The Time Course of Morphemic and Whole-Word Semantic Integration in Chinese Compound Words

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Abstract

Research has shown that morpheme meaning is automatically activated and influences whole-word semantic processing. However, it remains unclear when morpheme meaning is activated in Chinese compound word recognition and how it participates in and influences the temporal course of semantic integration. The study employed event-related potential (ERP) technology and constructed three types of two-character word materials: transparent compound words with morpheme meanings related to word meaning (e.g., 炽热), opaque compound words with morpheme meanings unrelated to word meaning (e.g., 风流), and monomorphemic words as a control condition (e.g., 伶俐), to comparatively investigate the temporal course of semantic participation of first and last morphemes in compound word processing. The results revealed that both the early (300~400 ms) and late (460~700 ms) stages of first-character processing exhibited morpheme effects, that is, both types of compound words elicited more negative amplitudes than monomorphemic words. In the early stage of last-character processing (260~420 ms), not only were morpheme effects found, but also semantic transparency effects, that is, opaque compound words elicited more negative amplitudes than transparent compound words. Whereas in the late stage of last-character processing (480~700 ms), a reversed morpheme effect emerged, that is, both types of compound words elicited more positive amplitudes than monomorphemic words. These results demonstrate that morphemes, as independent representational units, are automatically activated during early processing stages; semantic transparency plays a crucial role in early compound word processing, whereby morpheme integration in transparent compounds facilitates successful access to whole-word meaning, whereas morpheme integration in opaque compounds impedes whole-word meaning access.

Time Course of the Integration of Morpho-Semantics and Whole-Word Meaning in Chinese Compound Words

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Abstract

Previous research has demonstrated that morpheme meaning is automatically activated and influences whole-word semantic processing. However, the precise time course of when morpheme meaning is activated during Chinese compound word recognition and how it participates in and affects the semantic integration process remains unclear. The present study employed event-related potential (ERP) technology and constructed three types of two-character words: transparent compound words where morpheme meaning is related to word meaning (e.g., 炽热), opaque compound words where morpheme meaning is unrelated to word meaning (e.g., 风流), and monomorphemic words as a control condition (e.g., 伶俐). We examined the time course of how semantic information from the first and second morphemes participates in compound word semantic processing. The results revealed that both early (300~400 ms) and late (460~700 ms) time windows during first character processing showed morpheme effects, with both compound word types eliciting more negative amplitudes than monomorphemic words. During the early stage of second character processing (260~420 ms), not only were morpheme effects observed, but also semantic transparency effects, whereby opaque compound words elicited more negative amplitudes than transparent compound words. In contrast, during the late stage of second character processing (480~700 ms), a reversed morpheme effect emerged, with both compound word types eliciting more positive amplitudes than monomorphemic words. These findings indicate that morphemes, as independent representational units, are automatically activated during early processing stages, and that semantic transparency plays a crucial role in early compound word processing: morpheme integration facilitates successful whole-word semantic retrieval in transparent compounds, whereas it hinders such retrieval in opaque compounds.

Keywords: semantic integration, compound word, semantic transparency, ERP

1 Introduction

Semantic integration enables people to combine simple meaning chunks into higher-level semantic information, forming complex and coherent semantic expressions. As the smallest linguistic unit carrying form and meaning, morphemes constitute important components of compound words. In recent years, the internal morphological integration processing of compound words has attracted extensive attention from researchers (Brooks & Cid de Garcia, 2015; Fiorentino et al., 2014; Flick et al., 2018; Lee et al., 2021; Leminen et al., 2019). For example, studies have found that compound words require more cognitive processing than monomorphemic words (El Yagoubi et al., 2008; Ji et al., 2011; Rastle et al., 2004), involve more complex processing stages (Coch et al., 2012; Fiorentino et al., 2014), and elicit greater brain activation (Brooks & Cid de Garcia, 2015; Flick et al., 2018; Hsu et al., 2019). However, the time course of how morpheme meaning is activated and influences whole-word meaning access during compound word processing remains unclear. The present study employed event-related potential (ERP) technology to compare the processing time course differences between the first and second characters of Chinese two-character words, aiming to reveal the integration process of morpheme meaning in Chinese compound word recognition.

Compound words are composed of two or more morphemes with independent meanings, such as 微信 (WeChat), which is formed by integrating the morphemes 微 (micro) and 信 (message). The mental representation and processing mechanisms of compound words have long been central issues in psycholinguistic research. The mixed representation model posits that both morpheme representations and whole-word representations exist in the mental lexicon, and thus compound word recognition results from the interaction between morpheme and whole-word activation (Libben et al., 2020; Peng et al., 1999; Pollatsek et al., 2000; Taft, 2003, 2004). For instance, Taft (2003, 2004) proposed that morpheme and whole-word representation layers exist at different levels, with all words passing through the morpheme representation layer (also called the lemma level) before accessing whole-word representations. Based on empirical findings, Taft and Nguyen-Hoan (2010) proposed the lemma model, which specifies that the lemma level serves as an abstract connection layer between form and meaning, representing morpheme semantic information. According to this model, both morphological and semantic information at the lemma level are activated during early lexical processing stages and can influence semantic access in compound word recognition. These cognitive models of lexical processing were primarily proposed based on behavioral evidence, necessitating further investigation using neuroscientific techniques to examine the detailed processes of morpheme decomposition and integration during compound word processing.

Researchers have compared the processing of English monomorphemic and compound words (Fiorentino & Poeppel, 2007; Gagné & Spalding, 2016; Ji et al., 2011), finding behavioral response differences between the two lexical conditions. For example, monomorphemic words are written faster than compound words (Gagné & Spalding, 2016), demonstrating a morpheme effect that suggests different processing mechanisms for compound words. Specifically, when processing compound words, morpheme information may be decomposed and activated, whereas monomorphemic words contain only one morpheme (e.g., 玻璃, glass) and cannot be decomposed, thus requiring whole-word access for semantic retrieval (Fiorentino & Poeppel, 2007; Gagné & Spalding, 2016; Ji et al., 2011). Further ERP research (Fiorentino et al., 2014) found that within an early time window (275~400 ms), English compound words elicited more negative amplitudes than monomorphemic words, with a scalp distribution over midline and right posterior regions. This early morpheme effect indicates that participants can distinguish between the two word types early on, potentially activating different processing pathways. Compound words undergo morpheme decomposition, activating morpheme meaning information and initiating integration processes. This interpretation is supported by MEG research (Hsu et al., 2019), which found that Chinese compound words require additional brain activation compared to Chinese monomorphemic words, particularly in left anterior and posterior temporal regions.

Additional research suggests that morpheme meaning in compound words may be activated independently of whole-word processing. For example, Zhou et al. (1999) manipulated the morphological, orthographic, and semantic relationships between primes and targets, finding that morphological priming effects (e.g., 华丽 — 华贵) were greater than orthographic (e.g., 华侨 — 华贵) or semantic priming (e.g., 医生 — 护士) effects. Zou et al. (2019) found in an auditory lexical decision task that morpheme-sharing conditions (e.g., 火山 — 火箭) produced larger N400 effects in anterior brain regions, whereas meaning-sharing conditions (e.g., 车轮 — 车胎) produced smaller N400 effects in mid-posterior regions, suggesting neural dissociation between morpheme meaning and whole-word meaning in Chinese. Further studies have demonstrated automatic activation of morpheme meaning during early stages of compound word processing (Tsang & Chen, 2014; Wu et al., 2020; Zhao et al., 2017). For instance, Zhao et al. (2017) found that when primes and targets shared morphemes with identical form and meaning, both N250 and N400 effects were elicited, indicating that morpheme meaning can be automatically decomposed and influence early semantic access to target words.

Although morpheme meaning is automatically activated during early compound word processing, the mechanisms through which it influences whole-word semantic access remain unclear. To address this issue, researchers (Brooks & Cid de Garcia, 2015; Ji et al., 2011) compared two types of compound words: transparent compounds where whole-word meaning is related to constituent morpheme meanings (e.g., 炽热), and opaque compounds where whole-word meaning is unrelated to constituent morpheme meanings (e.g., 风流). Previous studies using priming paradigms (El-Bialy et al., 2013; Tsang & Chen, 2014), morpheme spacing paradigms (Frisson et al., 2008; Ji et al., 2011), and lexical decision tasks (Lee et al., 2021) consistently found longer reaction times and higher error rates for opaque than transparent compounds, demonstrating a semantic transparency effect in compound word processing. The meaning computation account posits that both transparent and opaque compounds require automatic morpheme decomposition, with processing differences arising during the integration stage. Specifically, for transparent compounds, morpheme semantics align with the integrated whole-word meaning, facilitating semantic access, whereas for opaque compounds, morpheme semantics conflict with the retrieved meaning, hindering whole-word semantic access (El-Bialy et al., 2013; Ji et al., 2011;

Tsang & Chen, 2014).

In recent years, cognitive neuroscience research has attempted to reveal the neural mechanisms of morpheme meaning integration by comparing neural processing differences between the two compound types. Unfortunately, existing research on alphabetic scripts has not clearly revealed neural processing differences between transparent and opaque compounds. For example, one MEG study found no temporal processing differences between English transparent and opaque compounds (Brooks & Cid de Garcia, 2015). Similarly, fMRI research found no brain activation differences when processing Persian transparent versus opaque compounds (Momenian et al., 2021). Some researchers have proposed that alphabetic scripts, being phonographic, have weaker form-meaning mapping relationships, such that morphemes primarily activate orthographic structure information during compound word processing, with morpheme meaning/semantic relational information contributing less to whole-word semantic processing, making it difficult to detect processing differences between the two compound types (Koester & Schiller, 2008, 2011).

The unique characteristics of Chinese orthography provide new opportunities for investigating morpheme integration in compound words. Chinese characters are logographic, with the vast majority of characters representing independent morphemes, and over 80% of Chinese vocabulary consists of two-character compounds (Huang et al., 2011; Zhou et al., 1999). Moreover, Chinese characters are square-shaped with clear boundaries between characters, making morphemes easier to decompose and thus influencing whole-word semantic access (Tsang & Chen, 2013; Wu et al., 2017). While English compounds are mostly modifier-head structures, Chinese compounds include various structures such as coordinate and modifier-head forms (Kuo & Anderson, 2006; Liu & McBride-Chang, 2010). When processing coordinate transparent compounds, both first and second morpheme meanings are activated. When morpheme meaning/semantic feature information is highly relevant to the whole word and aligns with the integrated meaning, morpheme meaning facilitates whole-word semantic access; conversely, it may interfere with or hinder such access.

Some researchers have attempted to investigate the neural mechanisms of semantic transparency effects. Using fMRI, studies have examined the brain mechanisms underlying morpheme integration through semantic transparency effects. For instance, Lee et al. (2021) found that opaque compounds activated the left prefrontal cortex more than transparent compounds, a region that may reflect online morpheme meaning integration during compound word processing. However, other researchers have suggested that the left prefrontal cortex may be responsible for morpheme decomposition processes (Gao et al., 2022; Zou et al., 2016). Additionally, some studies have proposed that temporal brain regions (e.g., anterior temporal lobe, posterior middle temporal gyrus) and inferior parietal regions (e.g., angular gyrus) may participate in morpheme semantic integration (Boylan et al., 2017; Flick et al., 2018). Activation in these brain regions suggests that morpheme integration in compound words may involve complex processes including morpheme decomposition, morpheme meaning access, and morpheme meaning integration.

ERP technology, with its high temporal resolution, can more precisely reveal the processing stages of morpheme integration in compound words. Unfortunately, research in this area is relatively scarce, and no clear conclusions have emerged. For example, one ERP study on auditory words (Tsang, Zou & Tse, 2022) found no neural processing differences between transparent and opaque compounds. In contrast, a visual word ERP study (Tsang & Zou, 2022) found transparency effects for both first and second morphemes, suggesting that morpheme meaning may be automatically activated and influence whole-word semantic processing. However, this study could not directly investigate the integration mechanism between morpheme semantics and compound word semantics. On the one hand, the study used mixed-effects models to examine multiple factors at both compound and morpheme levels from a multivariate perspective. The semantic transparency effects determined through annotation methods reflected differences relative to the average level of all morpheme meanings, without explicit comparison to opaque morphemes. On the other hand, when manipulating the semantic transparency of first/second morphemes relative to the compound word, the study did not simultaneously examine the role of the other morpheme' s semantic transparency. These methodological limitations prevented direct investigation of how the automatically activated meanings of two morphemes are integrated and influence compound word semantic access.

Therefore, the present study overcomes previous limitations by simultaneously manipulating the transparency of both morphemes to investigate the morpheme integration process in Chinese compound words. The experiment compared three types of two-character words: transparent compounds, opaque compounds, and monomorphemic words, while examining both morpheme effects and semantic transparency effects. Combining high-temporal-resolution ERP technology, we examined ERP amplitudes elicited by first and second characters to reveal the time course of automatic activation and integration of morpheme meaning and its influence on whole-word semantic access in Chinese compound word processing. We hypothesized that: (1) Participants would show morpheme effects during first character processing. Previous research (Wu et al., 2020; Zhao et al., 2017) found that morpheme meaning is automatically activated during early lexical recognition, and we expected morpheme effects to manifest as ERP amplitude differences during early first character processing stages. (2) During second character processing, participants would show not only significant morpheme effects but also semantic transparency effects, with amplitude differences between transparent and opaque compounds. Specifically, during early second character processing, morpheme meaning would be activated, followed by integration of first and second morpheme meanings. For transparent coordinate compounds, where both morpheme meanings are similar and related to whole-word meaning, morpheme integration would yield consistent meaning that facilitates rapid access to compound word semantic representations. Conversely, opaque compounds would experience semantic conflict during whole-word meaning access, interfering with or hindering retrieval. During later second morpheme processing stages, since semantic transparency is a processing attribute (El-Bialy et al., 2013; Ji et al., 2011; Momenian et al., 2021), the effect may disappear after completing semantic integration, resulting in no processing differences between transparent and opaque compounds during late second character processing.

2.1 Participants

On the one hand, sample size was calculated based on G*Power software to assess the effect size ($f = 0.30$, Cohen, 1992) of a medium-sized single-factor three-level interaction, with α set at 0.05 and statistical power at 0.95 (Faul et al., 2009), resulting in a calculated sample size of 31 participants. On the other hand, considering sample sizes from previous compound word processing studies (吴建设等, 2020; Wu et al., 2020), which ranged from 25 to 35 participants, we determined a sample size of 35 participants to ensure adequate statistical power. The experiment actually recruited 34 college students (19 female) with a mean age of 20.62 ± 1.04 years (19~24). All participants were right-handed, had normal or corrected-to-normal vision, were in good health, and had no history of neurological, psychiatric, or genetic disorders. All participants carefully read the “Participant Informed Consent Form” before the experiment and signed it. They received modest compensation after the experiment.

2.2 Materials

The experiment employed a single-factor three-level (transparent compound words, opaque compound words, and monomorphemic words) within-subjects design, with each condition containing 30 Chinese disyllabic words, totaling 90 stimulus items. Transparent compound words were defined as those where the meanings of both morphemes were identical or similar to the compound word meaning, such as “炽热”; opaque compound words were those where the morpheme meanings differed from the compound word meaning, such as “风流”; monomorphemic words contained only a single whole-word morpheme, such as “伶俐”. Additionally, 30 pseudowords were included as filler items and were not included in the analysis; pseudowords consisted of two single characters that did not form a lexical meaning, such as “仓挡”.

The classification of transparent and opaque compound words used a 7-point rating scale (7 = very high relatedness between morpheme meaning and compound word meaning; 1 = very low relatedness), with the sum of ratings for the first and second morphemes serving as the whole-word semantic transparency score (Brooks & Cid de Garcia, 2015). Fifteen college students who did not participate in the formal experiment rated the semantic transparency of the two-character compound words. Words with total scores > 7 were classified as transparent, and those with scores 7 as opaque, with significant differences in transparency ratings between transparent and opaque words ($t(58) = 20.73$, $p < 0.001$). This experiment selected coordinate transparent compound words where both first and second morpheme transparency ratings were 3.5, with no significant difference between first and second morpheme transparency ratings (t(58) = −0.44, p = 0.660). Behavioral research has shown that word frequency affects the semantic transparency effect in compound word processing, with larger effects for low-frequency than high-frequency compounds (Tsai, 1994). All experimental materials were low-frequency items (mean frequency = 3.24 per million). Moreover, transparent compound words, opaque compound words, and monomorphemic words were matched on word frequency (F(2, 58) = 1.65, p = 0.209, 2 = 0.054), first character component number (F(2, 58) = 1.06, p = 0.354, 2 = 0.035), second character component number (F(2, 58) = 0.17, p = 0.845, 2 = 0.006), whole-word component number (F(2, 58) = 1.36, p = 0.266, 2 = 0.045), first character stroke number (F(2, 58) = 0.45, p = 0.643, 2 = 0.015), second character stroke number (F(2, 58) = 0.16, p = 0.856, 2 = 0.005), and whole-word stroke number (F(2, 58) = 0.64, p = 0.533, 2 = 0.021). Detailed material attribute matching is presented in Table 1 .

Table 1. Relevant attribute information of experimental materials

Word type/	Transparent compound	Opaque compound	Monomorphemic word
First character transparency	5.59(0.59)	2.58(0.64)	3.23(0.82)
Second character transparency	5.66(0.72)	2.76(0.75)	3.13(0.78)
Whole-word transparency	11.25(1.21)	5.34(0.98)	9.70(2.26)
First character component number	2.97(1.00)	2.87(1.01)	3.00(0.98)
Second character component number	3.03(0.72)	3.00(0.98)	3.13(0.78)
First character stroke number	9.57(2.99)	9.07(3.05)	9.70(2.21)
Second character stroke number	9.80(2.44)	9.70(2.84)	10.07(2.82)
Whole-word component number	6.00(1.08)	5.87(1.31)	6.37(0.96)
Whole-word frequency	3.17(3.35)	4.66(9.43)	1.90(2.01)
Whole-word stroke number	19.37(3.58)	18.77(4.17)	19.77(2.82)

Note: Values in parentheses are standard deviations. Word frequency is from the Modern Chinese General Word List (2003).

2.3 Procedure

The experiment was conducted in a dedicated ERP laboratory. During the experiment, participants sat in a quiet testing room approximately 60 cm from the computer screen. In each trial, a fixation cross “+”was presented at the center of the screen for 500 ms, followed by the first character for 800 ms, then a blank screen for 200 ms, and finally the second character. At this point, participants were required to quickly and accurately judge whether the two sequentially presented characters could form a real word. If participants judged the stimulus as a real word, they made no response, and the second character remained on screen for 800 ms before disappearing. If participants judged it as a pseudoword, they pressed the “F” key, and the second character disappeared immediately. A blank screen was then presented for 2200 ms before the next trial began. To obtain reliable EEG signals, the 120 stimulus items were each presented twice. The experiment consisted of 6 blocks, each containing 40 trials, with 10 trials for each of the transparent compound, opaque compound, monomorphemic word, and pseudoword conditions. Each block lasted approximately 3 minutes, and the entire experimental procedure required approximately 18 minutes. Stimulus presentation and data collection were implemented using E-Prime 3.0.

2.4 ERP Recording

A 64-channel electrode cap based on the extended international 10-20 system was used to record EEG signals with the NeuroScan system. Electrodes M1 and M2 were placed on the left and right mastoids, respectively. Horizontal electrooculography (HEOG) was recorded from the outer canthi of both eyes, and vertical electrooculography (VEOG) was recorded from above and below the left eye. The online recording filter bandpass was 0.1~100 Hz, and the sampling rate was 1000 Hz. Impedance at each electrode site was maintained below 5 kΩ. Data were time-locked to the onset of each character presentation to clearly record the neural responses elicited by each character.

3.1 Behavioral Results

All 32 participants successfully completed the lexical decision task. The average number of erroneous button presses in the three real-word conditions was only 1.41 trials (2.34%). Specifically, the mean error trials in the transparent compound condition was 1.53 (2.55%), in the opaque compound condition was highest at 2.31 (3.85%), and in the monomorphemic word condition was only 0.38 (0.63%). A one-way repeated measures ANOVA on error rates across the three conditions revealed a significant main effect of word type ($F(2, 62) = 12.98$, $p < 0.001$, $2 = 0.295$). Participants’ error rates in the monomorphemic word condition were significantly lower than in the transparent compound condition ($t(31) = -3.97$, $p = 0.001$, Cohen’ s $d = -0.826$) and the opaque compound condition (t(31) = -3.96, p = 0.001, Cohen’ s d = -0.919). Error responses in the transparent compound condition were also slightly lower than in the opaque compound condition (t(31) = -2.31, p = 0.083, Cohen’ s d = -0.500).

3.2.1 First Character Processing

For first character processing, the number of valid trials retained was identical across the transparent compound, opaque compound, and monomorphemic word conditions, with 97.91% of trials retained. For the two time windows of first character processing (300~400 ms, 460~700 ms), repeated measures ANOVAs were conducted on mean amplitudes with 3 (word type: transparent compound/opaque compound/monomorphemic word) × 3 (hemisphere: left/midline/right) × 3 (region: anterior/central/posterior) factors. Waveforms at each electrode and topographic distributions of each effect are shown in Figure 1 [Figure 1: see original paper], and statistical results of the ANOVAs are detailed in Table 2 . Additionally, post-hoc test results for significant main effects of region and hemisphere, and follow-up simple effects analyses for significant region × hemisphere interactions are detailed in Supplementary Tables 1 and 2 .

Figure 1. A. Average waveform changes elicited by different word conditions during first character processing; B. Topographic distributions of main word type effect (top), morpheme effect (middle), and semantic transparency effect (bottom).

(1) 300~400 ms time window

Repeated measures ANOVA on mean amplitudes in this time window revealed a significant main effect of word type, with both transparent and opaque compounds eliciting more negative amplitudes than monomorphemic words (t(31) = -2.85, p = 0.023, Cohen’ s d = -0.505; t(31) = -2.50, p = 0.055, Cohen’ s d = -0.443), while the difference between the two compound types was not significant (t(31) = -0.04, p = 1.000, Cohen’ s d = -0.007). No interactions between word type and region or hemisphere were found.

The mean amplitudes elicited by first characters showed a significant main effect of hemisphere, with left and midline electrodes exhibiting more negative amplitudes than right electrodes, while the difference between left and midline electrodes was not significant. Furthermore, a significant interaction between hemisphere and region was observed. Simple effects analysis revealed a significant hemisphere effect in central brain regions (F(2, 62) = 10.99, p < 0.001, 2 = 0.262), with left and midline electrodes eliciting more negative amplitudes than right electrodes, while the difference between left and midline electrodes was not significant. Hemisphere effects in anterior and posterior regions did not reach significance (F(2, 62) = 3.05, p = 0.054, 2 = 0.090; F(2, 62) = 1.38, p = 0.260, 2 = 0.042).

Table 2. ANOVA results for mean amplitudes elicited by first characters

Effect	300~400 ms	460~700 ms
Word type (2, 62)		
Region (2, 62)		
Hemisphere (2, 62)		
Region × Hemisphere (4, 124)		
Word type × Region (4, 124)		
Word type × Hemisphere (4, 124)		
Word type × Region × Hemisphere (8, 248)		

(2) 460~700 ms time window

Repeated measures ANOVA in this late time window also revealed a significant main effect of word type, with both transparent and opaque compounds eliciting more negative amplitudes than monomorphemic words (t(31) = -4.35, $p < 0.001$, Cohen’ s d = -0.784; t(31) = -2.90, p = 0.021, Cohen’ s d = -0.512), while the difference between the two compound types was not significant (t(31) = -0.56, p = 1.000, Cohen’s d = -0.101). Unlike the early results, this time window showed a significant interaction between word type and region, with significant word type effects at central (F(2, 62) = 13.19, $p < 0.001$, 2 = 0.299) and posterior (F(2, 62) = 10.78, $p < 0.001$, 2 = 0.258) electrodes, and a marginally significant effect at anterior electrodes (F(2, 62) = 2.41, p = 0.098, 2 = 0.072). The pattern of differences among the three word types was identical at central and posterior electrodes: transparent compounds elicited more negative amplitudes than monomorphemic words (central: t(31) = -5.15, $p < 0.001$, Cohen’ s d = -0.933; posterior: t(31) = -4.93, $p < 0.001$, Cohen’ s d = -0.893), and opaque compounds also elicited more negative amplitudes than monomorphemic words (central: t(31) = -3.54, p = 0.004, Cohen’ s d = -0.627; posterior: t(31) = -3.38, p = 0.006, Cohen’ s d = -0.600), while differences between the two compound types were not significant (central: t(31) = -0.56, p = 1.000, Cohen’s d = -0.101; posterior: t(31) = -0.49, p = 1.000, Cohen’ s d = -0.090).

A significant main effect of hemisphere was also found in the late time window, but only left electrodes showed more negative amplitudes than midline electrodes, while differences between left and right, and midline and right electrodes were not significant. Unlike the early time window, the late time window also revealed a significant main effect of region, with anterior and posterior regions eliciting more negative amplitudes than central regions, while the difference between anterior and posterior regions was not significant. A significant interaction between hemisphere and region was also observed in this time window. The late window interaction was primarily manifested in significant hemisphere effects in central (F(2, 62) = 7.21, p = 0.002, 2 = 0.189) and posterior (F(2, 62) = 12.43, $p < 0.001$, 2 = 0.286) brain regions. In central regions, left and midline electrodes showed more negative mean amplitudes than right electrodes, while the difference between left and midline electrodes was not significant. In posterior regions, left and right brain regions both showed more negative amplitudes than midline regions, while the difference between left and right regions was not significant.

3.2.2 Second Character Processing

For second character processing, the number of valid trials retained was identical across the three experimental conditions, with 98.43% of trials retained. For the two time windows of second character processing (260~420 ms, 480~700 ms), repeated measures ANOVAs were conducted with 3 (word type: transparent compound/opaque compound/monomorphemic word) × 3 (hemisphere: left/midline/right) × 3 (region: anterior/central/posterior) factors. Waveforms at each electrode and topographic distributions of each effect are shown in Figure 2 [Figure 2: see original paper], and statistical results of the ANOVAs are detailed in Table 3 . Additionally, post-hoc test results for significant main effects of region and hemisphere, and follow-up simple effects analyses for significant region × hemisphere interactions are detailed in Supplementary Tables 3 and 4 .

Figure 2. A. Average waveform changes elicited by different word conditions during second character processing; B. Topographic distributions of main word type effect (top), morpheme effect (middle), and semantic transparency effect (bottom).

(1) 260~420 ms time window

During early second character processing, a significant main effect of word type was also found, similar to that for first characters, with both transparent and opaque compounds eliciting more negative amplitudes than monomorphemic words ($t(31) = -3.72$, $p = 0.002$, Cohen’ s $d = -0.670$; $t(31) = -5.48$, $p < 0.001$, Cohen’ s $d = -0.971$), while the difference between the two compound types was not significant ($t(31) = 1.61$, $p = 0.353$, Cohen’ s $d = 0.308$).

Unlike first character processing, second character processing in the early window revealed a significant interaction between word type and region, while the interaction between word type and hemisphere was only marginally significant. Further simple effects analysis found that the significant word type effect showed the same pattern in anterior ($F(2, 62) = 13.74$, $p < 0.001$, $2 = 0.307$) and central ($F(2, 62) = 22.75$, $p < 0.001$, $2 = 0.423$) brain regions, but a different significant pattern in posterior regions ($F(2, 62) = 10.80$, $p < 0.001$, $2 = 0.258$). In posterior regions, a semantic transparency effect was found, with opaque compounds eliciting more negative amplitudes than transparent compounds ($t(31) = -2.72$, $p = 0.032$, Cohen’ s $d = -0.514$), and opaque compounds also eliciting more negative amplitudes than monomorphemic words ($t(31) = -4.63$, $p < 0.001$, Cohen’ s $d = -0.824$), while the difference between transparent compounds and monomorphemic words was not significant ($t(31) = -2.11$, $p = 0.128$, Cohen’ s $d = -0.378$). In contrast, in anterior and central electrodes, differences between the two compound types were not significant ($t(31) = -0.02$, $p = 1.000$, Cohen’ s $d = -0.004$; $t(31) = 1.95$, $p = 0.180$, Cohen’ s $d = 0.372$), showing no semantic transparency effect, while both transparent and opaque compounds elicited more negative amplitudes than monomorphemic words (anterior: $t(31) = -3.93$, $p = 0.001$, Cohen’ s $d = -0.670$; $t(31) = -4.25$, $p = 0.001$, Cohen’ s $d = -0.754$; central: $t(31) = -4.28$, $p = 0.001$, Cohen’ s $d = -0.774$; $t(31) = -6.49$, $p < 0.001$, Cohen’ s $d = -1.149$).

A significant main effect of hemisphere was found in early second character processing, with left electrodes eliciting more negative amplitudes than right and midline electrodes, while the difference between right and midline electrodes was not significant. A significant main effect of region was also observed, with anterior regions eliciting more negative amplitudes than central and posterior regions, and central regions also more negative than posterior regions. A significant region × hemisphere interaction was also found. Further simple effects analysis revealed that the significant hemisphere effect in anterior regions ($F(2, 62) = 7.11$, $p = 0.003$, $2 = 0.187$) was due to left regions being more negative than midline regions, while differences between left and right, and midline and right regions were not significant. The significant hemisphere effect in central regions ($F(2, 62) = 14.00$, $p < 0.001$, $2 = 0.311$) was due to left regions being more negative than right and midline regions, while the difference between midline and right regions was not significant. In posterior regions, the significant hemisphere effect ($F(2, 62) = 11.26$, $p < 0.001$, $2 = 0.266$) was due to left regions being more negative than both midline and right regions, while the difference between midline and right regions was not significant.

Table 3. ANOVA results for mean amplitudes elicited by second characters

Effect	260~420 ms	480~700 ms
Word type (2, 62)		
Region (2, 62)		
Hemisphere (2, 62)		
Region × Hemisphere (4, 124)		
Word type × Region (4, 124)		
Word type × Hemisphere (4, 124)		
Word type × Region × Hemisphere (8, 248)		

(2) 480~700 ms time window

In the late time window of second character processing, repeated measures ANOVA also revealed a significant main effect of word type, with transparent and opaque compounds eliciting more positive amplitudes than monomorphemic words ($t(31) = 4.08$, $p = 0.001$, Cohen’ s $d = 0.722$; $t(31) = 4.31$, $p < 0.001$, Cohen’ s $d = 0.769$), while the difference between the two compound types was not significant ($t(31) = -0.13$, $p = 1.000$, Cohen’ s $d = -0.024$).

A significant word type × hemisphere interaction was also found. Simple effects of word type were significant at left ($F(2, 62) = 12.50$, $p < 0.001$, $2 = 0.287$), midline (F(2, 62) = 14.62, p < 0.001, 2 = 0.320), and right (F(2, 62) = 12.92, p < 0.001, 2 = 0.294) electrode sites, all showing no significant differences between the two compound types (left: t(31) = -0.42, p = 1.000, Cohen’ s d = -0.075; midline: t(31) = -0.48, p = 1.000, Cohen’ s d = -0.087; right: t(31) = 0.52, p = 1.000, Cohen’ s d = 0.093), while both compound types elicited more positive amplitudes than monomorphemic words, though the magnitude of difference varied across regions, being largest at midline brain regions (t(31) = 4.49, p < 0.001, Cohen’ s d = 0.809) and smallest in right regions (t(31) = 3.89, p = 0.002, Cohen’ s d = 0.689).

Moreover, the interaction between word type and brain region was also significant. Simple effects of word type were significant at anterior (F(2, 62) = 8.61, p = 0.001, 2 = 0.217), central (F(2, 62) = 11.66, p < 0.001, 2 = 0.273), and posterior (F(2, 62) = 19.77, p < 0.001, 2 = 0.389) electrode sites. All three regions showed no significant differences between the two compound types (anterior: t(31) = -1.44, p = 0.481, Cohen’ s d = -0.262; central: t(31) = 0.14, p = 1.000, Cohen’ s d = 0.025; posterior: t(31) = 0.80, p = 1.000, Cohen’ s d = 0.025), while both transparent and opaque compounds elicited more positive amplitudes than monomorphemic words, though the magnitude of difference varied, being largest in posterior brain regions (t(31) = 5.20, p < 0.001, Cohen’ s d = 0.922; t(31) = 4.79, p < 0.001, Cohen’s d = 0.848) and smallest in anterior regions (t(31) = 2.64, p = 0.039, Cohen’ s d = 0.469; t(31) = 3.67, p = 0.003, Cohen’ s d = 0.672).

The mean amplitudes elicited by second character processing showed significant main effects of both hemisphere and region. For the hemisphere effect, left regions were more negative than right regions, which were also more negative than midline regions. The significant region effect was primarily manifested as anterior regions being more negative than central and posterior regions, while the difference between central and posterior electrodes was not significant.

4 Discussion

The present study employed ERP technology to investigate the time course of morpheme meaning integration in Chinese compound word processing. The results revealed morpheme effects during first character processing of Chinese two-character words, manifesting as processing differences between the two compound word types and monomorphemic words. Moreover, significant differences between the two compound types were found at posterior electrode sites during early second character processing, demonstrating a semantic transparency effect, while a reversed morpheme effect was observed during late second character processing. These findings reveal the time course of automatic decomposition and integration of morpheme meaning in Chinese compound words, which we discuss in detail below.

4.1 Morphological Meaning Activation in Chinese Compound Word Recognition

By comparing the processing of Chinese compound words and monomorphemic words during first character processing, this study found that both compound types elicited more negative amplitudes than monomorphemic words. This is consistent with previous research indicating that morphemes are decomposed and activated during multimorphemic word recognition. For example, Lavric et al. (2007) reported in an ERP study that within an early time window (140~260 ms), neural priming effects in morpheme-related semantic transparent conditions (e.g., hunter—HUNT) differed significantly from those in morpheme-unrelated orthographic conditions (e.g., brothel—BROTH). This demonstrates that morphemes are decomposed during early processing stages, distinct from pure orthographic processing. The present study also showed amplitude differences between Chinese compound and monomorphemic words during early first character processing. These results suggest that, on the one hand, Chinese morphemes are decomposed and activated during early processing stages as independent representational units, rather than merely undergoing orthographic analysis. On the other hand, the morpheme effect observed for first characters might also result from pure single-character processing differences, which requires more precise control of first characters (e.g., character frequency) to rule out this possibility. fMRI research on Chinese ambiguous morphemes has shown that homographic morpheme conditions produce significant neural priming effects in distributed brain networks, including left superior temporal gyrus and right inferior occipital gyrus (Zhao et al., 2021). The present results also demonstrated significant morpheme effects across the whole brain, indicating that morpheme processing is not subserved by a single brain region but by multiple brain regions working together.

Morpheme effects were also found during late first character processing, but unlike the early scalp distribution pattern, late morpheme effects were observed in central and posterior brain regions. This suggests that after Chinese morphemes are activated, they may undergo further morpheme meaning processing in central and posterior brain regions, thereby influencing subsequent whole-word semantic access. This view is supported by other research evidence. For instance, Wu et al. (2017) used ERP technology to investigate the neural processing of Chinese morphemes, finding significant amplitude differences between morpheme-sharing and baseline conditions across the whole brain during early processing stages, and a central-posterior scalp distribution pattern during late processing stages. Other researchers combined fMRI to examine the neural mechanisms of German compound word processing, finding that real compound words activated the angular gyrus in posterior brain regions more strongly (Forgács et al., 2012), a region considered important for semantic processing (Binder et al., 2009; Seghier, 2013). A French MEG study showed that morpheme processing involves activation in left inferior and superior temporal gyri (Cavalli et al., 2016). Additionally, fMRI research on Chinese ambiguous morphemes found that bilateral middle temporal gyri participate in ambiguous morpheme meaning processing (Zhao et al., 2021). Based on this cross-linguistic evidence, we can conclude that central and posterior brain regions likely participate in morpheme meaning processing.

Significant morpheme effects were also observed during second character processing, with both compound types eliciting more negative amplitudes than monomorphemic words. This result is consistent with behavioral research on alphabetic scripts (Ji et al., 2011; Rastle et al., 2004) and ERP/MEG findings (Coch et al., 2012; Fiorentino & Poeppel, 2007), as well as with behavioral results from Chinese studies (Yen et al., 2008; Zhou & Marslen-Wilson, 1995). For example, Coch et al. (2012) found in an ERP study that English compound words elicited more negative N400 amplitudes than English monomorphemic words during reading (Coch et al., 2012). The morpheme effect observed in early second character processing in the present study may indicate that morphemes are automatically activated during early stages of Chinese compound word processing, whereas monomorphemic words cannot undergo decomposition and thus show amplitude differences from compound words. This view is also supported by research on alphabetic scripts. For instance, Fiorentino and Poeppel (2007) found that compound words had significantly earlier peak latencies on M350 than monomorphemic words, with earlier processing of compound words primarily reflecting automatic activation of morpheme meaning. Researchers have proposed that compound and monomorphemic words have different processing pathways: compound words require initial morpheme decomposition, whereas monomorphemic words contain only one morpheme and cannot be decomposed, thus requiring whole-word semantic access (Coch et al., 2012; El Yagoubi et al., 2008).

4.2 How Chinese Morpheme Meaning Influences Compound Word Semantic Integration

A key finding of this study is the significant semantic transparency effect during the relatively early stage (260~420 ms) of second character processing, with Chinese opaque compounds eliciting more negative amplitudes than transparent compounds. Researchers have proposed that both compound types require automatic morpheme decomposition, with processing differences primarily manifesting during the integration stage of morpheme meaning and whole-word semantics (Brooks & Cid de Garcia, 2015). Some studies have found that opaque compounds are better remembered than transparent compounds, possibly because the inconsistency between retrieved whole-word meaning and meaning computed from constituent morphemes creates greater distinctiveness (Han et al., 2014). The present study found semantic transparency effects at the neurophysiological level, and together with previous research (Lee et al., 2021; Tsang & Zou, 2022), this demonstrates that semantic transparency robustly modulates lexical semantic access in Chinese compound word processing. Importantly, the present study found that opaque compounds elicited more negative amplitudes than transparent compounds during early second character processing, providing direct neurophysiological evidence for the meaning computation account (El-Bialy et al., 2013; Ji et al., 2011; Tsang & Chen, 2014). This indicates that morpheme meaning is automatically activated and integrated, subsequently influencing whole-word semantic access in compound words. Specifically, the present study used coordinate transparent compounds where both first and second morpheme meanings are related to the whole word, and the first and second morpheme meanings are similar. Therefore, based on the full processing of first morpheme meaning information that provides contextual information for subsequent processing, the second morpheme’ s meaning is automatically activated during early processing stages, followed by rapid integration of first and second morpheme meanings. The meaning obtained through online integration is consistent with the stored meaning, successfully retrieving the lexical representation from the mental lexicon and thereby facilitating whole-word semantic access. In contrast, although morpheme meaning is automatically activated in opaque compounds, the meaning obtained through morpheme integration may conflict with the stored meaning, preventing successful retrieval of the compound representation and even hindering whole-word meaning access. Individuals must expend more cognitive resources to process opaque compounds, thus eliciting more negative amplitudes.

During later stages of second character processing, no amplitude differences exist between transparent and opaque compounds, and the semantic transparency effect disappears. Some researchers have noted that semantic transparency is a processing attribute: both transparent and opaque compounds can undergo morpheme decomposition and integration, with no representational differences between the two compound types (El-Bialy et al., 2013; Ji et al., 2011; Momenian et al., 2021). Therefore, the disappearance of the semantic transparency effect during late second character processing indicates that both compound types have completed morpheme meaning integration and achieved whole-word semantic access by this late stage. However, morpheme effects remained significant during late second character processing, showing a different pattern from first character and early second character processing, specifically with both compound types eliciting more positive amplitudes than monomorphemic words. The morpheme effect differences observed at this stage may not reflect automatic activation of morpheme meaning in compound words, but rather further processing of whole-word semantics or morpheme structure reanalysis. This view is also supported by other research evidence. For example, researchers using MEG compared neural processing differences between English compound and monomorphemic words, finding that within a 430~660 ms time window, transparent compounds activated posterior superior temporal gyrus more strongly than monomorphemic words, which the authors interpreted as reflecting delayed semantic processing of compound words (Brooks & Cid de Garcia, 2015). Kwon et al. (2012) found that large family words elicited more positive amplitudes than small family words within a 500~700 ms time window (Kwon et al., 2012). Other researchers using priming paradigms found a main effect of priming type between 450~500 ms, with morpheme-related priming conditions eliciting more positive amplitudes than orthographic priming conditions (Beyersmann et al., 2014). Therefore, later stages of multimorphemic word processing may involve broad semantic activation (Beyersmann et al., 2014; Brooks & Cid de Garcia, 2015) or morpheme structure reanalysis (Kim et al., 2022; Kwon et al., 2012).

4.3 Theoretical Contributions

The present study combined ERP technology with the structural advantages of Chinese compound words to deeply investigate the integration process of morpheme meaning and whole-word semantics in Chinese compound word processing, providing neurophysiological evidence for models of Chinese compound word processing. The findings provide support for Taft’ s lemma model. This model proposes that morphemes exist as an independent representational lemma level, and that both morpheme form and semantics play a role during early lexical processing stages (Taft & Nguyen-Hoan, 2010). The present study found morpheme effects during early first character processing, demonstrating that morphemes are activated during early processing stages. The lemma model also proposes that each morpheme may correspond to different lemmas involving morpheme semantic representations; therefore, morpheme effects observed during late first character processing may reflect further processing of morpheme meaning.

The results also provide neurophysiological evidence for the mixed representation model (Libben et al., 2020; Pollatsek et al., 2000). This model posits that both morpheme representations and whole-word representations exist in the mental lexicon, and that compound word recognition results from the interaction between morpheme and whole-word activation. The morpheme effects observed during early second character processing in this study indicate that morpheme representations are automatically decomposed and activated during recognition of both compound types, whereas monomorphemic words cannot undergo morpheme decomposition and must access meaning through whole-word representation processing. The semantic transparency effect observed during early second character processing demonstrates that transparent compounds can successfully access word meaning through morpheme integration, whereas morpheme integration in opaque compounds hinders whole-word semantic access, causing a shift to direct whole-word representation processing to achieve semantic access.

4.4 Limitations and Future Directions

This study has two aspects that require further investigation. On the one hand, we observed changes in scalp electrode distribution patterns of experimental effects over time, but due to the limitations of ERP technology, interpretation of these findings requires further investigation combining high spatial resolution fMRI. The present study found posterior electrode distributions for the transparency effect, which may reflect the sensitivity of posterior brain regions to compound word semantic integration. Consistent with our results, Bai et al. (2008) manipulated morpheme meaning consistency in an auditory compound word study and found that semantic inconsistency effects in second morpheme processing primarily manifested at posterior electrode sites, which the authors suggested may reflect morpheme meaning integration in compound word processing (Bai et al., 2008). However, inconsistent with our findings, Lee et al. (2021) found that semantic transparency effects in Chinese compound words were primarily manifested in left prefrontal cortex. A recent Chinese compound word study using functional near-infrared spectroscopy (fNIRS) combined with EEG found that left prefrontal cortex, particularly inferior frontal gyrus, is responsible for morpheme parsing, while temporal brain regions are responsible for semantic analysis (Gao et al., 2022). The brain mechanisms underlying morpheme integration in compound words require further in-depth research combining fMRI and transcranial magnetic stimulation (TMS) technologies.

On the other hand, this study deeply investigated the internal integration of morpheme semantics and whole-word semantics in Chinese compound words using a sequential stimulus presentation method. Sequential presentation has been applied in research on phrase semantic integration (Bemis & Pylkkänen, 2011; Zhang & Pylkkänen, 2015; Ziegler & Pylkkänen, 2016) and can effectively investigate the brain mechanisms of semantic integration. Previous researchers have examined the activation of Chinese morphemes in compound word processing by comparing morpheme priming effects between morpheme-sharing and unrelated conditions in primes and targets (Wu et al., 2020; Zhao et al., 2017). Although these findings showed that morphemes influence whole-word semantic access across different time windows, they did not allow for detailed dissociation of morpheme decomposition and integration processes, particularly how morphemes participate in and influence compound word semantic integration. The present study combined sequential presentation with ERP technology and found morpheme effects and semantic transparency effects during both first and second character processing, demonstrating that morpheme integration in Chinese compound words involves complex processing stages including morpheme decomposition, morpheme meaning access, and morpheme meaning integration. Notably, compared to simultaneous presentation, sequential presentation may increase competition between morpheme and whole-word representation processing. Additionally, it should be acknowledged that the stimulus presentation time in this study was 800 ms, allowing for full processing of both first and second characters, which not only fully activated morpheme meaning representations but may also have spread-activated additional semantic information, thereby influencing integration processing. Future research could compare different stimulus presentation methods or incorporate linguistic properties such as lexical ambiguity to further investigate the neural mechanisms underlying compound word processing in greater detail and depth.

5 Conclusion

By leveraging the structural characteristics of Chinese compound words and addressing limitations of previous research, the present study employed ERP technology to reveal the time course of morpheme integration processing in Chinese compound words. By simultaneously manipulating and examining the time course of semantic transparency effects for both first and second morphemes, the results demonstrated that compound word morphemes are automatically decomposed, allowing discrimination between compound and monomorphemic words during the first character stage. First morpheme meaning is automatically activated and influences second morpheme processing, resulting in semantic transparency effects reflecting morpheme meaning integration during early second character processing. These findings provide neurophysiological evidence for the morpheme integration process in compound word recognition.

References

Bai, C., Bornkessel-Schlesewsky, I., Wang, L. M., Hung, Y., C, Schlesewsky, M., & Burkhardt, P. (2008). Semantic composition engenders an N400: Evidence from Chinese compounds. *Neuroreport, 19*(6), 695—699.

Bemis, D. K., & Pylkkanen, L. (2011). Simple composition: A magnetoencephalography investigation into the comprehension of minimal linguistic phrases. *Journal of Neuroscience, 31*(8), 2801—2814.

Beyersmann, E., Iakimova, G., Ziegler, J. C., & Colé, P. (2014). Semantic processing during morphological priming: An ERP study. *Brain Research, 1579*, 45—55.

Binder, J. R., Desai, R. H., Graves, W. W., & Conant, L. L. (2009). Where is the semantic system? a critical review and meta-analysis of 120 functional neuroimaging studies. *Cerebral Cortex, 19*(12), 2767—2796.

Boylan, C., Trueswell, J. C., & Thompson-Schill, S. L. (2017). Relational vs. attributive interpretation of nominal compounds differentially engages angular gyrus and anterior temporal lobe. *Brain and Language, 169*, 8—21.

Brooks, T. L., & Cid de Garcia, D. (2015). Evidence for morphological composition in compound words using MEG. *Frontiers in Human Neuroscience, 9*, 215.

Cavalli, E., Colé, P., Badier, J.-M., Zielinski, C., Chanoine, V., & Ziegler, J. C. (2016). Spatiotemporal dynamics of morphological processing in visual word recognition. *Journal of Cognitive Neuroscience, 28*(8), 1228—1242.

Coch, D., Bares, J., & Landers, A. (2012). ERPs and morphological processing: The N400 and semantic composition. *Cognitive, Affective, & Behavioral Neuroscience, 13*(2), 355—370.

Cohen, J. (1992). A power primer. *Psychological Bulletin, 112*(1), 155—159.

Chinese Linguistic Data Consortium. (2003). 现代汉语通用词表 [Chinese lexicon] (CLDC-LAC 2003-001). Beijing, China: Tsinghua University, State Key Laboratory of Intelligent Technology and Systems, and Chinese Academy of Sciences, Institute of Automation.

El-Bialy, R., Gagné, C. L., & Spalding, T. L. (2013). Processing of English compounds is sensitive to the constituents' semantic transparency. *The Mental Lexicon, 8*(1), 75—95.

El Yagoubi, R., Chiarelli, V., Mondini, S., Perrone, G., Danieli, M., & Semenza, C. (2008). Neural correlates of Italian nominal compounds and potential impact of headedness effect: An ERP study. *Cognitive Neuropsychology, 25*(4), 559—581.

Faul, F., Erdfelder, E., Buchner, A., & Lang, A. G. (2009). Statistical power analyses using G*Power 3.1: tests for correlation and regression analyses.* Behavior Research Methods, 41*(4), 1149—1160.

Flick, G., Oseki, Y., Kaczmarek, A. R., Al Kaabi, M., Marantz, A., & Pylkkänen, L. (2018). Building words and phrases in the left temporal lobe. *Cortex, 106*, 213—236.

Fiorentino, R., Naito-Billen, Y., Bost, J., & Fund-Reznicek, E. (2014). Electrophysiological evidence for the morpheme-based combinatoric processing of English compounds. *Cognitive Neuropsychology, 31*(1—2), 123—146.

Fiorentino, R., & Poeppel, D. (2007). Processing of compound words: An MEG study. *Brain and Language, 103*(1), 18—19.

Forgács, B., Bohrn, I., Baudewig, J., Hofmann, M. J., Pléh, C., & Jacobs, A. M. (2012). Neural correlates of combinatorial semantic processing of literal and figurative noun noun compound words. *Neuroimage, 63*(3), 1432—1442.

Frisson, S., Niswander-Klement, E., & Pollatsek, A. (2008). The role of semantic transparency in the processing of English compound words. *British Journal of Psychology, 99*(1), 87—107.

Gagné, C. L., & Spalding, T. L. (2016). Effects of morphology and semantic transparency on typing latencies in English compound and pseudocompound words. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 42*(9), 1489—1495.

Gao, F., Wang, R., Armada-da-Silva, P., Wang, M., Lu, H., Leong, C., & Yuan, Z. (2022). How the brain encodes morphological constraints during Chinese word reading: An EEG-fNIRS study. *Cortex, 154*, 184—196.

Han, J., Zhang, X., & Yang, J. (2014). The role of semantic transparency in memory for compound words. *Journal of Memory and Language, 70*, 1—15.

Huang, H. W., Lee, C. Y., Tsai, J. L., & Tzeng, O. J. (2011). Sublexical ambiguity effect in reading Chinese disyllabic compounds. *Brain and Language, 117*(2), 77—87.

Hsu, C.-H., Pylkkänen, L., & Lee, C.-Y. (2019). Effects of morphological complexity in left temporal cortex: An MEG study of reading Chinese disyllabic words. *Journal of Neurolinguistics, 49*, 168–177.

Ji, H. b., Gagné, C. L., & Spalding, T. L. (2011). Benefits and costs of lexical decomposition and semantic integration during the processing of transparent and opaque English compounds. *Journal of Memory and Language, 65*(4), 406–430.

Kim, S., & Pylkkänen, L. (2019). Composition of event concepts: Evidence for distinct roles for the left and right anterior temporal lobes. *Brain and Language, 188*, 18–27.

Kim, J., Kang, J., Kim, J., & Nam, K. (2022). Temporal dynamics of form and meaning in morphologically complex word processing: An ERP study on Korean inflected verbs. *Journal of Neurolinguistics, 64*, 101098.

Koester, D., & Schiller, N. O. (2008). Morphological priming in overt language production: Electrophysiological evidence from Dutch. *Neuroimage, 42*(4), 1622–1630.

Koester, D., & Schiller, N. O. (2011). The functional neuroanatomy of morphology in language production. *Neuroimage, 55*(2), 732–741.

Kuo, L., & Anderson, R. C. (2006). Morphological awareness and learning to read: A cross-language perspective. *Educational Psychologist, 41*, 161–180.

Kwon, Y., Nam, K., & Lee, Y. (2012). ERP index of the morphological family size effect during word recognition. *Neuropsychologia, 50*(14), 3385–3391.

Lavric, A., Clapp, A., & Rastle, K. (2007). ERP evidence for morphological analysis from orthography: A masked priming study. *Journal of Cognitive Neuroscience, 19*(5), 866–877.

Lee, H.-J., Cheng, S., Lee, C.-Y., & Kuo, W.-J. (2021). The neural basis of compound word processing revealed by varying semantic transparency and morphemic neighborhood size. *Brain and Language, 221*, 104985.

Leminen, A., Smolka, E., Du˜nabeitia, J.A., Pliatsikas, C., 2019. Morphological processing in the brain: The good (inflection), the bad (derivation) and the ugly (compounding). *Cortex, 116*, 4–44.

Libben, G., Gagné, C. L., & Dressler, W. U. (2020). The representation and processing of compounds words. In V. Pirrelli, I. Plag & W. Dressler (Ed.), *Word Knowledge and Word Usage: A Cross-Disciplinary Guide to the Mental Lexicon* (pp. 336–352). Berlin, Boston: De Gruyter Mouton.

Liu, P. D., & Mcbride-Chang, C. (2010). Morphological processing of Chinese compounds from a grammatical view. *Applied PsychoLinguistics, 31*(4), 605–617.

Lo, J. C. M., McBride, C., Ho, C. S., & Maurer, U. (2019). Event-related potentials during Chinese single-character and two-character word reading in children. *Brain and Cognition, 136*, 103589.

Maurer, U., Schulz, E., Brem, S., der Mark, S. van, Bucher, K., Martin, E., & Brandeis, D. (2011). The development of print tuning in children with dyslexia: Evidence from longitudinal ERP data supported by fMRI. *Neuroimage, 57*(3), 714—722.

Momenian, M., Radman, N., Rafipoor, H., Barzegar, M., & Weekes, B. (2021). Compound words are decomposed regardless of semantic transparency and grammatical class: An fMRI study in Persian. *Lingua, 259*, 103058.

Peng, D., Ding, G., Wang, C., Taft, M., & Zhu, X. (1999). The processing of Chinese reversible words—–the role of morphemes in lexical access. *Acta Psychologica Sinica, 31*(1), 36—46. [彭聃龄, 丁国盛, 王春茂, MarcusTaft, & 朱晓平. (1999). 汉语逆序词的加工——词素在词加工中的作用. 心理学报, 31(1), 36—46.]

Pollatsek, A., Hyona, J., & Bertram, R. (2000). The role of morphological constituents in reading Finnish compound words. *Journal of Experimental Psychology Human Perception & Performance, 26*(2), 820—833.

Rastle, K., Davis, M. H., & New, B. (2004). The broth in my brother' s brothel: Morpho-orthographic segmentation in visual word recognition. *Psychonomic Bulletin & Review, 11*(6), 1090—1098.

Seghier, M. L. (2013). The angular gyrus: Multiple functions and multiple subdivisions. *Neuroscientist, 19*(1), 43—61.

Taft, M. (2003). Morphological representation as a correlation between form and meaning. In E. Assink & D. Sandra (Eds.), *Reading complex words* (pp. 113—137). Amsterdam: Kluwer.

Taft, M. (2004). Morphological decomposition and the reverse base frequency effect. *The Quarterly Journal of Experimental Psychology Section A, 57*(4), 745—765.

Taft, M., & Nguyen-Hoan, M. (2010). A sticky stick? The locus of morphological representation in the lexicon. *Language and Cognitive Processes, 25*(2), 277—296.

Tsai, C.-H. (1994). Effects of semantic transparency on the recognition of Chinese two-character words: Evidence for a dual-process model. Unpublished master' s thesis, National Chung Cheng University, Chia-Yi, Taiwan.

Tsang, Y.-K., & Chen, H.-C. (2013). Early morphological processing is sensitive to morphemic meanings: Evidence from processing ambiguous morphemes. *Journal of Memory and Language, 68*(3), 223—239.

Tsang, Y.-K., & Chen, H.-C. (2014). Activation of morphemic meanings in processing opaque words. *Psychonomic Bulletin & Review, 21*(5), 1281—1286.

Tsang, Y.-K., Zou, Y., Tse, C.-Y. (2022). Semantic transparency in Chinese compound word processing: Evidence from mismatch negativity. *Neuroscience, 490*, 216–223.

Tsang, Y. -K., & Zou, Y. (2022). An ERP megastudy of Chinese word recognition. *Psychophysiology, 59*(11), e14111.

Wu, Y., Tsang, Y.-K., Wong, A. W.-K., & Chen, H.-C. (2017). The processing of homographic morphemes in Chinese: An ERP study. *Language, Cognition and Neuroscience, 32*(1), 102–116.

Wu, Y., Duan, R., Zhao, S., & Tsang, Y.-K. (2020). Processing ambiguous morphemes in Chinese compound word recognition: Behavioral and ERP evidence. *Neuroscience, 446*, 249–260.

Wu, J., Chang, J., Qiu, Y., Joseph, D. (2020). The temporal process of visual word recognition of Chinese compound: Behavioral and ERP evidences based on homographic morphemes. *Acta Psychologica Sinica, 52*(2), 113–127. [吴建设, 常嘉宝, 邱寅晨, Joseph, & Dien. (2020). 汉语复合词视觉识别的时间进程: 基于同形语素的行为与 ERP 证据. 心理学报, 52(2), 113–127.]

Yen, M.-H., Tsai, J.-L., Tzeng, O. J.-L., & Huang, D. L. (2008). Eye movements and parafoveal word processing in reading Chinese. *Memory & Cognition, 36*(5), 1033–1045.

Zhang, L., & Pylkkänen, L. (2015). The interplay of composition and concept specificity in the left anterior temporal lobe: An MEG study. *Neuroimage, 111*, 228–240.

Zhang, R., Wang Z., Wang X., Yang J. (2021). N170 adaptation effect of the sub-lexical phonological and semantic processing in Chinese character reading. *Acta Psychologica Sinica, 53*(8), 807–820. [张瑞, 王振华, 王小娟, & 杨剑峰. (2021). 汉字识别中亚词汇语音和语义信息在 N170 上的神经适应. 心理学报, 53(8), 807–820.]

Zhao, S., Wu, Y., Tsang, Y.-K., Sui, X., & Zhu, Z. (2021). Morpho-semantic analysis of ambiguous morphemes in Chinese compound word recognition: An fMRI study. *Neuropsychologia, 157*, 107862.

Zhao, S., Wu, Y., LI, T., Guo, Q., (2017). Morpho-semantic processing in Chinese word recognition: An ERP study. *Acta Psychologica Sinica, 49*(3), 296–306. [赵思敏, 吴岩, 李天虹, 郭庆童. (2017). 词汇识别中歧义词素语义加工: ERP 研究. 心理学报, 49(3), 296–306.]

Zhou, X. L., & Marslen-Wilson, W. (1995). Morphological structure in the Chinese mental lexicon. *Language, Cognition and Neuroscience, 10*(6), 545–600.

Zhou, X. L., Marslen-Wilson, W., Taft, M., & Shu, H. (1999). Morphology, orthography, and phonology reading Chinese compound words. *Language and Cognitive Processes, 14*(5-6), 525–565.

Ziegler, J., & Pylkkänen, L. (2016). Scalar adjectives and the temporal unfolding of semantic composition: An MEG investigation. *Neuropsychologia, 89*, 161—171.

Zou, L., Packard, J. L., Xia, Z., Liu, Y., & Shu, H. (2016). Neural correlates of morphological processing: Evidence from Chinese. *Frontiers in Human Neuroscience, 9*, 714.

Zou, L., Packard, J. L., Xia, Z., Liu, Y., & Shu, H. (2019). Morphological and whole-word semantic processing are distinct: Event related potentials Evidence from spoken word recognition in Chinese. *Frontiers in Human Neuroscience, 13*, 133.

Supplementary Table 1. Post-hoc test results for significant main effects of region and hemisphere in first character processing

Supplementary Table 2. Pairwise comparisons among left, midline, and right brain regions across different regions in first character processing

Supplementary Table 3. Post-hoc test results for significant main effects of region and hemisphere in second character processing

Supplementary Table 4. Pairwise comparisons among left, midline, and right brain regions across different regions in second character processing

Note: Figure translations are in progress. See original paper for figures.

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