Temporal Dynamics of Visual Recognition of Chinese Compound Words: Behavioral and ERP Evidence from Homographic Morphemes

Authors: Wu Jianshe, Chang Jiabao, Qiu Yinchen, Dien,Joseph, Wu Jianshe, Chang Jiabao

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Abstract

Based on the homographic morpheme inhibition effect, this study investigated the time course of orthographic, phonological, and semantic activation in the visual recognition of Chinese compound words. The results showed that: (1) the homographic heterophonic, homographic homophonic, and identical conditions all produced morpheme priming effects relative to the control condition; (2) on the P2 and late N400 components, the homographic homophonic condition was more similar to the control condition, but differed significantly from the homographic heterophonic and identical conditions; (3) on the early N400 component, the homographic homophonic condition was more similar to the identical condition, but differed significantly from the homographic heterophonic condition. The study suggests that the early stage of visual recognition of Chinese compound words may involve lexeme-based morphological-orthographic processing, with orthographic matching and phonological information being the primary influencing factors, but whether semantic information is involved remains unclear; whereas the late stage may involve lexical entry-based morphological-semantic processing, mainly involving semantic competition and selection. The results of this study support the "Parallel Distributed Processing Model" proposed by McClelland et al.

Full Text

Preamble

The Temporal Process of Visual Recognition of Chinese Compound Words: Behavioral and ERP Evidence Based on Homographic Morphemes

WU Jianshe1; CHANG Jiabao1/2; QIU Yinchen3; Joseph DIEN
(1. School of English Studies, Beijing International Studies University, Beijing, 100024, China)
(2. Tangshan Kailuan No. 2 High School, Hebei, 063100, China)
(3. School of European Studies, Beijing International Studies University, Beijing, 100024, China)
(4. University of Maryland, College Park, MD, 20742, USA)

Abstract

Based on the homographic morpheme inhibition effect, this study investigates the temporal course of orthographic, phonological, and semantic activation in the visual recognition of Chinese compound words. The results show that: (1) heterophonic-homographic, homophonic-homographic, and identity conditions all produced morphological priming effects relative to the control condition; (2) on the P2 and late N400 components, the homophonic-homographic condition was more similar to the control condition but differed significantly from the heterophonic-homographic and identity conditions; (3) on the early N400 component, the homophonic-homographic condition was more similar to the identity condition but differed significantly from the heterophonic-homographic condition. These findings suggest that the early stage of Chinese compound word visual recognition may involve lexeme-based morpho-orthographic processing, where orthographic matching and phonological information are primary influencing factors, though whether semantic information is involved remains unclear. The late stage may involve lemma-based morpho-semantic processing, primarily concerning semantic competition and selection. The results support the Parallel Distributed Processing Model proposed by McClelland and colleagues.

Keywords: compound words; homographic morphemes; early N400; late N400

1. Introduction

Since Taft & Forster (1975) first discovered the morphological priming effect, numerous studies have investigated this phenomenon, yet several key issues remain debated: whether morphological processing involves dual routes (e.g., Grainger & Ziegler, 2011) or a single route (e.g., Crepaldi, Rastle, Coltheart, & Nickels, 2010); whether semantic involvement occurs early (e.g., Feldman, O' Connor, & Martín, 2009) or at post-lexical stages (e.g., Rastle, Davis, & New, 2004); whether morphological analysis occurs automatically (e.g., Taft, 2004) or depends on context (e.g., Burani & Caramazza, 1987); and how orthography and semantics interact to produce morphological priming effects (e.g., Allen & Badecker, 1999; Baayen, Milin, Durdevic, Hendrix, & Marelli, 2011; Gonnerman, Seidenberg, & Andersen, 2007). Resolving these issues largely depends on effectively dissociating orthographic and semantic processing. Most previous studies have attempted to achieve this separation using affixes in complex words, but affix separation involves numerous confounding factors. Recent research has begun to utilize special characters in different writing systems—such as "stem homographs” in Italian, Spanish, and Finnish (where word stems share the same form but different meanings, e.g., Spanish “cerr-ar” / “to close” vs. “cerr-o” / “hill”) and homographic morphemes in compound words (where characters or words share the same form but different meanings, e.g., Chinese “光线/光头” or English “banknote/riverbank”)—to achieve this separation. However, while previous studies have separated orthography from semantics via homographic stems/morphemes or separated phonology from semantics via polyphonic characters and homographic morphemes, no study has simultaneously separated orthography, phonology, and semantics within a single experimental design. Therefore, based on a review of these two lines of research, the present study utilizes different types of homographic morphemes in Chinese compound words to simultaneously separate these three factors, thereby exploring the temporal course of visual recognition of Chinese compound words.

The first line of research has attempted to separate orthography from semantics using homographic stems/morphemes, but unexpectedly discovered a homographic stem inhibition effect opposite to the morphological priming effect. Subsequent studies have analyzed its mechanism and discussed orthographic and semantic processing in word recognition and their possible temporal courses.

Laudanna, Badecker, & Caramazza (1989, 1992) first reported the homographic stem inhibition effect. In a long-term priming paradigm (SOA = 200 ms), they found that Italian homographic stem conditions (e.g., “port-are” / “to carry” vs. “port-e”/“doors”) were more difficult to process than orthographically similar conditions. They inferred that this might occur because the same stem simultaneously activated different lexical representations, triggering an ambiguity conflict mechanism (Laudanna et al., 1992: 346). Allen & Badecker (1999) further investigated this using Spanish materials in a long-term priming paradigm (SOA = 250 ms) and found that the homographic stem inhibition effect (e.g., “cerr-ar” / “to close” vs. “cerr-o” / “hill”) was not due to orthographic similarity effects (e.g., “cerdo”/“pork”), and that allomorph conditions (where morphemes share meaning but differ in form, e.g., “cier-ra” / “closes”) produced similar inhibition effects. They concluded that morpheme recognition involves abstract lemma-based representations (independent of form and phonology) rather than lexeme-based representations (dependent on form and phonology) (p. 121). In psycholinguistic research, “lemma” refers specifically to semantic-syntactic features, while “lexeme” refers to morphophonological features of morphemes (see Kempen & Hoenkamp, 1987; Kempen & Huijbers, 1983; Levelt, 1989).

However, subsequent studies showed that homographic stem inhibition effects disappear in masked and short-term priming paradigms. Zhou, Marslen-Wilson, Taft, & Shu (1999, Experiment 1) found that homographic morphemes (e.g., “华侨—华贵”) showed no priming effect in a long-term priming paradigm (SOA = 200 ms) but produced priming effects in masked and short-term priming paradigms (SOA = 57 ms/57 ms). Compared to the identity morpheme condition (e.g., “华丽—华贵”), the homographic morpheme condition still produced a homographic stem inhibition effect. They inferred that different priming durations might trigger different intensities of semantic competition (among different semantic representations of the same character) (p. 539) and interaction (between characters composing the compound and the whole word) (pp. 560-561). Since their experimental materials were Chinese homographic morphemes, differing from previous studies in writing systems, Badecker & Allen (2002) replicated Allen & Badecker' s (1999) experiment in a masked priming paradigm (SOA = 67 ms). They also found homographic stem priming effects and inferred that in masked priming paradigms, homographic morphemes activate multiple semantic representations that facilitate target word recognition (p. 132), suggesting that homographic stem effects might involve consciously mediated semantic selection mechanisms. Subsequent studies (e.g., Carreiras, Perdomo, & Meseguer, 2005; Laudanna, Voghera, & Gazzellini, 2002; Tsang & Chen, 2010, 2013a, 2013b) reported similar homographic stem/morpheme priming effects.

Based on homographic stem/morpheme inhibition effects, researchers have used reaction time techniques (e.g., Dominguez, Cuetos, & Segui, 2002; Jarvikivi, Pyykkonen, & Niemi, 2009; Tsang, Wong, Huang, & Chen, 2014) and ERP/MEG neuroimaging techniques (Dominguez, de Vega., & Barber, 2004; Simon, Lewis, & Marantz, 2012; Wu, Tsang, Wong, & Chen, 2016; Zou, Packard, Xia, Liu, & Shu, 2019) to observe the possible temporal course of word recognition. Dominguez et al. (2002), using Spanish materials, found that in masked priming paradigms (SOA = 32 ms/64 ms), both homographic stem and identity morpheme conditions produced priming effects, whereas in long-term priming paradigms (SOA = 250 ms), only identity morpheme and semantically similar conditions produced priming effects, with homographic stem conditions showing inhibition effects. They inferred that these different SOA durations might correspond to orthographic/phonological, morphological, and semantic processing, respectively, and that early word recognition should be semantics-independent orthographic/phonological processing. Jarvikivi et al. (2009), using Finnish materials, found that in masked paradigms (SOA = 60 ms), heterophonic-homographic, allomorph, and identity morpheme conditions all produced priming effects relative to the control condition, while in long-term priming paradigms (SOA = 300 ms), only the identity morpheme condition produced priming effects. Combined with subsequent experimental results, they argued that early morphological processing is bottom-up, involving fast, automatic morph-based decomposition rather than top-down whole-word processing. Tsang et al. (2014) found that in masked priming paradigms (SOA = 40 ms), heterophonic-homographic and identity morpheme conditions both produced priming effects relative to the control condition with no significant difference between them; however, in unmasked priming (SOA = 100 ms) and long-delay (SOA = 2000 ms or response-locked) paradigms, only the identity morpheme condition produced facilitation effects relative to both the control and heterophonic-homographic conditions, with no significant difference between the latter two. They therefore argued that only morpho-orthographic processing occurs in masked priming paradigms, while morpho-semantic processing becomes possible only with priming durations of 100 ms or more.

Building on this, Taft & Nguyen-Hoan (2010) and Xu & Taft (2014), based on studies of English homographic stems, proposed a lemma-based morphological processing model suggesting that morphological processing can be divided into two stages: orthography-based morpho-orthographic and lemma-based morpho-semantic.

In ERP/MEG studies, Barber, Dominguez, & de Vega (2002) and Dominguez et al. (2004), using designs similar to Dominguez et al. (2002), found in long-term priming paradigms (SOA = 250 ms/300 ms) that homographic stem and identity morpheme conditions showed overlapping waveforms before 250 ms, after which the homographic stem condition became more negative and peaked around 450 ms, while the identity morpheme condition remained a slow negative wave. The two conditions showed no significant difference in the 250–350 ms window, but the homographic stem condition was significantly more negative than the identity morpheme condition in the 350–650 ms window. They therefore argued that word recognition involves two stages: lexeme processing at 250–350 ms and lemma processing after 350 ms. Wu et al. (2016), using a masked priming paradigm (SOA = 53 ms), found that both heterophonic-homographic and identity morpheme conditions produced enhanced P200 (150–250 ms) effects relative to the control condition, with no significant difference between them, but the waveforms began to diverge around 250–300 ms. In the N400 (250–500 ms) window, only the identity morpheme condition showed significant priming effects. A 50 ms window analysis revealed this significant effect occurred at 400–500 ms (central-posterior brain regions), while priming effects for heterophonic-homographic and semantic conditions were not significant. Based on Taft & Nguyen-Hoan' s (2010) lemma processing model, they concluded that 150–250 ms represents morpho-orthographic processing, while 250–500 ms represents morpho-semantic processing. Additionally, Simon et al. (2012) using MEG and Zou et al. (2019) using auditory recognition paradigms both found possible dissociation between orthographic and semantic processing around 300–450 ms.

The second line of research attempts to separate phonology from semantics. Studies based on polyphonic characters generally indicate that phonology may be involved in visual word recognition. Tan & Peng (1991) found in a long-term priming paradigm (SOA = 150 ms) that phonologically identical characters (e.g., “快”), phonologically erroneous characters (e.g., “汇”), and orthographically similar characters (e.g., “公”) all produced priming effects relative to primes whose first character was polyphonic (e.g., “会计”). Tan & Perfetti (1999, Experiment 2) manipulated polyphonic characters to create four conditions: first-character consistent (e.g., “形成”), first-character inconsistent (e.g., “见识” , where the first character has pronunciations jian4/xian4), final-character consistent (e.g., “明净”), and final-character inconsistent (e.g., “体重” , where the final character has pronunciations zhong4/chong4). They found that inconsistent pronunciation conditions had longer reaction times than the control condition (22 ms and 28 ms slower for first- and final-character inconsistencies, respectively), but no significant difference between the two inconsistent conditions. They concluded that participants were highly sensitive to phonological information of both initial and final characters in Chinese compound word recognition but insensitive to positional information, suggesting that visual recognition of polyphonic characters at both positions activates their corresponding different phonological representations. Liu, Zhang, & Liu (2017), using an audiovisual dual-channel sentence processing paradigm, found that phonologically identical/semantically identical conditions (e.g., "校长" /zhang3) showed enhanced P200 (280–380 ms) effects compared to phonologically identical/semantically different (e.g., "家长" /chang2), phonologically different/semantically identical (e.g., "船长" /yuan2), and phonologically different/semantically different (e.g., "班长"/mu4) conditions. Additionally, these four conditions showed sequentially enhanced N400 (400–550 ms) effects, with the phonologically different/semantically different condition being significantly more negative than the other three. In the late positive component (LPC) 600-700 ms window, the phonologically identical/semantically different condition showed enhanced effects compared to the phonologically identical/semantically identical condition, but no significant differences were found in the 750–800 ms window. They inferred that P200 effects might be related to phonological processing, N400 effects might be related to semantic mismatch during audiovisual integration (with phonological information possibly modulating semantic extraction), and the first LPC window might indicate conflict detection during audiovisual integration. Zhang et al. (2017), using the same design and multivoxel pattern analysis (MVPA) for functional connectivity, found that classification patterns changed across different time windows (P200, N400, LPC) and showed distinct spatial distributions in brain regions, suggesting that P200 and N400 might be related to phonological processing.

However, findings from studies based on Chinese homographic morphemes are not entirely consistent. Zhou et al. (1999, Experiment 4) found that in masked priming paradigms (SOA = 57 ms), heterophonic-homographic morphemes (e.g., "重复-重量"), homophonic control conditions (e.g., "崇高-重量"), and unrelated control conditions (e.g., "绝望-重量") showed no significant differences, but in long-term priming paradigms (SOA = 200 ms), only the heterophonic-homographic morpheme condition produced inhibition effects relative to both control conditions. They concluded that phonology of Chinese characters in compound words should not independently affect morphological-semantic processing, but its interaction with orthography might inhibit or facilitate Chinese compound word processing. Zou et al. (2012), using an auditory recognition paradigm (SOA = 150 ms), found that waveforms for heterophonic-homographic morphemes (e.g., "长城/长官") and identity morphemes (e.g., "面包/面孔") began to diverge around 450 ms, but showed no significant N400 differences. Additionally, the N400 peak for phonologically identical conditions (e.g., "灯光/登门") was delayed by about 50 ms compared to phonologically different conditions (e.g., "海带/电台") (529.43 ms vs. 475.86 ms). These results overall suggest that whether phonology affects morphological-semantic processing remains inconclusive in both masked and long-term priming paradigms.

In summary, the identical orthographic forms of homographic stems/morphemes may activate different semantic or phonological representations, allowing investigation of orthography-phonology-semantics interactions and exploration of word recognition time courses. Various word recognition and morphological processing models can be tested, including: the lexical decomposition-lemma model (Taft, 1994, 2004; Taft & Nguyen-Hoan, 2010; Xu & Taft, 2014), supralexical model (Giraudo & Grainger, 2001, 2003), form-semantics model (Crepaldi et al., 2010; Meunier & Longtin, 2007; Rastle & Davis, 2008; Rastle et al., 2004), morpho-orthographic/morpho-semantic hybrid model (Beyersmann, Coltheart, & Castles, 2012; Beyersmann, Iakinova, Ziegler, & Colé, 2014; Diependaele et al., 2005, 2009), and parallel distributed processing model (Gonnerman et al., 2007; McClelland & Rumelhart, 1981; Plaut & Booth, 2000; Seidenberg & McClelland, 1989).

A notable limitation is that while word recognition involves unified orthographic, phonological, and semantic processing, existing studies have only separated orthography from semantics or phonology from semantics in different designs; no study has simultaneously examined orthography, phonology, and semantics within a single investigation. However, this can be achieved using homographic morphemes in Chinese compound words, which are ubiquitous in the Chinese writing system. According to Liu, Shu, & Li (2007), among 2,423 commonly used Chinese characters, approximately 65% contain 2–5 meanings. These can be further distinguished into homophonic-homographic morphemes and heterophonic-homographic morphemes (e.g., in “作息” and “作坊” vs. “作诗”, “作” functions as a homophonic-homographic morpheme in the first two compounds but as a heterophonic-homographic morpheme in the third).

Based on the literature review, this study addresses three main research questions:
(1) Does phonological information participate in visual word recognition of Chinese compounds? If phonological information in homographic morphemes is not activated, both homophonic-homographic (e.g., “作息”) and heterophonic-homographic (e.g., “作坊”) conditions should produce homographic morpheme inhibition effects similar to those in Dominguez et al. (2004). If phonological information is activated, only the homophonic-homographic condition should produce homographic morpheme inhibition effects, while the heterophonic-homographic condition should not.
(2) When does phonological information become involved in visual word recognition? If the P200 component represents phonological processing, phonologically inconsistent conditions (heterophonic-homographic and control conditions) should be more negative than phonologically consistent conditions (homophonic-homographic and identity morpheme conditions) on the P200 component. Otherwise, phonological processing around 200 ms cannot be confirmed. Another reliable indicator for phonological involvement is when the homographic morpheme inhibition effect occurs.
(3) Do morpho-orthographic and morpho-semantic processing dissociate within the N400 time window? Given that homophonic-homographic, heterophonic-homographic, and identity morpheme conditions are orthographically identical,

if orthographic and semantic processing dissociate during N400, the three conditions should show no significant differences in early N400 but differ in late N400. If they do not dissociate, no significant differences should appear across the N400 component. Since five word recognition models make different predictions about the timing of orthographic and semantic activation, the findings can simultaneously test these models.

2.1.1 Participants

Twenty-five undergraduate students (19 females, 6 males) participated in the experiment, with a mean age of 22.5 years (SD = 1.07). All were right-handed with normal or corrected-to-normal vision and had no prior experience with similar experiments. To ensure good discriminability among morpheme conditions, all participants were native Mandarin speakers from northern China with no language or reading disabilities. They signed informed consent forms before the experiment and received monetary compensation.

2.1.2 Design and Materials

The experiment employed a single-factor four-level within-subjects design (see Table 1). The first character of the prime word belonged to one of four conditions: heterophonic-homographic morpheme (+O-P-S, e.g., “作坊” / zuo1 fang / workshop), homophonic-homographic morpheme (+O+P-S, e.g., “作息” / zuo4 xi1 / work-and-rest), identity morpheme (+O+P+S, e.g., “作诗” / zuo4 shi1 / poetry-composing), and control condition (-O-P-S, e.g., “账本” / zhang4 ben3 / account-book). The target word was identical across all conditions (e.g., “作画” / zuo4 hua4 / painting). Each condition contained 48 item sets, totaling 192 sets, matched on stroke count and word frequency ($ps > 0.05$). An additional 192 pseudo-word filler sets were included.

To ensure semantic and phonological distinctiveness of materials, participants rated semantic similarity between prime and target initial characters on a 1-5 Likert scale and phonological identity (“yes/no”) after the experiment. For semantic similarity, the identity morpheme condition differed significantly from all other conditions ($ps < 0.05$). For phonological identity, homophonic and heterophonic conditions differed significantly ($ps < 0.05$).

Table 1 Example stimuli and characteristics for each condition

Condition	+O-P-S	+O+P-S	+O+P+S	-O-P-S	Target
Example	作坊	作息	作诗	账本	作画
Semantic	1.87	1.99	4.58	1.19	–
Similarity	(1.05)	(1.11)	(0.71)	(0.53)	
Phonological	0.07	0.95	0.96	0.00	–
Identity	(0.25)	(0.22)	(0.18)	(0.00)	
Stroke Count	16 (4.7)	16 (4.6)	17 (4.1)	17 (4.3)	16 (4.1)

Condition	+O-P-S	+O+P-S	+O+P+S	-O-P-S	Target
Word Frequency	8.15 (3.33)	8.15 (3.33)	8.15 (3.33)	8.26 (3.1)	8.15 (3.33)
Prime Frequency	7.78 (3.24)	8.33 (3.02)	8.61 (2.6)	9.07 (3.1)	8.30 (2.5)

Note: Values in parentheses are standard deviations. Word frequencies were log-transformed.

2.1.3 Procedure

The experiment was programmed in E-Prime 2.0 and presented on a desktop computer with black background and white text. To avoid interference from pure physical similarity, primes and targets were presented in different fonts and sizes following psychological conventions: primes in Microsoft YaHei 40-point font, targets in SimSun 42-point font.

A masked priming paradigm was adopted for three reasons: (1) researchers such as Zhou et al. (1999), Feldman, Kostić, Gvozdenović, O' Connor, & Martín (2012), and Tsang et al. (2014) argue that non-masked paradigms with SOA $>$ 100 ms are susceptible to strategic processing; (2) Forster (1998) noted that "despite its limitations, it can still serve as an index of fully automatic processes" (p. 229); and (3) previous relevant studies have used masked priming to separate early and late stages of word recognition.

The SOA was set at 47 ms. To ensure participants could not detect the prime, forward and backward masks were strictly implemented following previous research settings and adjusted through pilot testing.

The procedure (see Figure 1 [Figure 1: see original paper]) was as follows: A fixation cross "+" appeared for 1000 ms, followed by a forward mask (###) for 500 ms, the prime for 47 ms, a backward mask (###) for 20 ms, a blank screen for 30 ms, and then the target for 2000 ms awaiting a button press. If no response occurred within 2 s, the screen automatically advanced and the trial was recorded as an error. To prevent strategic responses due to fixed inter-trial intervals, a jitter of 0–2 s was added at the end.

Figure 1 [Figure 1: see original paper] Experimental procedure for Experiment 1

2.1.4 Data Processing and Analysis

Trials with reaction times beyond three standard deviations were excluded (less than 2%). Repeated measures ANOVA was conducted using SPSS 20.0, with Greenhouse-Geisser correction applied when necessary and Bonferroni correction for pairwise comparisons.

2.2 Results and Analysis

Behavioral reaction times and accuracy rates are presented in Table 2 .

Table 2 Reaction times and accuracy rates for different priming types

Priming Type	Reaction Time (ms)	95% CI	Accuracy (%)
+O-P-S	605 (11)	583, 628	94.8 (1.2)
+O+P-S	613 (10)	593, 634	95.3 (1.1)
+O+P+S	601 (9)	583, 619	96.1 (0.9)
-O-P-S	641 (9)	623, 660	94.2 (1.3)

Note: Values in parentheses are standard errors.

For reaction times, the main effect of priming type was significant, F(3, 72) = 23.82, $p < 0.001$, partial ^{2} = 0.498. Following Cohen’ s (1988) guidelines (^{2} = 0.01 = small, ^{2} = 0.06 = medium, ^{2} = 0.14 = large effect), this represents a large effect size. Further analysis revealed significant priming effects for all three morpheme conditions compared to the control condition, F(1, 24) = 66.78 / 18.68 / 51.62, all ps < 0.001. The identity morpheme condition (+O+P+S) showed significantly stronger priming than the homophonic-homographic condition (+O+P-S), F(1, 24) = 8.92, $p = 0.006$. Although the heterophonic-homographic condition (+O-P-S) was 8 ms faster than the homophonic-homographic condition, this difference was not significant ($p > 0.1$). Among the three morpheme priming effects, the identity condition showed the largest effect, the homophonic-homographic condition the smallest, and the heterophonic-homographic condition fell in between. For accuracy, the main effect of priming type was not significant, nor was the difference between homophonic-homographic and identity morpheme conditions.

2.3 Discussion

The results of Experiment 1 clearly show that only the homophonic-homographic condition produced inhibition effects relative to the identity morpheme condition. Zhou et al. (1999) reported similar findings in a masked priming paradigm (their orthographic condition corresponds to our homophonic-homographic condition), with the identity condition (RT = 563 ms) showing a 20 ms faster priming effect than the homophonic-homographic condition (RT = 583 ms). Tsang et al. (2014) also found stronger priming for the identity morpheme condition than the homographic morpheme condition in an unmasked priming paradigm (SOA = 40 ms), though not in masked paradigms. Experiment 1 not only replicates previous findings but further reveals that the heterophonic-homographic condition did not show inhibition effects similar to the homophonic-homographic condition. This suggests that the phonological difference between the two conditions on the initial character may have caused the observed differences, indicating that phonological information participates in visual word recognition.

Experiment 1 also shows that all three morpheme conditions produced priming effects relative to the control condition, suggesting that early word recognition involves lexeme-level processing without semantic involvement. However, priming effects for both homographic morpheme conditions were significantly weaker than for the identity condition, with significant effects appearing in the homophonic-homographic condition. If early word recognition involves only morpho-orthographic/phonological processing as assumed in Taft’ s lexical decomposition-lemma model, these anomalous results would be difficult to explain.

Given that behavioral studies are not sensitive to the temporal course of word recognition and some results from Experiment 1 conflict with existing word processing models, Experiment 2 employed event-related potential (ERP) technology for further investigation.

3.1.1 Participants

The same 25 participants from Experiment 1 participated in Experiment 2.

3.1.2 Design and Materials

The design and materials were identical to Experiment 1, except that two target words with high error rates were excluded, leaving 46 item sets (accuracy > 88%).

3.1.3 Procedure

Participants sat in a sound-attenuated booth approximately 80 cm from the computer screen. For ERP recording purposes, target presentation was modified from 2000 ms to “500 ms presentation + 700 ms blank screen + presentation of ‘?’ ” (see Figure 2 [Figure 2: see original paper]). Other aspects remained identical to Experiment 1.

Figure 2 [Figure 2: see original paper] Experimental procedure for Experiment 2

3.1.4 ERP Recording and Processing

A 64-channel Brain Products ERP recording system (10-20 system) was used with FCz as the reference and forehead ground. Impedance was kept below 5 kΩ. Horizontal EOG was recorded from 2 cm lateral to the left eye canthus, and vertical EOG from 2 cm below the right orbit. Sampling rate was 500 Hz with a bandpass filter of 0.01-100 Hz.

Data were analyzed offline using Brain Vision Analyzer 2.1. Reference electrodes were converted to averaged mastoids (TP9, TP10), bandpass filtered at 0.01-30 Hz, ocular artifacts were corrected using ICA, trials with artifacts exceeding ±80 V were automatically rejected, and a 100 ms pre-stimulus baseline was used with a 1000 ms post-stimulus epoch. EEG data were then averaged by condition to obtain mean amplitudes for each participant in each condition.

3.1.5 Data Processing and Analysis

Scalp electrodes were grouped into 15 regions: left frontal (F3, F5, F7), left frontocentral (FC3, FC5, FT7), left central (C3, C5, T7), left centroparietal (CP3, CP5, TP7), left parietal (P3, P5, P7); midline frontal (F1, Fz, F2), midline frontocentral (FC1, FCz, FC2), midline central (C1, Cz, C2), midline centroparietal (CP1, CPz, CP2), midline parietal (P1, Pz, P2); right frontal (F4, F6, F8), right frontocentral (FC4, FC6, FT8), right central (C4, C6, T8), right centroparietal (CP4, CP6, TP8), and right parietal (P4, P6, P8) (see Figure 3 [Figure 3: see original paper]). Averaged amplitudes for each region were subjected to a 4 (priming type) × 3 (hemisphere: left/midline/right) × 5 (region: frontal/frontocentral/central/centroparietal/parietal) repeated measures ANOVA. Other analysis parameters were identical to Experiment 1.

Figure 3 [Figure 3: see original paper] Electrode regions used for statistical analysis

3.2 Results

Visual inspection (see Figures 4 [Figure 4: see original paper], 5 [Figure 5: see original paper], and 6 [Figure 6: see original paper]) revealed that in the 120-540 ms window, the homophonic-homographic (+O+P-S) condition showed clear priming effects compared to the control condition during the middle processing stage (280-400 ms), but overlapped with the control condition in early (120-220 ms) and late (430-540 ms) stages. Therefore, three time windows were analyzed: P2, early N400, and late N400. Statistical results are summarized in Table 3 .

3.2.1 P2 Component (120-220 ms)

The main effect of priming type was significant, F(3, 72) = 3.48, p = 0.026, partial ^{2} = 0.127. The region × priming type interaction was significant, F(12, 288) = 2.62, p = 0.048, partial ^{2} = 0.098. The hemisphere × region × priming type interaction was significant, F(24, 576) = 2.51, p = 0.022, partial ^{2} = 0.095. All effect sizes were medium or larger.

Further analysis revealed that compared to the control condition, heterophonic-homographic and identity conditions elicited enhanced P200 effects at midline frontocentral (0.704 V, p = 0.038; 0.704 V, p = 0.049) and midline central (1.078 V, p < 0.001) regions, while the homophonic-homographic condition showed no significant effect (p > 0.1). Compared to the homophonic-homographic condition, heterophonic-homographic and identity conditions produced enhanced P200 effects at midline frontocentral (0.686 V, p = 0.065, marginal; 0.685 V, p = 0.014) and central (1.041 V, p < 0.001; 0.589 V, p = 0.022) regions. Thus, on the P2 component, the homophonic-homographic condition was more similar to the control condition but clearly different from the other two morpheme conditions at midline frontocentral and central regions.

3.2.2 Early N400 Component (280-400 ms)

The main effect of priming type was significant, F(3, 72) = 3.77, p = 0.024, partial ^{2} = 0.136. The hemisphere × priming type interaction was significant, F(6, 144) = 5.0, p = 0.001, partial ^{2} = 0.172. The region × priming type interaction was significant, F(12, 288) = 7.56, $p < 0.001$, partial ^{2} = 0.239. The hemisphere × region × priming type interaction was marginally significant, F(24, 576) = 1.92, p = 0.059, partial ^{2} = 0.074. All effect sizes were medium or large.

Further analysis showed that compared to the control condition, heterophonic-homographic, homophonic-homographic, and identity conditions all produced N400 priming effects at midline frontal (0.923 V, p = 0.027; 0.973 V, p = 0.049; 1.156 V, p = 0.002), midline frontocentral (1.066 V, p = 0.025; 0.952 V, p = 0.05; 1.338 V, p = 0.003), and midline central (1.474 V, p = 0.002; 0.893 V, p = 0.039; 1.129 V, p = 0.013) regions. Compared to the homophonic-homographic condition, only the heterophonic-homographic condition produced larger priming effects at midline central (0.581 V, p = 0.027), right frontocentral (0.588 V, p = 0.049), and right central (0.617 V, p = 0.02) regions (see Figures 4 and 5), while the identity condition showed no significant difference ($p > 0.7$). These results indicate that on the early N400 component, all three morpheme conditions differed from the control condition, but the homophonic-homographic condition was clearly more similar to the identity condition than to the heterophonic-homographic condition in right frontocentral regions.

3.2.3 Late N400 Component (430-540 ms)

The main effect of priming type was significant, F(3, 72) = 3.31, p = 0.039, partial ^{2} = 0.121. The hemisphere × priming type interaction was significant, F(6, 144) = 3.91, p = 0.008, partial ^{2} = 0.14. The region × priming type interaction was not significant, F(12, 288) = 1.23, p = 0.3, partial ^{2} = 0.049. The hemisphere × region × priming type interaction was significant, F(24, 576) = 2.65, p = 0.009, partial ^{2} = 0.099. Except for the region × priming type interaction, all effect sizes were medium or large.

Further analysis revealed that compared to the control condition, heterophonic-homographic and identity conditions produced N400 priming effects at midline centroparietal regions (1.015 V, p = 0.049; 1.313 V, p = 0.014), while the homophonic-homographic condition showed no significant effect ($p > 0.1$). Compared to the homophonic-homographic condition, heterophonic-homographic and identity conditions produced N400 priming effects at midline central (0.948 V, p = 0.002; 1.125 V, $p < 0.001$), midline centroparietal (0.712 V, p = 0.047; 1.01 V, $p < 0.001$), and midline parietal (1.067 V, p = 0.02; 1.178 V, $p < 0.001$) regions. Additionally, the heterophonic-homographic condition showed effects at right central region (0.692 V, p = 0.048), and the identity condition at midline frontocentral region (1.073 V, p = 0.003). These results indicate that on the late N400 component, the homophonic-homographic condition was more similar to the control condition but clearly different from the other two morpheme conditions in midline centroparietal regions.

Table 3 Summary of statistical results for P200, early N400, and late N400 components

Baseline (I)	Priming Type (J)	Mean Difference (I-J)	p-value	95% CI Lower	Upper
P200					
+O+P-S	-O-P-S (midline frontocentral)	-0.685*	0.014	-1.238	-0.132
+O+P-S	+O-P-S (midline frontocentral)	-0.686†	0.065	-1.411	0.039
+O+P-S	+O+P+S (midline frontocentral)	-0.685*	0.014	-1.238	-0.132
+O+P-S	+O-P-S (midline central)	-1.041*	<0.001	-1.619	-0.463
+O+P-S	+O+P+S (midline central)	-0.589*	0.022	-1.089	-0.089
Early N400					
-O-P-S	+O-P-S (midline frontal)	-0.923*	0.027	-1.734	-0.112
-O-P-S	+O+P-S (midline frontal)	-0.973*	0.049	-1.944	-0.002
-O-P-S	+O+P+S (midline frontal)	-1.156*	0.002	-1.879	-0.433
-O-P-S	+O-P-S (midline frontocentral)	-1.066*	0.025	-1.993	-0.139
-O-P-S	+O+P-S (midline frontocentral)	-0.952*	0.05	-1.904	0

Baseline (I)	Priming Type (J)	Mean Difference (I-J)	p-value	95% CI Lower	Upper
-O-P-S	+O+P+S (midline frontocentral)	-1.338*	0.003	-2.208	-0.468
+O+P-S	+O-P-S (midline central)	-0.581*	0.027	-1.096	-0.066
-O-P-S	+O-P-S (midline central)	-1.474*	0.002	-2.395	-0.553
-O-P-S	+O+P-S (midline central)	-0.893*	0.039	-1.739	-0.047
-O-P-S	+O+P+S (midline central)	-1.129*	0.013	-2.012	-0.246
+O+P-S	+O-P-S (right frontocentral)	-0.588*	0.049	-1.174	-0.002
+O+P-S	+O-P-S (right central)	-0.617*	0.02	-1.133	-0.101
Late N400					
+O+P-S	+O+P+S (midline frontocentral)	-1.073*	0.003	-1.777	-0.369
+O+P-S	+O-P-S (midline central)	-0.948*	0.002	-1.543	-0.353
+O+P-S	+O+P+S (midline central)	-1.125*	<0.001	-1.774	-0.476
+O+P-S	+O-P-S (midline centroparietal)	-0.712*	0.047	-1.414	-0.01
+O+P-S	+O+P+S (midline centroparietal)	-1.01*	<0.001	-1.551	-0.469
-O-P-S	+O-P-S (midline centroparietal)	-1.015*	0.049	-2.025	-0.005
-O-P-S	+O+P+S (midline centroparietal)	-1.313*	0.014	-2.357	-0.269

Baseline (I)	Priming Type (J)	Mean Difference (I-J)	p-value	95% CI Lower	Upper
+O+P-S	+O-P-S (midline parietal)	-1.067*	0.02	-1.959	-0.175
+O+P-S	+O+P+S (midline parietal)	-1.178*	<0.001	-1.888	-0.468
+O+P-S	+O-P-S (right central)	-0.692*	0.048	-1.378	-0.006

Note: indicates significant mean difference, p < .05. † indicates marginal significance.*

Figure 4 [**Figure 4: see original paper**] ERP waveforms for different priming types

Figure 5 [**Figure 5: see original paper**] ERP waveforms for different priming types at Cz electrode

Figure 6 [**Figure 6: see original paper**] Difference wave topographies for different priming conditions
Note: Following Dominguez et al. (2004), "control condition -priming condition" was used.

4. General Discussion

Both experiments demonstrate significant morphological priming effects for all three morpheme conditions relative to the control condition, supporting the conclusion that Chinese compound words undergo morphological decomposition, consistent with numerous previous studies (e.g., Amenta & Crepaldi, 2012; Crepaldi et al., 2010; Ford, Davis, & Marslen-Wilson, 2010; Marslen-Wilson, Tyler, Waksler, & Older, 1994; Zhou et al., 1999; Chen & Peng, 2001; Chen, Wang, & Peng, 2003; Zhang & Yang, 2004). The findings are discussed in relation to each research question below.

4.1 Phonological Information and Visual Word Recognition

The results indicate that although heterophonic-homographic and homophonic-homographic conditions did not differ significantly in reaction times, they showed significant differences on P2 (midline frontocentral/central), early N400 (midline central, right frontocentral/central), and late N400 (midline central/centroparietal/parietal, right central). Overall, the processing pattern of the heterophonic-homographic condition was clearly different from the homophonic-homographic condition but more similar to the identity condition. Since the only difference between the two homographic conditions and the identity condition lies in whether the initial character' s pronunciation matches the target' s initial character, these results suggest that phonological information is activated even during visual word recognition. Furthermore, on early N400 (right frontocentral), the homophonic-homographic condition differed significantly only from the heterophonic-homographic condition, not from the identity condition. Given that many studies have found phonological processing activates right frontal regions, this provides further evidence for phonological involvement in Chinese compound word recognition.

A critical question is why homographic morpheme inhibition effects appear only in the homophonic-homographic condition. Previous research suggests that identical stems/morphemes activate different lexical semantic representations, requiring selection among them. ERP studies by Barber et al. (2002), Dominguez et al. (2004), and Wu et al. (2016), as well as MEG research by Simon et al. (2012), found waveform divergence between homophonic-homographic and identity conditions beginning around 250–350 ms, and the present study found similar separation on early N400 (280–400 ms). Moreover, the homophonic-homographic condition differed from the other two morpheme conditions on late N400, seemingly confirming this interpretation. This could also explain phonological interference effects found in polyphonic Chinese characters by Tan & Perfetti (1999), Liu et al. (2017), and Zhang et al. (2017): polyphonic characters with identical orthography, or interfering phonological items, activate multiple lexical semantic representations, triggering semantic competition. However, the specific timing of waveform divergence varies across studies. The current results show significant differences between homophonic-homographic and identity conditions as early as P200, similar to Liu et al. (2017) and Zou et al. (2019) but conflicting with other studies, suggesting this cannot be simply explained by activation of different semantic representations.

The study also found no significant differences between heterophonic-homographic and identity conditions on P2, early N400, or late N400. This aligns with Zou et al. (2012) but contradicts Zhou et al. (1999, Experiment 4) based on reaction times in long-term priming paradigms. A plausible inference is that with phonological involvement, processing mechanisms for heterophonic-homographic and homophonic-homographic conditions may differ between masked and long-term priming paradigms. The inhibition effect in the homophonic-homographic condition may stem from competition among lexical semantic representations activated by identical stems/morphemes, observable in both masked and long-term paradigms. In contrast, the inhibition effect in the heterophonic-homographic condition may result from strategic processing in long-term priming paradigms, making it difficult to observe in masked paradigms. However, given the inconsistent P200 results for the homophonic-homographic condition and the scarcity of research on heterophonic-homographic conditions, this inference requires rigorous testing in future studies.

4.2 Phonological Information, P2, and N400

The timing of phonological involvement is closely related to the functional significance of P2 and N400. Previous accounts of P2' s cognitive mechanisms have been diverse, suggesting it may be related to orthographic and phonological processing (Beyersmann et al., 2014; Liu et al., 2017; Liu, Perfetti, Hart, 2003; Liu, Jin, Qing, & Wang, 2011; Meng, Jian, Shu, Tian, & Zhou, 2008; Morris, Frank, Grainger, & Holcomb, 2007), spelling/orthography-phonology matching or regularity (Lee et al., 2007; Sereno, Rayner & Posner, 1998), target word frequency, regularity, and lexicality (Chen, Liu, Wang, Peng, & Perfetti, 2007; Kong et al., 2010; Sereno et al., 1998; Zhang, Zhang, & Kong, 2009), homophonic radicals in Chinese characters (Zhou, Fong, Minett, Peng, & Wang, 2014) or position (Su, Mak, Cheung, & Law, 2012), lexical processing (Carreiras et al., 2005; Dambacher, Kliegl, Hofmann, & Jacobs, 2006; Martin, Kaine, & Kirby, 2006; Meyler & Breznitz, 2005), and semantic processing tasks in L2 learners (Landi & Perfetti, 2007). The present study found a P2 component in the 120-220 ms window at midline frontal, frontocentral, and central regions. The waveform and difference topographies show that on P2, the homophonic-homographic condition showed virtually no difference from the control condition and was statistically non-significant, while heterophonic-homographic and identity conditions showed P2 enhancement. Since all three morpheme conditions were orthographically identical to the target, if P2 solely represented orthographic processing, such clear divergence should not occur.

If P2 represented phonological processing, one would expect the homophonic-homographic (rather than heterophonic-homographic) condition to be more similar to the identity condition on P2, which contradicts our results. Although Liu et al. (2017) found more negative P2 for heterophonic-homographic than identity conditions and concluded P2 reflects phonological processing, their study included phonological interference conditions, and Niznikiewicz & Squires (1996) found that phonologically interfering homophones produce more negative N2, suggesting the more negative P2 might stem from phonological interference itself. Grainger, Kiyonaga, & Holcomb (2006) also argued that phonological processing should occur after 250 ms post-target onset.

A reasonable explanation is that P2 in this study may not be related to phonological or orthographic processing but rather represents a general, abstract mental processing mechanism (see Binder, Medler, Westbury, Liebenthal, & Buchanan, 2006). For language processing, it likely reflects pre-lexical stages of selective attention, matching, categorization, or identification of incoming stimuli by the mental lexicon network (see Hackley, Woldorff, & Hillyard, 1990; Luck & Hillyard, 1994), with abnormal or conflicting information in visual stimuli causing more negative P2 or N2 components (see Ziegler, Benraiss, & Besson, 1999). The homophonic-homographic condition in this study, the heterophonic-homographic condition in Liu et al. (2017), and homophones in Niznikiewicz & Squires (1996) all contain some form of conflicting information (not limited to phonological conflict), leading to more negative P2/N2 amplitudes. In this study, the conflicting information may stem from the masked priming paradigm (primes may activate semantic conflict in target initial characters, see Kiefer & Brendel, 2006) or from some inherent but unknown rule-based linguistic conflict property of homophonic-homographic morphemes. However, without detailed research or theoretical predictions about how the mental lexicon network can identify such conflict information so rapidly, a definitive answer cannot be provided and awaits future investigation.

Phonological involvement most likely occurs before late N400. Although heterophonic-homographic and homophonic-homographic conditions share no semantic similarity with target initial characters, the heterophonic-homographic condition did not show inhibition effects similar to the homophonic-homographic condition on late N400, indicating it had already resolved multiple ambiguities before late N400. Combined with Experiment 1 results (8 ms faster than homophonic-homographic condition, though non-significant) and the P2 analysis above, we can confidently conclude that phonological information participates in Chinese compound word recognition and does so before late N400. Due to phonological involvement prior to late N400, ambiguity triggered by orthographic overlap in the heterophonic-homographic condition was resolved.

Based on the P2 and late N400 analyses, the most likely time window for phonological involvement is early N400. Bentin, Mouchetant-Rostaing, & Giard (1999) and Grainger et al. (2006) both argued that phonological processing occurs at 250–350 ms post-target onset, which largely overlaps with our early N400 window. Moreover, unlike P2 and late N400, on early N400 the homophonic-homographic condition differed significantly only from the heterophonic-homographic condition (at midline central, right frontocentral, and right central regions), not from the identity condition. A reasonable conclusion is that phonological involvement most likely occurs during early N400 (280–400 ms), possibly in right frontocentral brain regions.

4.3 Morpho-Orthographic and Morpho-Semantic Processing

The above analyses suggest that visual word recognition may involve distinct processing stages corresponding to P2, early N400, and late N400, with clear dissociation after early N400. Based on homographic stem/morpheme effects, studies by Barber et al. (2002), Dominguez et al. (2004), and Wu et al. (2016) found waveform divergence beginning around 350 ms, but could not determine whether semantic or phonological information caused homographic stem/morpheme effects since they used only homophonic-homographic materials. By including a heterophonic-homographic condition, this study effectively separated these factors, credibly demonstrating that phonological involvement during early N400 resolved orthographically triggered ambiguity in the heterophonic-homographic condition before late N400, thereby preventing homographic morpheme inhibition effects.

Setting aside the uncertain P2, a reasonable hypothesis is that Chinese compound word recognition involves a two-stage process. Early N400 may reflect morpho-orthographic processing primarily at the lexeme level, where orthographic matching and phonological information are key factors, making the three morpheme conditions similar to each other but all significantly different from the control condition. Late N400 may represent morpho-semantic processing primarily involving semantic selection and competition at the lemma level. Since the homophonic-homographic condition shares both orthography and phonology with the target’ s initial character, different meanings compete at the lemma level, with appropriate semantics being selected and inappropriate ones inhibited, resulting in inhibition effects relative to the other two morpheme conditions.

These results seem to support Taft & Nguyen-Hoan’ s (2010) and Xu & Taft’ s (2014) lexical decomposition-lemma model (developed from the form-semantics model), which posits that morphological processing involves an early orthography-based morpho-orthographic stage without semantic involvement, and a late lemma-based morpho-semantic stage where semantic processing occurs (e.g., Meunier & Longtin, 2007; Rastle & Davis, 2003; Rastle et al., 2004). However, if P2 involves monitoring and feedback of semantic conflict information as speculated, this would indicate that early word recognition stages are not limited to isolated morpho-orthographic processing, requiring cautious interpretation of Taft’ s model.

The results are also incompatible with the supralexical model (Giraudo & Grainger, 2001, 2003), which assumes whole-word processing precedes morphological decomposition. Since final characters in Chinese compounds can effectively distinguish homophonic-homographic from heterophonic-homographic conditions in this design, if whole-word recognition occurred first, all three morpheme conditions should yield similar results given identical targets. This clearly contradicts our findings.

The morpho-orthographic/morpho-semantic hybrid model, also developed from the lexical decomposition-lemma model, acknowledges that early word recognition involves both morpho-orthographic and morpho-semantic processing (Diependaele et al., 2005). However, like other models, it was proposed based on behavioral research defining “early word recognition” by priming SOA (e.g., 40 ms or 53 ms). Current ERP research shows that even masked priming paradigms can produce N400 effects (e.g., our late N400) and even late positive components closely related to semantic processing. Therefore, the model’ s predictive power depends on how “early word recognition” is defined. If defined by priming duration, our masked priming paradigm did reveal morpho-semantic involvement, supporting the model. But if defined by actual word processing time course in ERP research, semantic processing involvement in P2 must be demonstrated; otherwise, our results do not support this model.

Overall, the parallel distributed processing (PDP) model (McClelland & Rumelhart, 1981) appears most compatible with our results. This model suggests that connection strength affects processing time course. Regardless of whether P2' s conflicting information in the homophonic-homographic condition originates from the masked priming paradigm or the materials themselves, its connection strength with lexical/semantic/social networks differs from other conditions. Its differences on late N400 can be similarly explained. The model' s focus on processing differences between objects rather than the objects themselves may explain its better fit.

5. Conclusion

(1) Heterophonic-homographic, homophonic-homographic, and identity conditions all produced morphological priming effects relative to the control condition.

(2) On the P2 component (midline frontocentral) and late N400 component (midline centroparietal), the homophonic-homographic condition was more similar to the control condition but differed significantly from heterophonic-homographic and identity conditions.

(3) On the early N400 component (right frontocentral), the homophonic-homographic condition was more similar to the identity condition but differed significantly from the heterophonic-homographic condition.

These findings tend to support the Parallel Distributed Processing Model proposed by McClelland and colleagues.

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