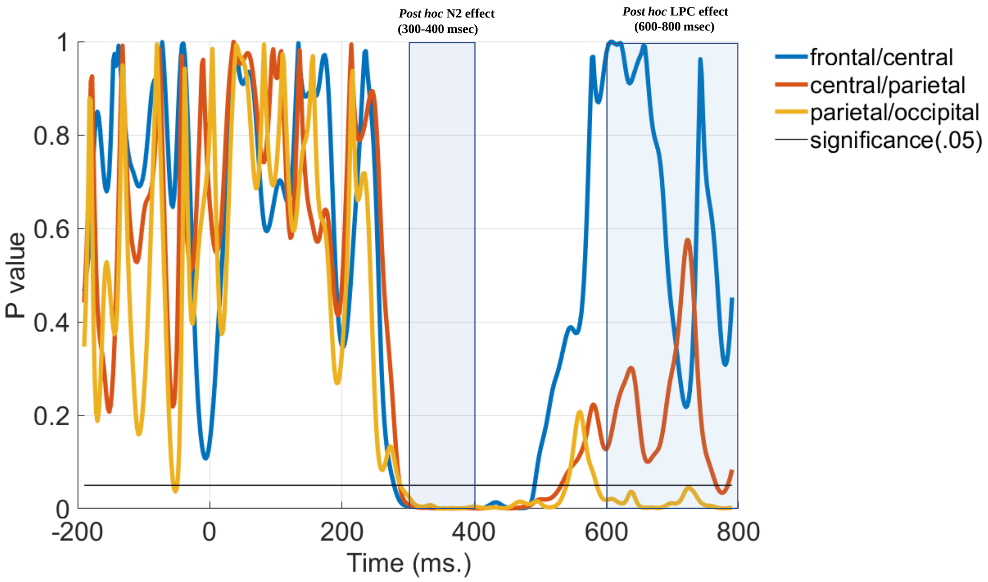

Figure 7. Significance of TCD vs. LCD difference across time for Experiment 2. LPC effects beginning at ~500 msec post-stimulus onset were only significant at parietal/occipital electrode sites. Effects between 300 msec and 500 msec post-stimulus onset were broadly distributed across the scalp, possibly due to overlap of N2 and N400 effects. TCD: tight chunk decomposition; LCD: loose chunk decomposition.

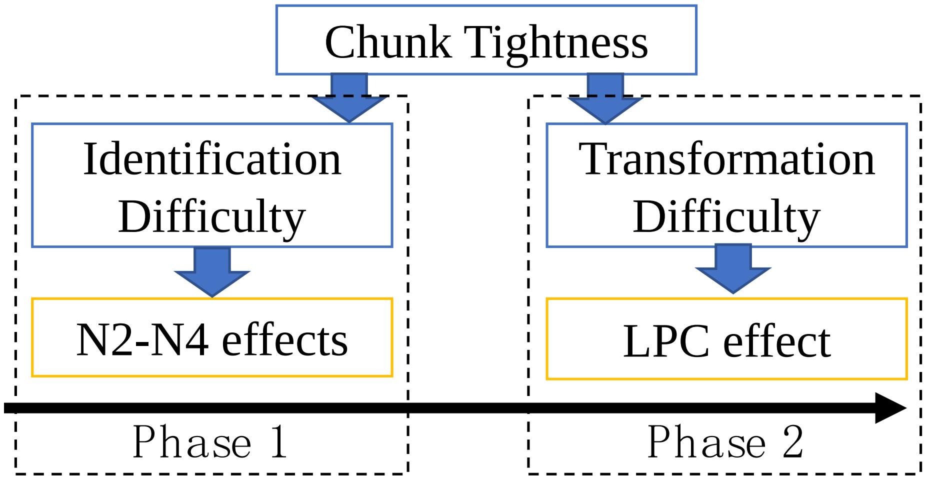

Figure 8. A two-phase model of difficulty during insight problem solving. Difficulty caused by chunk tightness influences two phases of insight problem solving. In phase 1, the N2-N400 effects index neural conflict during probe identification. In phase 2, the LPC effect indexes the difficulty of perceptual transformation.