Stimulus complexity and chunk tightness interact to impede perceptual restructuring during problem solving

Zhonglu Zhang[a,b*], Christopher M. Warren[c*], Yi Lei[b,d,e*], Qiang Xing[a*], Hong Li[b,d,e]

[a] *Department of Psychology, School of Education, Guangzhou University, Guangzhou 510006, China*

[b] *Research Centre for Brain Function and Psychological Science, Shenzhen University, Shenzhen 518060, China*

[c] *Department of Psychology, Utah State University, Logan UT, United States of America*

[d] *Shenzhen Institute of Neuroscience, Shenzhen, China*

[e] *Institute of Affective and Social Neuroscience, Shenzhen University, Shenzhen, China*

Running Head: Neural underpinnings of perceptual restructuring

*The correspondence should be sent to Yi Lei (leiyi821@vip.sina.com), Christopher M. Warren (chris.warren@usu.edu), Qiang Xing (qiang_xingpsy@126.com) or Zhonglu Zhang (zzllzz_2005@126.com)

Abstract: The mutual influence of stimulus complexity and chunk tightness on perceptual restructuring was examined using a chunk decomposition task (CDT). Participants attempted to remove components of Chinese characters in order to produce new, valid characters. Participants had their electroencephalogram recorded while completing a CDT in conditions of low or high stimulus complexity, crossed with two levels of chunk tightness. Tight chunks overlapped spatially whereas loose chunks did not. Both increasing chunk tightness and increasing stimulus complexity impaired performance (lower accuracy, longer reaction times), and these factors interacted such that highly complex, tight chunks produced the worst performance. These factors also had interacting effects on the late positive complex (LPC). The LPC amplitude was reduced by increasing chunk tightness, but this effect was attenuated for highly complex stimuli. These results suggest that though chunk tightness and stimulus complexity impair performance in the CDT, they have dissociable neural underpinnings.

Keywords: stimulus complexity; perceptual restructuring; chunk tightness; chunk decomposition; event-related potential

1. Background

Mental restructuring is essential to insight problem solving, allowing people to quickly adapt to new circumstances. An impasse describes the moment when individuals are unable to make progress with a problem, and are unaware of how to proceed (Cranford & Moss, 2012; Knoblich, Ohlsson, Haider, & Rhenius, 1999). In order to overcome the impasse, restructuring allows the problem solver to see the problem in a novel way, facilitating new progress (Duncker, 1945; Kounios & Beeman, 2014; Öllinger & Knoblich, 2009; Wagner et al., 2004; Wertheimer, 1959). Restructuring can be realized through constraint relaxation (Huang et al., 2018; Knoblich et al., 1999), when problem solving is impeded by experience-based factors such as a mental set or functional fixedness (e.g., Duncker, 1945; Kershaw & Ohlsson, 2004; Knoblich et al., 1999, 2001; Luchins, 1942; Ohlsson, 1984; Smith, 1995; Storm & Angello, 2010; Wu et al., 2013). Restructuring can also be realized through chunk decomposition (Knoblich et al., 1999; Luo et al., 2006), especially when problem solving is impeded by stimulus features such as when the features have a tightly-organized spatial relationship (Huang, He, & Luo, 2017; Knoblich et al., 1999; Tang et al., 2016; Zhang et al., 2015, 2019). The current study focuses on chunk decomposition. In contrast to “chunking”, which refers to integrating pieces of information into chunks to improve memory (Miller, 1956), chunk decomposition involves restructuring a stimulus by decomposing a “chunk” into smaller components to form new combinations (Knoblich et al., 1999; Luo et al., 2006; Tang et al., 2016; Zhang et al., 2015).

A basic question in the study of problem solving is what makes problems difficult to solve. Overcoming an impasse in problem solving has been studied extensively in the chunk decomposition context by Knoblich and colleagues (Knoblich et al., 1999, 2001). According to Knoblich et al. (1999), the difficulty of chunk decomposition is largely determined by chunk tightness. They specified a conceptual definition of chunk tightness whereby a chunk is tight when none of its components carry individual meaning, and a chunk is loose when it can be decomposed into components that have meaning on their own (Knoblich et al., 1999, 2001; Luo et al., 2006). For example, the chunk “X” (meaning ten in Roman numerals) is tight because the components “/” or “\” have no meaning in the Roman mathematical system. In contrast, the chunk “VI” (meaning six) is loose because the component “V” (five) and “I” (one) are meaningful chunks. A wealth of previous studies has demonstrated that conceptually tight chunks are more difficult to decompose than conceptually loose chunks (Knoblich et al., 1999, 2001; Luo et al., 2006; Wu, Knoblich, & Luo, 2013; Wu, Knoblich, Wei, & Luo, 2009). Behaviorally, problem solvers spend more time and solve fewer problems when problems involve tight chunks relative to loose chunks during chunk decomposition of both Roman symbols (Knoblich et al., 1999) and Chinese characters (Luo et al., 2006; Wu, Knoblich, Wei, & Luo, 2009). In addition, eye-tracking data shows that solvers fixate longer on tight chunks than loose chunks (Knoblich et al., 2001).

Neuroimaging studies have demonstrated that the decomposition of tight chunks (relative to loose chunks) recruits executive control networks including the right lateral prefrontal cortex and the anterior cingulate cortex (Huang et al., 2015; Luo et al., 2006; Tang et al., 2016; Wu, Knoblich, & Luo, 2013). In addition, decomposing tight chunks elicits increased alpha oscillations in the EEG, as well as deactivation of the primary visual cortex, both of which are associated with the suppression of visual information (Luo et al., 2006; Tang et al., 2016; Wu, Knoblich, Wei, & Luo, 2009).

Examining chunk decomposition entirely in terms of conceptual chunk tightness raises two critical issues. First, though previous studies have demonstrated that chunk tightness has a fundamental influence on the difficulty of chunk decomposition problem solving, they did not distinguish between perceptual characteristics and conceptual characteristics in defining chunk tightness. Zhang and colleagues (2015) showed that perceptual chunk tightness can confound conceptual manipulations of chunk tightness. A chunk is perceptually tight when its components intersect in space, and loose when they do not. Several recent studies have now shown that perceptual characteristics are more influential in determining the difficulty of chunk decomposition problems than conceptual characteristics (Tang et al., 2016; Zhang et al., 2015, 2019). Specifically, Zhang and colleagues (2015) demonstrated that perceptually tight chunks were more difficult to decompose than conceptually tight chunks, and further, that perceptual tightness had a more consistent effect on performance in a chunk decomposition task (CDT) than conceptual tightness. Similarly, Tang and colleagues (2016) showed that increasing perceptual tightness not only increased difficulty, but also increased brain activity (as indexed by fMRI) in a network of regions across the frontal, parietal, and dorsal occipital cortices.

Second, stimulus complexity has not been considered nor well controlled in previous chunk decomposition studies (e.g., Knoblich et al., 1999, 2001; Luo et al., 2006; Tang et al., 2016; Wu, Knoblich, & Luo, 2013; Wu, Knoblich, Wei, & Luo, 2009). This is problematic given that many studies have confirmed that stimulus complexity, as described by the local details and/or intricacy of a visual pattern (Snodgrass & Vanderwart, 1980), has a pervasively negative influence on cognitive performance during a large range of tasks such as feature classification (Ullman, Vidalnaquet, & Sali, 2002), object recognition (Ellis & Morrison, 1998; Gerlach & Marques, 2014), perception (Bradley, Hamby, Löw, & Lang, 2007; Folta-Schoofs, Wolf, Treue, & Schoofs, 2014), reading (Hsu, Lee, & Marantz, 2011; Li, Bicknell, Liu, Wei, & Rayner, 2014; Liversedge et al., 2014; Ma & Li, 2015), and learning (Chang, Plaut, & Perfetti, 2016). Given that chunk decomposition requires decomposing a perceptual chunk into its local parts (Knoblich et al., 1999), and may require the suppression of irrelevant visual information (Luo et al., 2006; Tang et al., 2016; Wu et al., 2009), one may hypothesize that stimulus complexity should impede chunk decomposition.

To this end, we investigated how chunk tightness and stimulus complexity impact perceptual restructuring using a Chinese character decomposition task adapted from previous studies (Wu et al., 2013; Tang et al., 2016). Participants were presented with a probe cueing the component that should be removed from a subsequently presented source character. The target was a valid character that would be produced when the probe was removed from the source. We manipulated chunk tightness in the source character as the degree of spatial intersection between the probe and the other elements in the source character (Tang et al., 2016; Zhang et al., 2015, 2019). Tight chunks were formed when both the probe and the target were intersecting with each other within the source character, hidden in a manner very similar to camouflage (Ludmer, Dudai, & Rubin, 2011). By contrast, loose chunk decomposition is relatively easy due to spatial separation between the probe and the target in the source character (see examples in Figure 1). In addition, we manipulated stimulus complexity following previous work, based on the number of strokes in the source character (Coney, 1998; Ma, & Li, 2015; Li et al., 2014; Liversedge et al., 2014). Finally, previous work has demonstrated that whether the to-be-removed component is itself a meaningful chunk or a set of strokes has a limited influence on the difficulty of chunk decomposition (Zhang et al., 2015). We therefore balanced this variable in our design, but did not include probe type as a factor in our statistical analysis.

In this study, we examined the effect of stimulus complexity and chunk tightness on chunk decomposition by focusing on behavioral indices of difficulty (accuracy and response times) and on a neural marker previously shown to be sensitive to chunk tightness: the late positive complex (LPC) component of the event-related potential (Wu et al., 2013; Zhang et al., 2019). Behaviorally, we hypothesized that both stimulus complexity and chunk tightness would impact task difficulty, with high complexity and tight chunks leading to lower accuracy and longer response times, relative to low complexity or loose chunks, respectively. The LPC is a positive deflection broadly distributed over the parietal cortex that is sensitive to the chunk decomposition task (Wu et al., 2013; Zhang et al., 2019). Bilateral parietal areas are sensitive to manipulations of visuospatial processing, such as during mental rotation (Harris et al., 2000; Harris & Miniussi, 2003) and perceptual reversal of the Necker cube (Pitts et al., 2009). In addition, fMRI studies have shown increased activation of parietal areas during the chunk decomposition task (Huang et al., 2015; Luo et al., 2006; Wu et al., 2013; Tang et al., 2016), and LPC amplitude is reduced when participants decompose tight chunks relative to loose chunks (Zhang et al., 2019; but see Wu et al., 2013). Thus, though parietal regions may be engaged by the visuospatial transformation required during chunk decomposition, the difficulty of chunk decomposition may be reflected by the amplitude of the LPC, whereby as transformation gets more difficult, the LPC is reduced. Within this framework, the current research has two goals. First, to determine if stimulus complexity affects the difficulty of chunk decomposition, which if so, would indicate that it should be controlled in future chunk decomposition studies. Second, to replicate and extend previous findings associating the LPC with chunk decomposition. A key question is whether chunk tightness and stimulus complexity affect the difficulty of chunk decomposition through a common neural mechanism. That is, superficially, spatial intersection and number of strokes could seem to be similar contributions to the general visual "chaos" that makes a chunk decomposition problem difficult. An interaction of chunk tightness and stimulus complexity on the amplitude of the LPC would suggest that the neural generator(s) of the LPC react differently to these sources of difficulty in chunk decomposition problems.

2. Method

2.1 Participants

Twenty-six participants took part in this experiment (12 males, mean age = 20.26, SD = 1.74). All participants were right-handed and had normal or corrected-to-normal vision, with Chinese as their native language. They did not report any brain damage or psychiatric history. All participants gave informed consent and received monetary compensation for participating (￥50 yuan per person). This study was in accordance with the Declaration of Helsinki, and approved by Shenzhen university ethics committee.

2.2 Stimuli

One hundred and sixty normal Chinese characters were collected as the source characters. Chinese characters are perceptual chunks (Fu et al., 2002), and have been used previously for chunk decomposition tasks (e.g. Luo et al., 2006). All the source characters were comprised of subcomponents whereby a probe component (a character or stroke) could be removed to create a valid character (see procedure and task). Chunk tightness was defined by whether the probe/to-be-removed part was spatially intersecting or non-intersecting with the remaining part in the source characters (Zhang et al., 2015, 2019). Stimulus complexity was defined by the number of strokes in the source characters (Li et al., 2014; Liversedge et al., 2014). The 160 characters were pooled into four tightness by complexity conditions (see descriptions in Table 1 and examples in Figure 1). In Condition 1, the source characters were of loose chunk and low complexity. For example, the stroke number of the source character “亢” was relatively less and the probe and the remaining part “几” were in spatially non-intersecting relationship with each other. In Condition 2, the source characters were of loose chunk and high complexity. For example, the stroke number of the source characters “昆” was relatively more and the probe and the remaining part “比” were in non-intersecting relationship with each other. In condition 3, the source characters were of tight chunk and low complexity. For example, the stroke number of the source characters “大” was relatively less and the probe and the remaining part “人” were in intersecting relationship with each other. In condition 4, the source characters were of tight chunk and high complexity. For example, the stroke number of the source characters “典” was relatively less and the probe and the remaining part “共” were in intersecting relationship with each other.

Table 1. Stroke number and spatial relationships in the four stimulus complexity by chunk tightness conditions

Condition	Type	Average stroke number of the source character	Spatial relationships between probe and target in the source character
Condition 1	loose chunk and low complexity (LL)	5.5	Non-intersecting
Condition 2	loose chunk and high complexity (LH)	7.8	Non-intersecting
Condition 3	tight chunk and low complexity (TL)	5.15	Intersecting
Condition 4	tight chunk and high complexity (TH)	8.15	Intersecting

There were 40 source characters in each condition, with half of the probes characters and half strokes. To balance response tendency, there were another 160 source characters serving as foils, from which no valid character could be formed by removing the probe part. The foils were constructed to conform to the four experiment conditions, matching the critical stimuli for tightness crossed with complexity. All the stimuli were stored in .bmp file format and presented in their original size (166 * 166 pixels), with visual angle subtending 3.3 * 3.3°.

2.3 Procedure and task

Participants completed the character decomposition task individually in a silent room, sitting approximately 100 cm from the display monitor (Dell 22, refresh rate = 60 Hz, resolution = 1280 * 1024). Trials began with a 1 s fixation, followed by the presentation of the probe for 1 s. There was a randomized blank interval ranging from 0.8 s to 1.2 s, followed by the presentation of the source character for 3 s. Participants were instructed to mentally remove the probe from the source character in order to get a valid (target) character. Participants pressed either the 1 or 2 on the keyboard to indicate if they had found the solution (the identity of the valid target character), or to indicate they could not find a valid solution (the target was not a valid Chinese character). Key mapping was counterbalanced across participants. A 0.8 s blank interval followed the source presentation, and then the target character (valid or invalid) was shown for 1 s. Trials ended with a blank inter-trial interval of 2.5 s. The experiment was programmed in E-prime 2.0 (Psychology software tools). All of the 320 trials were presented in completely random order. Participants were given a self-paced break every 64 trials. In addition, there were 32 practice trials (16 trials involving valid characters and another 16 trials involving invalid characters) before the formal experiment, that were exactly like the formal trials.

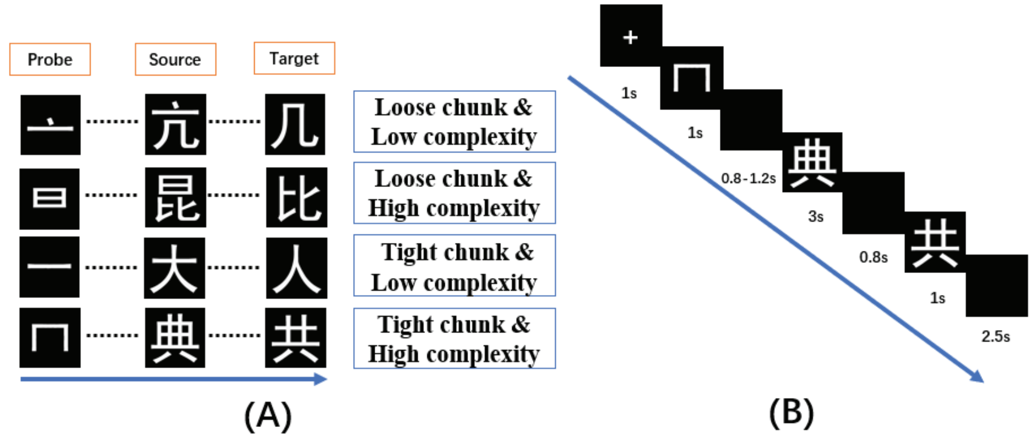

Figure 1. **Examples of the character decomposition task and the sequence of one exemplary trial. (A)**: Examples of character decomposition tasks in the four complexity by tightness conditions. Individuals have to remove the previously-presented probe (a character or strokes) from the source character in order to get a valid character (the target). Chunk tightness is crossed with low or high stimulus complexity. Note that these source characters all carry meaning to the Chinese participants. **(B):** The sequence of one exemplary trial. Trials began with a 1 s fixation followed by presentation of the probe stimulus (the to-be-removed part) for 1 s. The screen then went blank for a jittered interval between 0.8-1.2 s). Next the source character from which the probe should be removed was shown for 3 s. During this time, participants were required to indicate if removal of the probe from the source character would result in a valid Chinese character. Trials concluded with a brief (.8 s) blank interval, presentation of the correct resulting character (valid or invalid) for 1 s, and finally, a 2.5 s blank screen.

2.4 EEG recording and analysis

EEG activity 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. The EEG was referenced to TP9 during recording. The ground electrode was placed at AFz. The vertical electrooculograph (EOG) was recorded from approximately 1 cm below the left eye, and the horizontal EOG was recorded from approximately 1 cm to the right side of the right eye. Impedance was kept equal to or below 5 kΩ. EEG and EOG signals were amplified, band-pass filtered at 0.01-100 Hz and sampled at 500 Hz per channel. The EEG was re-referenced offline to the average of the left and right mastoids (TP9 and TP10). Artifacts caused by blinks and eye movement were removed by the algorithm recommended by Gratton, Coles, and Donchin (1983) using the horizontal and vertical EOG with the common reference. EEG below 0.1Hz and higher than 30 Hz were filtered by using IIR Filters: Zero Phase Shift Butterworth Filters (order was set at 4). EEG data was notch-filtered at 50Hz. Trials contaminated by large artifacts (with amplitudes greater than +60μV or less than -60 μV) were automatically removed, resulting in 2.97 % data loss. The event-related potential (ERP) was time-locked to the onset of the source character. Correct trials were segmented into 1000 ms epochs including a 200 ms baseline. The parietal late positive complex (LPC) was quantified as the average amplitude across 10 central and parietal electrode sites (CP1/2/3/4, CPz, P1/2/3/4, Pz) within the time window of 500 ms to 700 ms after stimulus onset, in line with previous studies (Wu et al., 2013; Zhang et al., 2019).

2.5 Statistical analysis

Behavioral data (accuracy and response times) and LPC amplitude (pooled across 10 electrodes) were all analyzed using two-way ANOVAs with stimulus complexity (low vs. high) and chunk tightness (loose vs. tight) as repeated measures. Results with $p<.05$ were reported as significant. Where appropriate, p values were corrected using the Greenhouse-Geisser method. The Bonferroni method was used to control for multiple comparisons, where appropriate. Only correct trials were included in the analysis of reaction time and LPC amplitude, and no outlier trimming was performed. Trials where the participant did not respond at all were counted as incorrect. Partial eta squared (η_p^2) was given to estimate the effect size of the omnibus ANOVA results (Cohen, 1973; Pierce, Block, & Aguinis, 2004). According to Cohen (1988), effect sizes in the current study were interpreted as small when η_p^2 was smaller or equal to .02; medium when η_p^2 was between .02 and .26, large when η_p^2 was larger or equal to .26. The above principles and criteria were applied to the results reported for both behavioral and EEG data.

3. Results

3.1 Behavioral results

A 2 * 2 repeated-measured ANOVA showed that there was a significant main effect of both factors on accuracy (see Figure 2A): chunk tightness (F (1, 25) = 147.57, p <.001, η_p^2 =.86), stimulus complexity (F (1, 25) = 14.79, p <.001, η_p^2 =.37). The interaction effect was also significant, F (1, 25) = 18.11, p <.001, η_p^2 =.42. Follow-up analyses indicated that there was no significant difference in accuracy between high and low stimulus complexity in the loose chunk condition, F (1, 25) = .05, p = .830, η_p^2 =. 002. However, in the tight chunk condition, there was a lower solution rate (accuracy) for the high complexity trials than for the low complexity trials, F (1, 25) = 20.37, p <.001, η_p^2 =.45. Chunk tightness exhibited a significant effect on accuracy in both the low stimulus complexity (F (1, 25) = 79.54, p < .001, η_p^2 = .76) and high stimulus complexity (F (1, 25) = 131.73, p < .001, η_p^2 = .84) conditions.

Only correct trials were included to calculate the response times. Response times (see Figure 2B) were similarly affected by both chunk tightness (F (1, 25) = 434.26, p <.001, η_p^2 =.95) and stimulus complexity (F (1, 25) = 117.02, p <.001, η_p^2 =.82).

There was also an interaction of stimulus complexity with chunk tightness (F (1, 25) = 132.91, p <.001, η_p^2 =.84). Simple effects analysis indicated that there was no significant difference between high and low complexity in the loose chunk condition, F(1, 25) = 0.45, p =.507, η_p^2 =.02, but, for the tight chunk condition response times were longer in the high complexity than that in the low complexity condition, F (1, 25) = 154.20, p <.001, η_p^2 =.86. Again, Chunk tightness exhibited a significant effect on response times in both the low stimulus complexity, F (1, 25) = 278.21, p < .001, η_p^2 =.92) and high stimulus complexity conditions, F (1, 25) = 383.56, p <.001, η_p^2 =.94.

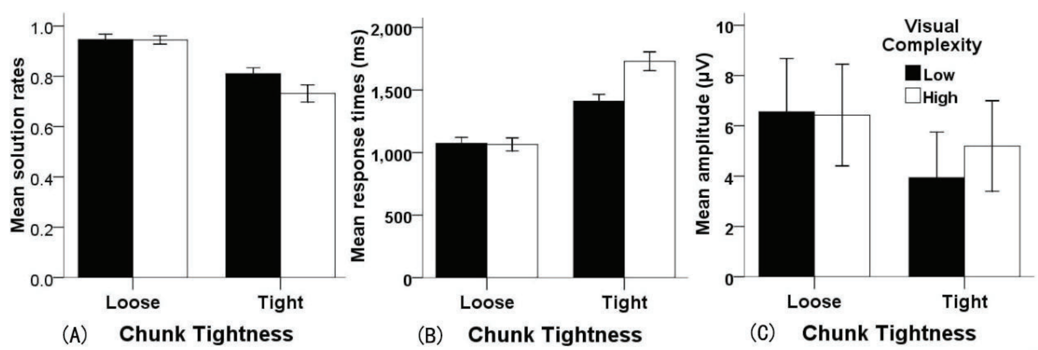

Figure 2. The effects of chunk tightness and stimulus complexity on mean solution rates (A), mean response times (B) and mean amplitude of the late positive component (C). Error bar denotes 95% confidence interval (CI).

3.2 ERP results

Tight chunks elicited a smaller LPC than loose chunks, F (1, 25) = 17.80, p <.001, η_p^2 = .42. There was no main effect of stimulus complexity on LPC amplitude. Critically, there was an interaction of chunk tightness and stimulus complexity on LPC amplitude (see Figure 2C, Figure 3 and 4), F (1, 25) = 6.36, p =.018, η_p^2 = .20, suggesting that though chunk tightness reduced LPC amplitude, this effect was attenuated in the high stimulus complexity condition. This was confirmed by follow-up simple effects analysis. Follow-up simple effect analysis showed that, in the loose chunk condition, there was no significant difference between high and low stimulus complexity, F (1, 25) = .14, p =.713, η_p^2 = .006, whereas in the tight chunk condition, high stimulus complexity elicited a more positive LPC than low stimulus complexity, F (1, 25) = 5.19, p =.031, η_p^2 = .17. By comparison, tight chunk decomposition induced smaller LPC amplitude than loose chunk decomposition in both the low complexity, F (1, 25) = 28.15, p <.001, η_p^2 = .53, and high stimulus complexity conditions, F (1, 25) = 4.68, p =.040, η_p^2 = .16.

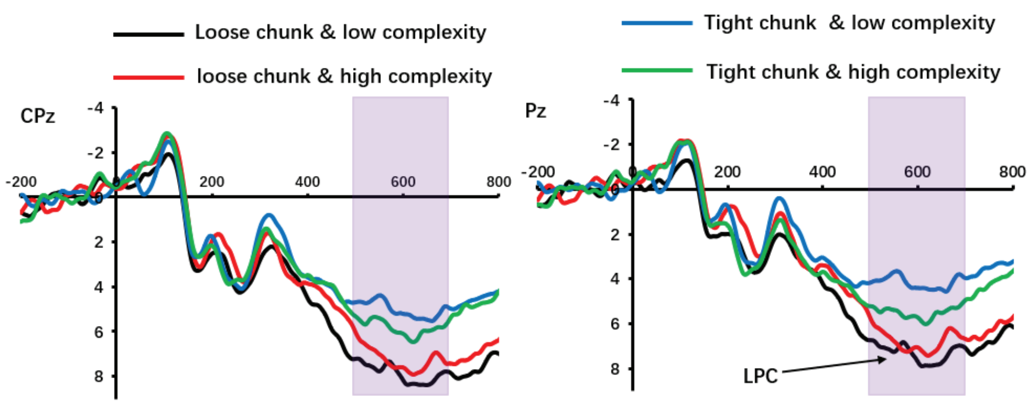

Figure 3. Grand average of LPC (500-700ms) deflections in four conditions across all subjects.

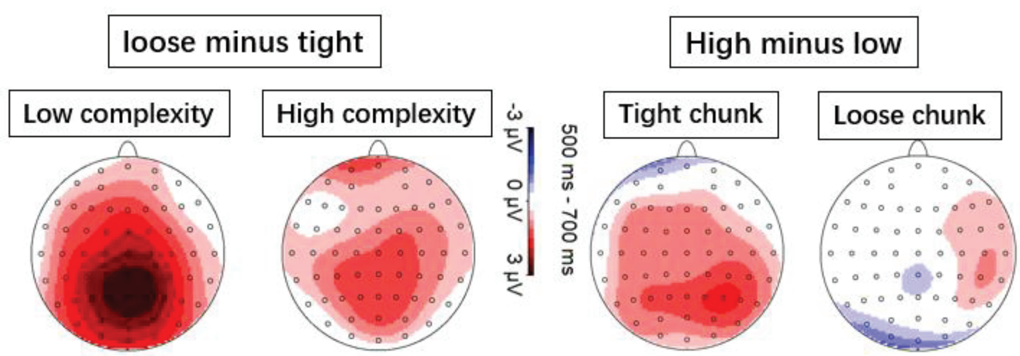

Figure 4. **Topography for difference waves of LPC**. Topographies show the distribution of voltage differences between conditions across the scalp. Scalp topographies of the difference waves created by subtracting tight trials from loose trials in each complexity condition (left) and by subtracting low complexity trials from high complexity trials in each chunk tightness condition (right). **Topographies were created using interpolation by spherical splines with an**

order of 4.

Note that VanRullen (2011) has argued that excluding incorrect trials from EEG/ERP analyses can lead to artifactual differences between conditions due to response bias. That is, VanRullen (2011) shows that if neural activity independent of the task biased a participant to respond in one way or another on a particular set of trials when the participant was undecided on the correct, task-based response, then including only accurate trials would prevent that independent activity from being averaged out of the task-related brain signal (see VanRullen 2011 for detailed examples). To account for this concern, we re-analyzed our ERP data including incorrect trials. This check did not meaningfully affect the pattern of our significant findings.

4. Discussion

The current study examined two sources of difficulty in chunk decomposition problems. Behaviorally, chunk tightness and stimulus complexity both influenced the difficulty of chunk decomposition and interacted such that stimulus complexity affected the behavioral measures of problem difficulty only in the tight chunk condition. A similar interaction was shown at the electrophysiological level. Chunk tightness and stimulus complexity interacted such that LPC amplitude was affected by stimulus complexity only in the tight chunk condition. However, LPC amplitude was *smaller* for tight relative to loose chunks, but *greater* for high relative to low visual complexity. This pattern of results suggests that though chunk tightness and stimulus complexity both contribute to the difficulty of chunk decomposition problems, these factors are dealt with differently at the neural level.

4.1 Multiple interacting sources of difficulty in chunk decomposition

One challenge in the domain of problem solving is to understand why individuals often get stuck on problems that require restructuring a representation (Knoblich et al., 1999, 2001). According to the view of multiple, interacting sources of difficulty (Kershaw & Ohlsson, 2004; Wu et al., 2013), the cause of an impasse involves multiple factors, such as perceptual, and conceptual bias (Kershaw & Ohlsson, 2004), as well as basic sensory qualities of the stimulus. Moreover, these factors may interact, thereby creating greater obstacles in problem solving (Wu et al., 2013). The behavioral results in the current study support this view by revealing that a single thinking step in problem solving can be simultaneously impeded by multiple and interacting sources of difficulty. This point is particularly important when designing and interpreting problem solving experiments. Though substantial research has shown that chunk tightness significantly affects the difficulty of chunk decomposition problems, most previous studies have ignored the influence of stimulus complexity (e.g. Knoblich et al., 1999, 2001; Luo et al., 2006; Tang et al., 2016; Wu, Knoblich, & Luo, 2013; Wu, Knoblich, Wei, & Luo, 2009; Zhang et al., 2015, 2019). The effect of stimulus complexity on problem solving reported here suggests that controlling for stimulus complexity in future work, and taking the larger view that multiple sources of difficulty could be at play in these types of problems could give a clearer picture into the cognitive and neural processes involved in problem solving.

4.2 Dissociable neural underpinnings engaged by chunk tightness and stimulus

complexity

The current study suggests that chunk tightness and stimulus complexity are two distinct but interacting sources of difficulty in chunk decomposition problems. On the one hand, though increasing chunk tightness and increasing stimulus complexity both increased difficulty as measured by behavioral performance, these factors had opposite effects on the LPC. This result dissociates these sources of difficulty in the neural signal. Whereas the LPC has been interpreted as a manifestation of mentally transforming the stimulus (Wu et al., 2013; Zhang et al., 2019), stimulus complexity in this task may engage a different process directed at suppressing distracting information. Indeed, demand on short-term memory resources, and the need to suppress distracting information have been dissociated in the EEG signal in previous work (Sauseng et al., 2009). Thus, we speculate that the LPC was pushed more positive by complex stimuli due to overlapping neural activity related to managing the complexity. Regardless, complexity and chunk tightness interact to impede problem solving during chunk decomposition. This finding is similar to those presented by Wu and colleagues (2013), who demonstrated that chunk familiarity, which was defined by whether the to-be-decomposed character is an existing Chinese character (the familiar condition) or a pseudo character (the unfamiliar condition), and chunk tightness were associated with distinct underlying neural mechanisms, yet interact to amplify the difficulty of chunk decomposition.

4.3 Neural underpinning of the LPC in chunk decomposition problems

The electrophysiological results revealed that the decomposition of tight (vs. loose) chunks attenuated the LPC, consistent with previous work (Zhang et al., 2019; but see Wu et al., 2003 and discussion below). The LPC is likely generated at least in part in bilateral parietal areas, that are also activated in chunk decomposition tasks (Huang et al., 2015; Luo et al., 2006; Wu et al., 2013; Tang et al., 2016), and during mental rotation (Harris et al., 2000; Harris & Miniussi, 2003). In addition, when visuospatial transformation occurs during the perceptual reversal of a Necker cube, LPC amplitude is increased (Pitt et al., 2009). Taken together, these findings suggest that the LPC exhibited in chunk decomposition tasks reflects the visuospatial transformation from the source character to the target character. From the perspective of the current findings, the LPC may reflect activity associated with remapping neural patterns of activity to the new percept, such that it is reduced in the tight chunk condition because the process is less robust, or potentially more smeared out in time. This explanation is in line with the finding that LPC amplitude is attenuated by increasing mental load (Johnson, 1986; reviewed in Kok, 2001). However, Wu and Colleagues (2013) found that LPC amplitude was increased in the tight chunk condition, not attenuated. They speculated that the LPC reflected activity in the parietal cortex associated with mentally manipulating the source character, and that greater exertion was required for tight chunks. This explanation aligns with the interpretation presented here, except that the LPC findings are opposite between studies. In this work, and in previous work (Zhang et al. 2019), the LPC was attenuated in the tight chunk condition, which can be interpreted as a more difficult, less robust transformation process. In contrast, Wu and colleagues (2013) demonstrate an enhanced LPC in the tight chunk condition, and interpret the effect as a more difficult, more effortful exertion. Though Wu and colleagues also used a Chinese character chunk decomposition task, there are important differences between experiment designs. Most notably, Wu and colleagues presented the source character and probe character together on the screen at the same time, whereas in this work the probe was presented in isolation, and the participants were required to hold the source character in memory. Given that visuospatial transformation necessarily engages working memory, this difference in memory requirements between tasks could be the cause of difference in LPC findings. It is possible that when the task requires less memory resources, increasing chunk tightness increases exertion (and activation) but is still fluent and fast enough to produce a robust LPC. However, as more memory resources are required to perform the manipulation, the LPC becomes less prominent, following an inverted U-shape pattern akin to the Yerkes-Dodson curve (Yerkes & Dodson, 1908). It is worth noting that though we (and many others) hold that the LPC is a distinct component from the P300, the two ERP components share many similarities, and the inverted U-shape curve has been referenced in relation to the P300 as well (e.g. Murphy, Robertson, Balsters, & O'Connell, 2011). Further research is needed to fully investigate this explanation.

4.4 Limitations

One limitation of these findings is that the effect of stimulus complexity could be confounded by luminance differences between the high complexity and low complexity stimuli. Specifically, because the source characters were white on black background, high complexity stimuli were brighter than low complexity stimuli due to differences in stroke number. The possibility that luminance differences are driving the observed stimulus complexity effects cannot be ruled out, however, luminance differences typically affect ERP components over occipital cortex within the first 200 ms, and no such effects were observed in this study. In addition, slightly brighter luminance does not typically increase the difficulty of visual tasks, whereas stimulus complexity usually does (Bradley, Hamby, Löw, & Lang, 2007; Ellis & Morrison, 1998; Folta-Schoofs, Wolf, Treue, & Schoofs, 2014; Gerlach & Marques, 2014).

A second issue to consider is the potential role of floor and ceiling effects in driving the interaction between chunk tightness and stimulus complexity on problem reaction time, and accuracy. In particular, accuracy in the loose chunk condition was quite close to 100%. Thus, it may be that the interaction was caused by a restricted range of accuracy scores in the loose chunk condition, constraining any ability to see effect of stimulus complexity. This explanation cannot be ruled out, however, the relatively high average reaction time (~1000 ms) in the loose chunk condition suggests that no floor effects were at play with the reaction time data, which also show the interaction of chunk tightness with stimulus complexity. Furthermore, the LPC data also exhibited this interaction, and there is no reason to worry about floor or ceiling effects there. Even so, future research should attempt to make the loose chunk decomposition problems more difficult, to bring accuracy down from ceiling and potential reveal further effects to consider.

4.5 Conclusion

Chunk decomposition problems were developed to study the mechanism of restructuring during problem solving (Knoblich et al., 1999). The work reported here shows that perceptual features of the stimuli in such tasks are important determinants of problem difficulty. The moment of finding the solution is made more difficult to achieve when stimulus complexity is increased, and when chunks must be extracted from other spatially overlapping chunks. Both factors impede breaking the impasse, but dealing with these two sources of difficulty appears to rely on different neural mechanisms.

References

Bradley, M. M., Hamby, S., Löw, A., & Lang, P. J. (2007). Brain potentials in perception: picture complexity and emotional arousal. *Psychophysiology, 44*(3), 364-373. doi.org/10.1111/j.1469-8986.2007.00520.x

Chang, L. Y., Plaut, D. C., & Perfetti, C. A. (2016). Stimuli complexity in orthographic learning: modeling learning across writing system variations. *Scientific Studies of Reading, 20*(1), 64-85. doi.org/10.1080/10888438.2015.1104688

Cohen, J. (1973). Eta-squared and partial eta-squared in fixed factor ANOVA designs. *Educational and Psychological Measurement, 33*, 107-112, doi: 10.1177/001316447303300111

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences* (2nd ed.). Hillsdale, NJ: Erlbaum.

Coney, J. (1998). The effect of complexity upon hemispheric specialization for reading Chinese characters. *Neuropsychologia, 36,* 149–153. doi.org/10.1016/S0028-3932(97)00088-2

Cranford, E. A., & Moss, J. (2012). Is insight always the same? a protocol analysis of insight in compound remote associate problems. *Journal of Problem Solving, 4*(2), 128–53 DOI: 10.7771/1932-6246.1129

Duncker, K. (1945). On problem-solving. Psychological Monographs, 58(3), 1–113 doi:10.1037/h0093599

Ellis, A. W., & Morrison, C. M. (1998). Real age-of-acquisition effects in lexical retrieval. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 24*(2), 515-523. doi.org/10.1037/0278-7393.24.2.515

Foltaschoofs, K., Wolf, O. T., Treue, S., & Schoofs, D. (2014). Perceptual complexity, rather than valence or arousal accounts for distracter-induced overproductions of temporal durations. *Acta Psychologica, 147(*2), 51-59. DOI:10.1016/j.actpsy.2013.10.001

Fu, S., Chen, Y., Smith, S., Iversen, S., & Matthews, P. M. (2002). Effects of word form on brain processing of written Chinese. *Neuroimage 17*, 1538–1548.doi: 10.1006/nimg.2002.1155

Gerlach, C., & Marques, J. F. (2014). Stimuli complexity exerts opposing effects on object categorization and identification. *Visual Cognition, 22*(6), 751-769. doi.org/10.1080/13506285.2014.915908

Gratton, G., Coles, M. G., & Donchin, E. (1983). A new method for off-line removal of ocular artifact. *Electroencephalography and Clinical Neurophysiology*, *55*, 468–484. doi: 10.1016/0013-4694(83)90135-9

Harris, I. M., Egan, G. F., Sonkkila, C., Tochon-Danguy, H. J., Paxinos, G., Watson, J. D. (2000). Selective right parietal lobe activation during mental rotation: A parametric PET study. *Brain, 123*, 65–73. Doi: 10.1093/brain/123.1.65

Harris, I. M., Miniussi, C. (2003). Parietal lobe contribution to mental rotation demonstrated with rTMS. *Journal of Cognitive Neuroscience, 15*, 315–323. Doi: 10.1162/089892903321593054

Hsu, C. H., Lee, C. Y., & Marantz, A. (2011). Effects of stimuli complexity and sublexical information in the occipitotemporal cortex in the reading of Chinese phonograms: a single-trial analysis with MEG. *Brain & Language, 117*(1)*,* 1-11. doi: 10.1016/j.bandl.2010.10.002

Huang, F. R., Fan, J., & Luo, J. (2015). The neural basis of novelty and appropriateness in processing of creative chunk decomposition. *Neuroimage, 113*, 122-132. doi: 10.1016/j.neuroimage.2015.03.030

Huang, F., Tang, S., Sun, P., & Luo, J. (2018). Neural correlates of novelty and appropriateness processing in externally induced constraint relaxation. *Neuroimage, 172*, 381-389. doi:10.1016/j.neuroimage.2018.01.070

Huang F. R., He M., Luo J. (2017). The cognitive and neural mechanism of chunk decomposition: A particular form of insight (in Chinese). *Chinese Science Bulletin, 62*(31), 3594–3604. doi: 10.1360/N972017-00693

Johnson, R. (1986). A triarchic model of P300 amplitude. *Psychophysiology, 23*(4), 367–384. https://doi.org/10.1111/j.1469-8986.1986.tb00649.x.

Kershaw, T. C., & Ohlsson, S. (2004). Multiple causes of difficulty in insight: the case of the nine-dot problem. *Journal of Experimental Psychology Learning Memory & Cognition, 30*(1), 3-13. doi:10.1037/0278-7393.30.1.3

Knoblich, G., Ohlsson, S., Haider, H., & Rhenius, D. (1999). Constraint relaxation and chunk decomposition in insight problem solving. *Journal of Experimental Psychology-Learning Memory and Cognition, 25*(6), 1534-1555. doi:10.1037/0278-7393.25.6.1534

Knoblich, G., Ohlsson, S., & Raney, G. E. (2001). An eye movement study of insight problem solving. *Memory & Cognition, 29*, 1000-1009. doi.org/10.3758/BF03195762

Kok, A. (2001). On the utility of P3 amplitude as a measure of processing capacity. *Psychophysiology, 38*(3), 557–577. https://doi.org/10.1017/S0048577201990559.

Kounios, J., & Beeman, M. (2014). The cognitive neuroscience of insight. *Annual Review of Psychology, 65*(1), 71-93. doi: 10.1146/annurev-psych-010213-115154.

Li, X. S., Bicknell, K., Liu, P. P., Wei, W., & Rayner, K. (2014). Reading is fundamentally similar across disparate writing systems: a systematic characterization of how words and characters influence eye movements in Chinese reading. *Journal of Experimental Psychology General, 143*(2), 895-913. doi: 10.1037/a0033580

Liversedge, S. P., Zang, C. L., Zhang, M. M., Bai, X. J., Yan, G. L., & Drieghe, D. (2014). The effect of stimuli complexity and word frequency on eye movements during Chinese reading. *Visual Cognition, 22*(3), 441-457.

doi.org/10.1080/13506285.2014.889260

Luchins, A. S. (1942). Mechanization in problem solving – The effect of Einstellung. *Psychological Monographs, 54*, 1–95. doi: 10.1037/h0093502

Ludmer, R., Dudai, Y., & Rubin, N. (2011). Uncovering camouflage: amygdala activation predicts long-term memory of induced perceptual insight. *Neuron, 69*(5), 1002-1014. doi:10.1016/j.neuron.2011.02.013.

Luo, J., Niki, K., & Knoblich, G. (2006). Perceptual contributions to problem solving: Chunk decomposition of Chinese characters. *Brain Research Bulletin 70*, 430-443. doi: 10.1016/j.brainresbull.2006.07.005

Ma, G. J., & Li, X. S. (2015). How character complexity modulates eye movement control in Chinese reading. *Reading & Writing, 28*(6), 747-761. DOI 10.1007/s11145-015-9548-1

Miller, G. A. (1956). The magical number seven plus or minus two: Some limits on our capacity for processing information. *Psychological Review, 63*(2): 81–97. doi.org/10.1037/h0043158

Murphy, P. R., Robertson, I. H., Balsters, J. H., & O'connell, R. G. (2011). Pupillometry and P3 index the locus coeruleus–noradrenergic arousal function in humans. *Psychophysiology, 48*(11), 1532-1543. doi: 10.1111/j.1469-8986.2011.01226.x

Ohlsson, S. (1984). Restructuring revisited: ii. an information processing theory of restructuring and insight. *Scandinavian Journal of Psychology, 25*, 117-129. doi.org/10.1111/j.1467-9450.1984.tb01001.x

Öllinger, M, & Knoblich, G. K. (2009). *Psychological research on insight problem solving.* Recasting Reality. Springer Berlin Heidelberg.

Pierce, C. A., Block, R. A., & Aguinis, H. (2004). Cautionary note on reporting eta-squared values from multifactor anova designs. *Educational and Psychological Measurement, 64*(6), 916-924. Doi: 10.1177/0013164404264848

Pitts, M. A., Martinez, A., Stalmaster, C., Nerger, J. L., Hillyard, S. A. (2009). Neural generators of ERPs linked with Necker cube reversals. *Psychophysiology, 46*, 694–702. Doi: 10.1111/j.1469-8986.2009.00822.x

Sauseng, P., Klimesch, W., Heise, K. F., Gruber, W. R., Holz, E., Karim, A. A., ... Hummel, F. C. (2009). Brain oscillatory substrates of visual short-term memory capacity. *Current Biology, 19*(21), 1846-1852.

Smith, S.M. (1995). *Getting into and out of mental ruts: a theory of fixation, incubation, and insight*, in: Sternberg, R.J., Davidson, J.E. (Eds.), The Nature of Insight, MIT, Press, Cambridge, MA, pp. 229–251

Snodgrass, J. G., & Vanderwart, M. (1980). A standardized set of 260 pictures: norms for name agreement, image agreement, familiarity, and stimuli complexity. *Journal of Experimental Psychology: Human Learning & Memory, 6*(2), 174-215. doi.org/10.1037/0278-7393.6.2.174

Storm, B. C., & Angello, G. (2010). Overcoming fixation. creative problem solving and retrieval-induced forgetting. *Psychological Science, 21*(9), 1263–1265. doi.org/10.1177/0956797610379864.

Tang, X. C., Pang, J. Y., Nie, Q. Y., Conci, M., Luo, J. L., & Luo, J. (2016). Probing the cognitive mechanism of mental representational change during chunk decomposition: a parametric fMRI study. *Cerebral Cortex, 26*(7), 2991-2999. doi: 10.1093/cercor/bhv11

Ullman, S., Vidalnaquet, M., & Sali, E. (2002). Visual features of intermediate complexity and their use in classification. *Nature Neuroscience, 5*(7), 682-687. doi:10.1038/nn870

VanRullen, R. (2011). Four common conceptual fallacies in mapping the time course of recognition. *Frontiers in Psychology, 2:* 365. doi: 10.3389/fpsyg.2011.00365

Wagner, U., Gais, S., Haider, H., Verleger, R., Born, J. (2004). Sleep inspires insight. *Nature 427,* 352–355.doi.org/10.1038/nature02223

Wertheimer, M. (1959): *Productive Thinking*. Harper, New York.

Wu, L. L., Knoblich, G., & Luo, J., (2013). The role of chunk tightness and chunk familiarity in problem solving: Evidence from ERPs and FMRI. *Human Brain Mapping, 34*, 1173-1186. doi: 10.1002/hbm.21501

Wu, L. L., Knoblich, G., Wei, G. X., & Luo, J., (2009). How perceptual processes help to generate new meaning: An EEG study of chunk decomposition in Chinese characters. *Brain Research, 1296*, 104-112. doi: 10.1016/j.brainres.2009.08.023

Wu, Q. Y., Wu, L. L., & Luo, J. (2010). Effective connectivity of dorsal and ventral visual pathways in chunk decomposition. *Science China Life Sciences, 53*(12), 1474-1482. doi: 10.1007/s11427-010-4088-z

Yerkes, R. M., & Dodson, J. D. (1908). The relation of strength of stimulus to rapidity of habit formation. *Journal of Comparative Neurology and Psychology, 18*(5), 459–482. doi:10.1002/cne.920180503.

Zhang, Z. L., Luo, Y., Wang, C. L., Warren, C. M., Xia, Q., Xing, Q., Cao, B. H., Lei, Y., Li, H. (2019). Identification and transformation difficulty in problem solving: Electrophysiological evidence from chunk decomposition. *Biological Psychology, 143*, 10-21. doi: 10.1016/j.biopsycho.2019.02.004

Zhang, Z. L., Yang, K., Warren, C. M., Zhao, G., Li, P., Lei, Y., & Li, H., (2015). The influence of element type and crossed relation on the difficulty of chunk decomposition. *Frontiers in Psychology 6*, 1025. doi: 10.3389/fpsyg.2015.01025

Acknowledgements

This work was supported by MOE (Ministry of Education in China) Project of Humanities and Social Sciences (18YJC190033); The National Natural Science Foundation of China (31571153, 31571144, and 31671150).

The authors declared that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.