NEUROSCIENCE
RESEARCH ARTICLE

Y. Wu et al./Neuroscience 446 (2020) 249–260

Processing Ambiguous Morphemes in Chinese Compound Word Recognition: Behavioral and ERP Evidence

Yan Wu, [a] **Rujun Duan,** [a] **Simin Zhao** [a] **and Yui-Kei Tsang** [b*]

[a] *School of Psychology, Northeast Normal University, Hong Kong, China*

[b] *Department of Education Studies, Hong Kong Baptist University, Hong Kong, China*

Abstract—This study examined the processing of ambiguous morphemes in Chinese word recognition with a masked priming lexical decision task. Both behavioral and event-related potential (ERP) were recorded. All targets were bimorphemic compound words that contained ambiguous morphemes as the first morphemes. The ambiguous morphemes either took the dominant or subordinate interpretation, depending on the second morphemes. The prime words contained the same ambiguous morphemes in the dominant interpretation, the subordinate interpretation, or were unrelated to the targets. Analyses on response times revealed significant facilitative priming whenever primes and targets shared morphemes, but the strength of facilitation was stronger when the morpheme meanings were consistent. A similar pattern was found in the analyses of N400 (300–500 ms after target onset) amplitudes. However, in the earlier N250 time window (200–300 ms after target onset), only the dominant targets, but not the subordinate ones, were primed by the morpheme-sharing primes. More importantly, the strength of facilitation was similar between the dominant and subordinate primes. These results have two implications to the processing of ambiguous morphemes during Chinese compound word recognition. First, the morpheme meanings could be activated rapidly. Second, the more frequently used dominant meanings could be activated more easily than the less frequently used subordinate meanings.

Key words: Chinese word recognition, morphological processing, morphemic ambiguity, morpho-semantics, ERP.

INTRODUCTION

Adopting a morpho-syllabic system, most Chinese characters correspond to morphemes. For example, the character "草" (/cao3/) represents the morpheme "grass" and "地" (/di4/) represents "ground". The two morphemes combine to form the compound word "草地" ("grassland"). Sometimes, the mapping between characters and morphemes is not one-to-one. The character "草" is also used to represent "rough", as in "草率" (/cao3shuai4/, "hasty") and "草擬" (/cao3ni3/, "draft"). This creates a phenomenon called "morphemic ambiguity" (Tsang and Chen, 2013ab; Wu et al., 2017). This phenomenon is not restricted to Chinese. It also exists in English (e.g., the "-er" in "taller" and "teacher" or the "in-" in "inside" and "invalid") and other languages like Finnish and Spanish. However, ambiguous morphemes are much more prevalent in Chinese: Over 65% of the common Chinese characters have multiple meanings (Liu et al., 2007). When a compound word contains an ambiguous morpheme, its correct interpretation is determined by the other morpheme in the word, which effectively serves as the context for ambiguity resolution. In daily life, meaning resolution appears to be so rapid that most ordinary language users are unaware of its existence. Despite its prevalence and relevance to comprehending word meanings, not many studies have been conducted to investigate the processing of ambiguous morphemes. The available evidence is also inconclusive. This study intends to further investigate the issue, which will have important implications on understanding morphological processing and language comprehension.

The few studies that examined the topic did show that the human cognitive system is sensitive to ambiguous morphemes. In one early study of morphemic ambiguity in Spanish homographic stems, Allen and Badecker (1999) adopted the unmasked priming lexical decision paradigm with a stimulus-onset-asynchrony (SOA) of 250 ms. They showed that responses were slower and less accurate to target words that contained homographic stems (e.g., "cerr-ar", "to close") when prime words contained the same morphemes in different meanings (e.g., "cerr-o", "hill"), as compared to orthographically related primes (e.g., "cerd-o", "pig") or an unrelated baseline

*Corresponding author. Tel: +852-34115325.
E-mail address: yktsang@hkbu.edu.hk (Y.-K. Tsang).
Abbreviations: ERP, event-related potential; SOA, stimulus-onset-asynchrony.

https://doi.org/10.1016/j.neuroscience.2020.08.006
0306-4522/

(e.g., "noble", "noble"). In a subsequent study, Badecker and Allen (2002) presented similar materials to participants using the masked priming lexical decision procedure (SOA = 67 ms). In contrast to the inhibitory priming effects observed with unmasked priming, when the primes were presented too briefly to be processed consciously in masked priming, facilitation was observed when primes and targets shared homographic stems of different interpretations. A similar pattern of facilitation in masked priming and inhibition in unmasked priming was also found with Finnish ambiguous morphemes (Järvikivi et al., 2009; SOA = 60 ms or 300 ms). These results are consistent with the proposal that ambiguous morphemes are activated early during word recognition, and then a time-consuming selection process is needed to select the correct interpretations (Badecker and Allen, 2002).

Given that the prime-target pairs in the aforementioned studies always involved ambiguous morphemes of different meanings, it remains unclear about the exact nature of the early activation of ambiguous morphemes. There are two major views. According to the form-then-meaning account (Rastle and Davis, 2008), the initial activation only involves morphemic form, and the intended morphemic meaning is activated subsequently. In contrast, the form-with-meaning account (Feldman et al., 2009; Taft and Nguyen-Hoan, 2010) assumes that morphemic forms and meanings are both available early. For ambiguous morphemes, this implies that the multiple meanings are activated non-selectively at the initial stage, and then the intended meaning is selected based on context.

The prevalence of ambiguous morphemes in Chinese makes it the ideal language to verify the two views. For example, Zhou et al. (1999) adopted the masked priming lexical decision task (SOA = 57 ms) to investigate the recognition of bimorphemic Chinese words that contained ambiguous morphemes (e.g., "华贵", /hua2gui4/, "luxurious"). Prime words contained the same ambiguous morphemes in the same meaning (e.g., "华丽", /hua2li4/, "magnificent") or a different meaning (e.g., "华侨", /hua2-qiao2/, "overseas Chinese"). Results showed that, as compared to the unrelated control condition, facilitative priming was found in both the same and different meaning conditions. Most importantly, the strength of facilitation was significantly stronger in the same meaning than the different meaning condition. Given that no masked priming effect was observed when primes and targets shared lexical level semantics in a control experiment, the results were attributed to morpheme level processing and could be interpreted as supporting early activation of the intended morphemic meanings. However, using similar procedure, Tsang et al. (2014) obtained statistically comparable priming effects between the same meaning and different meaning conditions, which challenged the robustness of Zhou et al. (1999).

It is worth noting that the interpretation of the inconsistent results between Zhou et al. (1999) and Tsang et al. (2014) can be tricky. Given the low temporal resolution of behavioral measures, which reflect the summation of all cognitive processes that lead to a response, the differences between the two studies can reflect processing other than the morphological processing of interest. It is difficult to isolate and study the target cognitive process with behavioral measures. In contrast, event-related potential (ERP) recording measures the brain electrical signals as participants perform a task. It has high temporal resolution that allows the continuous monitoring of cognitive processes before a response is made. Most importantly, through years of empirical studies, researchers have already identified several ERP components that have distinctive latencies and scalp distributions, which are considered to reflect different language-related processes. For example, early components like P200 and N250 are considered to reflect prelexical and morphological processing (Morris et al., 2007, 2008; Wu et al., 2017), whereas the later component N400 has been well-known to reflect meaning-related processing (Huang et al., 2006; Lavric et al., 2011; Beyersmann et al., 2014).

Several ERP studies have been conducted to investigate the processing of ambiguous morphemes. For example, in a simple lexical decision experiment, Huang and Lee (2018) showed that a stronger N400 was elicited when the target bimorphemic Chinese words contained ambiguous morphemes than when the morphemes were unambiguous. Differences were found only in N400, but not in earlier time windows, suggesting that the effect likely reflected difficulty in selecting and integrating the ambiguous morphemic meanings. In another study, Wu et al. (2017) adopted the masked priming lexical decision task. Targets were Chinese bimorphemic words that contained ambiguous morphemes, and primes words contained the same ambiguous morphemes in either the same or different meanings. As compared with the unrelated control condition, significant facilitative priming was observed in both morpheme-sharing conditions for P200 and N400. Moreover, the strength of facilitation was statistically identical between the two conditions in the early P200 time windows, which appeared to be inconsistent with the differences between same and different meaning primes observed in Zhou et al. (1999).

Another reason that makes it difficult to interpret the inconsistent results in previous studies of morphemic ambiguity is the ignorance of relative meaning frequency. Research in lexical ambiguity resolution (Duffy et al., 1988) has shown that the multiple meanings of ambiguous words are activated simultaneously, but the level of activation depends on relative meaning frequency, such that the more frequently used dominant meanings are by default more strongly activated even without contextual supports. The subordinate meanings only become more strongly activated with contextual supports, which ultimately suppress the dominant meanings when time is sufficient. Assuming that similar mechanism also applies to morphemic ambiguity, it is expected that when the primes are only briefly presented in masked priming, both dominant and subordinate meaning primes will activate the dominant meanings of ambiguous morphemes to facilitate the recognition of target words that take the dominant meanings. On the other hand, targets that take the subordinate meanings will only be facilitated by primes that take the same subordinate meanings. This was exactly what Tsang and Chen (2013a,b) observed in a series of masked priming experiments. In other words, the inconsistent results in previous studies may be attributed to using different meanings in target words[1]. If most of the targets took the dominant meanings, they would be primed by both the same (dominant) and different (subordinate) meaning primes. If the targets took the subordinate meanings, they would be primed only by the same (subordinate) meaning primes. This factor should receive more attention in the research of ambiguous morphemes.

This study re-examined the processing of Chinese ambiguous morphemes with ERP recording, which provided excellent temporal resolution. The experimental design was similar to Tsang and Chen (2013a,b). As discussed above, this design would provide better evidence about early morpho-semantic activation by considering the relative meaning frequency of the ambiguous morpheme meanings. A masked priming lexical decision task was conducted. Targets were Chinese bimorphemic words. The first morphemes of these words were ambiguous, and the second morphemes provided the context for disambiguation. For example, the character “月” (/yue2/) could form the dominant meaning target “月亮”, (/yue4liang4/, “The Moon”) and the subordinate meaning target “月份” (/yue4fen4/, “month”). Similarly, prime words were constructed with the dominant meanings (e.g., “月牙”, /yue4ya4/, “crescent moon”) or the subordinate meanings (e.g., “月末”, /yue4 mo4/, “the end of the month”). For dominant meaning targets, the dominant and subordinate meanings primes represented the same and different meanings primes, respectively. For subordinate targets, the relationship was reversed.

In Wu et al. (2017), the ERP time windows for analyses were selected by visual inspection. However, this is not a good practice because it equates to performing multiple comparisons implicitly and picks only those that obviously differ (Luck and Gaspelin, 2017). Therefore, in this study, we chose two a priori time windows for analyses based on previous ERP studies of morphological processing (Morris et al., 2007, 2008). Specifically, the N250 (200–300 ms) and N400 (300–500 ms) components were selected. The N250 component is considered to reflect orthographic processing and the activation of morphemes. It is somewhat controversial whether it reflects morpheme forms only or is also sensitive to morpheme meanings. Morris et al. (2007) showed that the strength of masked morphological priming on N250 was larger in the transparent than opaque condition. Yet, Lavric et al. (2007) did not observe any reliable differences in priming effects among the transparent, opaque, and letter-sharing conditions in a similar window (220–260 ms). In contrast, there has been stronger evidence that N400 is sensitive to morpheme meanings. For example, Morris et al. (2007) observed greater N400 priming for transparent than opaque items. Similarly, Wu et al. (2017) showed that N400 priming was significant only when primes and targets shared ambiguous morphemes in the same meanings, but not in different meanings. Furthermore, in a series of simple lexical decision experiments, Huang and colleagues (Huang et al., 2011; Huang and Lee, 2018) showed that the size of N400 was sensitive to the number of meanings an ambiguous morpheme carried.

According to the form-then-meaning account (Rastle and Davis, 2008), morphemic meanings become activated only after an initial stage of morphemic form activation. This view predicted that the early N250 priming would be purely morphemic form in nature, such that morphological priming could be found whenever primes and targets shared ambiguous morphemes, irrespective of whether the meanings were consistent. Morphemic meanings would have an effect only in N400, such that priming could be found only when primes and targets shared ambiguous morphemes of the same meanings. In contrast, the form-with-meaning account (Feldman et al., 2009) assumes that morphemes are meaning-bearing units, such that both morphemic forms and meanings are activated early and simultaneously. This implied that morpheme meanings would influence the strength of priming in both N250 and N400. Based on the behavioral results of Tsang and Chen (2013a,b) that initially, the dominant meanings could be activated strongly even without contextual support, it was expected that in the N250 window, the processing of dominant targets would be facilitated by both dominant (i.e., consistent context) and subordinate (i.e., inconsistent context) primes. In contrast, the subordinate meanings would need contextual supports to activate strongly, such that the subordinate targets would be facilitated only by the same meaning subordinate primes. In the later N400 time window, given more time to sufficiently constrain activation of the intended meaning, it was expected that both the dominant and subordinate targets would be facilitated only by the same meaning primes.

EXPERIMENTAL PROCEDURES

Participants

Twenty-six university students (12 males, 14 females) with an age range of 18–25 years (mean = 21.12; SD = 2.07) participated in the experiment and received monetary compensation. All of them were native Mandarin speakers and right-handed. They had normal or corrected vision, and none of them reported a history of neurological or linguistic impairments. This study was approved by the Research Committee of the School of Psychology at the Northeast Normal University. Written informed consent was obtained from all participants before the start of the experiment.

Materials

A number of Chinese characters/morphemes with at least two distinctive definitions were chosen from the dictionary. Based on a series of pilot testing (see below), 90 ambiguous morphemes were finally chosen. Given that corpus data about the relative meaning frequency of ambiguous morphemes is unavailable, a free-association pilot test was conducted to obtain relevant information. Forty-five students, who did not

[1] Zhou et al. (1999) and Wu et al. (2017) did not provide information about the meanings used in the target words. In Tsang et al. (2014), the ambiguous morphemes in target words always took the dominant meanings.

participate in the main experiment, were recruited. Their task was to write down the first meaning that came to their mind after reading each ambiguous morpheme. They could provide the meanings by using definition, forming words, or translating into English. On average, among the 90 ambiguous morphemes chosen, the dominant meanings were reported 87% of the time (range = 67–98%), while the subordinate meanings were reported 9% of the time (range = 2–19%). The average difference of report proportions between the dominant and subordinate meanings was 77.91% (range = 60–96%). The ambiguous morphemes used in this study were thus "biased" in the sense that they had a highly frequent dominant meaning.

To ensure that the dominant and subordinate meanings are distinctive "meanings", rather than related "senses", 15 pilot participants, who did not participate in other tests, were recruited to rate the degree of relatedness between the dominant and subordinate meanings. They were asked to rate the relatedness of each pair of meanings on a 6-point Likert scale (1 = highly unrelated; 6 = highly related). The average relatedness ratings of the materials chosen were always below 3 ($M = 2.2$, SD = .49). Bimorphemic target and prime words were constructed based on the 90 ambiguous morphemes chosen. All words were constructed through compounding, which is the primary word formation method in Chinese. The ambiguous morphemes always appeared at the first morpheme position for both primes and targets. To improve the signal-to-noise ratio of the ERP recording, 30 ambiguous morphemes were used to construct two sets of primes and targets to increase the total number of items (only the ambiguous morphemes were repeated, the prime and target words constructed were different). An unrelated prime (in orthography, phonology, and semantics) was also prepared for each set to assess the priming effects. In total, there were 120 sets of materials, comprising of 240 target words (dominant vs. subordinate) and 720 prime words (dominant vs. subordinate vs. unrelated). Table 1 shows a set of example material and the corresponding linguistic properties.

The words constructed were evaluated for semantic transparency. A rating test was completed by 18 participants who did not take part in other tests. They were asked to rate how much the first and second morphemes contributed to the whole-word meanings on a 7-point Likert scale (7 = strongest contribution). The ratings of the first and second morphemes were then averaged to produce one rating for each word. The average rating of all words was above 4.5, indicating that the materials were reasonably transparent. Moreover, there were no significant differences in transparency ratings among the three priming conditions ($F_{2,\ 34} = 1.06$, $p = .357$) or between the two target conditions ($t_{17} = .83$, $p = .419$). In addition, the number of strokes, log-transformed character frequency (averaged of the first and second characters), and log-transformed word frequency (Cai and Brysbaert, 2010) were matched across the three priming conditions (all ps > .05) and the two target conditions (all ps > .1).

On the other hand, it was impossible to match the semantic relatedness of the whole words across conditions because words sharing ambiguous morphemes in the same meanings would also be related at the whole word level. This was demonstrated by another pilot test with 15 participants, who was asked to rate the semantic relatedness of the prime-target word pairs on a 6-point Likert scale (6 = strongest relatedness). For dominant targets, there was a significant difference in semantic relatedness across conditions ($F_{2,\ 28} = 101.31$, $p < .001$, $\eta_p^2 = .879$), such that the dominant primes were more related to the targets than both the subordinate and unrelated primes, which did not differ by themselves (dominant prime vs. subordinate prime: $p < .001$; dominant vs. unrelated condition: $p < .001$; subordinate vs. unrelated condition: $p = .11$). Similarly, for subordinate targets, there was a significant difference in semantic relatedness across condition ($F_{2,\ 28} = 67.13$, $p < .001$, $\eta_p^2 = .827$). The subordinate primes were more related to the subordinate targets than the dominant and unrelated primes, which did not differ by themselves (subordinate prime vs. dominant prime: $p < .001$; subordinate vs. unrelated condition: $p < .001$; dominant vs. unrelated condition: $p = .20$). How such confound might affect the results in this study will be discussed in Discussion.

To avoid the same participant encountering the same target more than once, three experimental lists were created. Each list contained the 240 experimental targets (120 dominant meanings and 120 subordinate meanings). Each target was paired with one of the three primes (dominant, subordinate, and unrelated) such that there were 40 primes per condition. The prime-target pairing was rotated across lists according to the Latin square design to exhaust all possible pairings across lists. For the lexical decision task, 240 pseudoword targets were also prepared by concatenating two characters not used in the experimental trials in a non-interpretable manner. Two-thirds of the primes for these pseudowords shared characters with the target pseudowords, while the remaining one-third did not. The same set of pseudoword trials was used in the three experimental lists. Therefore, each list contained 480 items, which were further divided into 10 blocks of 48 trials (24 real word targets with 8 items per condition, and 24 pseudoword targets with 16 preceded by character-sharing primes). Targets that contained the same ambiguous morphemes were distributed to different blocks. Block order was randomized. Trial order within a block was pseudo-randomized with the constraint that no more than three consecutive trials were real word or pseudoword targets.

Procedure

Stimulus presentation, behavioral response recording, and the interface with ERP recording were controlled by E-Prime 2.0 (Psychology Software Tools, Pittsburgh, PA, USA). Stimuli were presented on a CRT monitor at 75 Hz refresh rate. Each trial began with a forward mask presented for 500 ms at the center of the screen. The mask was comprised of randomly arranged Chinese character strokes. Then the prime word was displayed in Regular script font (font size = 46) for 53 ms (four tics of a monitor with a 75 Hz refresh rate), which was immediately replaced by the target word in

Table 1. Sample stimuli and their linguistic properties

	Prime Type			Target Type	
	Dominant	Subordinate	Unrelated	Dominant	Subordinate
Example	月牙	月末	粉尘	月亮	月份
Translation	Crescent moon	Month-end	Dust	Moon	Month
Mean stroke number	7.97 (2.31)	8.35 (2.08)	8.31 (1.48)	8.23 (2.12)	8.54 (2.15)
Mean character frequency (log)	5.01 (0.47)	5.01 (0.53)	4.92 (0.49)	5.00 (0.47)	5.00 (0.47)
Whole-word frequency (log)	3.13 (0.84)	3.01 (1.00)	3.13 (0.48)	3.27 (0.67)	3.41 (0.85)
Semantic transparency	4.79 (0.71)	4.87 (0.57)	4.63 (0.60)	4.60 (0.54)	4.42 (0.54)
Whole word semantic relatedness with dominant targets	3.67 (0.36)	2.06 (0.44)	1.67 (0.52)	–	–
Whole word semantic relatedness with subordinate targets	1.97 (0.48)	3.56 (0.46)	1.69 (0.57)	–	–

Song font (font size = 48) for 400 ms. The prime and target words were of different fonts and sizes to decrease the possibility of perceptual feature overlapping. Participants were asked to judge whether the target stimulus was a real Chinese word or a pseudoword as quickly and accurately as possible by pressing corresponding keys on a computer keyboard. Half of the participants pressed "*Z*" for positive responses and "*M*" for negative responses. The pairing was reversed for the other participants. A sign (--) was presented at the center of the screen for 1500 ms after responses were made or after 3000 ms if no responses were detected. Participants were instructed to blink their eyes only when the sign was shown. After the offset of the sign, the next trial started after a blank screen of 1000–1300 ms. The whole experiment lasted for approximately 1.5 h.

ERP recordings and analyses

ERP data were recorded using the Neuroscan 4.3 system (Neuroscan Inc., Sterling, VA, USA) with a 64-channel Ag–AgCl electrode cap. The electrodes were arranged according to the extended 10–20 system. Two electrodes were positioned on the right and left mastoids: The right mastoid was recorded for offline re-referencing while the left mastoid served as online reference. The ground electrode was placed between FPz and Fz. Electro-oculograms (EOG) were measured from below versus above the left eye (vertical EOG) and the left versus right lateral orbital rim (horizontal EOG). All electrode impedances were kept below 5 kΩ. The data were continuously digitized with a sampling frequency of 1000 Hz with an initial bandwidth of 0.05–100 Hz.

Data processing was performed using SCAN 4.5. The data were re-referenced offline to the average of the right and left mastoids (i.e., linked mastoid reference) and bandpass filtered (0.05–30 Hz, zero phase shift mode, 24 dB/octave). Epochs were computed from -150 ms to 600 ms after target stimulus onset. Baseline correction was done with the signals from -150 ms to 0 ms. Epochs with signals $\pm 80\,\mu V$ and trials with incorrect responses in the lexical decision task were removed (12.76%).

Following previous ERP experiments that used masked priming to investigate morphological processing (e.g., Morris et al., 2007), ERP analyses were conducted in the N250 window (200–300 ms) and the N400 window (300–500 ms). In each time window, a 2 (Target Type: dominant vs. subordinate) $\times$ 3 (Prime Type: dominant vs. subordinate vs. unrelated) $\times$ 2 (Hemisphere: left vs. right) $\times$ 3 (Site: anterior vs. central vs. posterior) Repeated Measures ANOVA was performed with the mean amplitudes as the dependent variable. Shapiro–Wilk test was used to test for normality of the DV for each condition. All tests were non-significant, indicating normal distribution of each DV analyzed. The variables Hemisphere and Site were completely crossed, yielding six regions of interest, each including six electrodes: Left anterior (F5, F3, F1, FC5, FC3, and FC1), right anterior (F6, F4, F2, FC6, FC4, and FC2), left central (C5, C3, C1, CP5, CP3, and CP1), right central (C6, C4, C2, CP6, CP4, and CP2), left posterior (P5, P3, P1, PO7, PO5, and PO3), and right posterior (P6, P4, P2, PO8, PO6, and PO4). The inclusion of Hemisphere and Site improved statistical power. However, they were not of theoretical interest and would not be discussed in detail. Bonferroni correction was applied to correct for inflation of Type-I errors due to multiple comparisons. Not all ANOVAs met the assumption of sphericity. Greenhouse-Geisser correction was applied whenever the sphericity assumption was violated. The original degrees of freedom and the corrected *p*-values were reported.

RESULTS

Behavioral data

All incorrect responses and responses with reaction times above or below 2.5 standard deviations from the individual means were removed from further analyses (8.13%). Table 2 displays the mean reaction times and accuracies of the remaining data in different conditions. Data were analyzed with linear mixed models (LMM) implemented with the lme4 package in R 3.6.1. Target Type and Prime Type were fixed effects. Subject and Item were included as crossed random effects. Because the models that included random slopes for Subject and Item did not converge, the final random structure included random intercepts only. The *p*-value of each effect was obtained by Satterthwaite approximation implemented with the lmerTest package (Kuznetsova et al., 2013, Luke, 2016).

Table 2. Mean reaction times (RT) and accuracy (ACC) across conditions

	Dominant target			Subordinate target		
	Dominant	Subordinate	Unrelated	Dominant	Subordinate	Unrelated
RT (ms)	673.2 (102)	686.7 (108)	709.9 (91)	684.8 (98)	670.3 (108)	707.4 (90)
ACC (%)	96.0 (0.03)	94.6 (0.05)	94.4 (0.04)	92.4 (0.05)	94.5 (0.04)	93.2 (0.06)

Reaction time analyses revealed that the effect of Target Type was not significant ($F < 1$). However, there was a significant main effect of Prime Type ($F_{2, 659} = 17.18$, $p < .001$). The interaction between Target Type and Prime Type was also significant ($F_{2, 659} = 3.65$, $p = .027$). To further examine the interaction, separate models were constructed for dominant and subordinate targets. For dominant targets, a linear trend was observed, such that the same meaning dominant primes led to faster responses than the different meaning subordinate primes ($p = .042$), which in turn led to faster responses than the unrelated primes ($p < .001$). For subordinate targets, there was again a linear trend, such that the same meaning subordinate primes led to marginally faster responses than the different meaning dominant primes ($p = .077$), which in turn led to faster responses than the unrelated primes ($p < .001$). In other words, results of the reaction time analyses showed that for both dominant and subordinate targets, all morpheme-sharing primes produced significant facilitative priming, but the strength of priming effect was stronger when primes and targets took the same meanings of the ambiguous morphemes.

Analyses on accuracy showed that all main effects and interaction were statistically non-significant.

Electrophysiological data

As aforementioned, ERP data were analyzed in the 200–300 ms time window (N250) and the 300–500 ms time window (N400)[2]. The average ERP waveforms at representative electrodes and topographic maps in the two time windows for the dominant targets are shown in Figs. 1 and 2. Those for the subordinate targets are presented in Figs. 3 and 4.

N250 time window (200–300 ms)

The main effect of Prime Type was significant ($F_{2, 50} = 12.75$, $p < .001$, $\eta_p^2 = .338$). There was a significant three-way interaction among Prime Type, Hemisphere, and Site ($F_{4, 100} = 5.75$, $p = .002$, $\eta_p^2 = .187$), which was attributed to a more prominent Prime Type effect in the posterior sites. The three-way interaction among Target Type, Hemisphere, and Site ($F_{2, 50} = 5.06$, $p = .021$, $\eta_p^2 = .168$) was also significant. However, subsequent analyses indicated that the dominant and subordinate targets did not differ significantly in all regions. Finally, there was a theoretically interesting three-way interaction among Target Type, Prime Type, and Hemisphere ($F_{2, 50} = 5.87$, $p = .006$, $\eta_p^2 = .190$), which would be reported in more detail below.

Further analyses were conducted separately for dominant and subordinate targets to better understand the three-way interaction among Target Type, Prime Type, and Hemisphere. For dominant targets (Fig. 1), the main effect of Prime Type ($F_{2, 50} = 10.76$, $p < .001$, $\eta_p^2 = .301$) and the interaction between Prime Type and Hemisphere ($F_{2, 50} = 7.51$, $p = .002$, $\eta_p^2 = .231$) were significant. In the left hemisphere, both the dominant and subordinate primes led to smaller N250s than the unrelated primes ($ps < 0.01$). The same pattern was found in the right hemisphere, although the effects were weaker ($ps < 0.05$). The differences between the dominant and subordinate primes were non-significant in either hemisphere. In other words, the dominant and subordinate primes produced significant and comparable N250 priming effects in the recognition of dominant targets.

In contrast, for subordinate targets (Fig. 2), the interaction between Prime Type and Hemisphere was non-significant ($p = .569$). In addition, although there was a significant Prime Type main effect in the overall analysis ($F_{2, 50} = 3.77$, $p = .033$, $\eta_p^2 = .131$), further pairwise comparison showed that the dominant and subordinate primes did not differ significantly from the unrelated primes (unrelated vs. dominant: $p = .065$; unrelated vs. subordinate: $p = .098$). These findings indicated that no reliable N250 priming effects could be observed in the recognition of subordinate targets[3].

[2] Following the advice of an anonymous reviewer, analyses were also conducted in the N170 window (130–200 ms) on PO7 and PO8 electrodes. This analysis revealed only a marginally significant prime type effect ($F_{2,50} = 3.72$, $p = .044$, $\eta_p{}^2 = 0.129$). Further pairwise comparisons with Bonferroni correction showed no significant differences between the dominant and unrelated condition ($p = .830$) or the subordinate and unrelated condition ($p = .171$). Therefore, it was unlikely that the effects observed in this study could be attributed to lower level orthographic priming.

[3] The absence of N250 priming for subordinate targets was a null effect. To provide further information, we also calculated the Bayes Factor (Wagenmakers et al., 2018) for this analysis. Bayes Factor could quantify the relative evidence supporting the alternative (Prime Type had an effect) and null hypothesis (Prime Type had an effect). For dominant targets, the BF_{10} was over 175, suggesting that the alternative hypothesis was 175 times more likely that the null hypothesis. According to the general guideline of interpreting Bayes Factor, this value indicated extreme evidence supporting the alternative hypothesis. In contrast, for subordinate targets, the BF_{10} was just 1.81. This strength of evidence was anecdotal. In other words, there was much stronger evidence of Prime Type effect for dominant than subordinate targets.

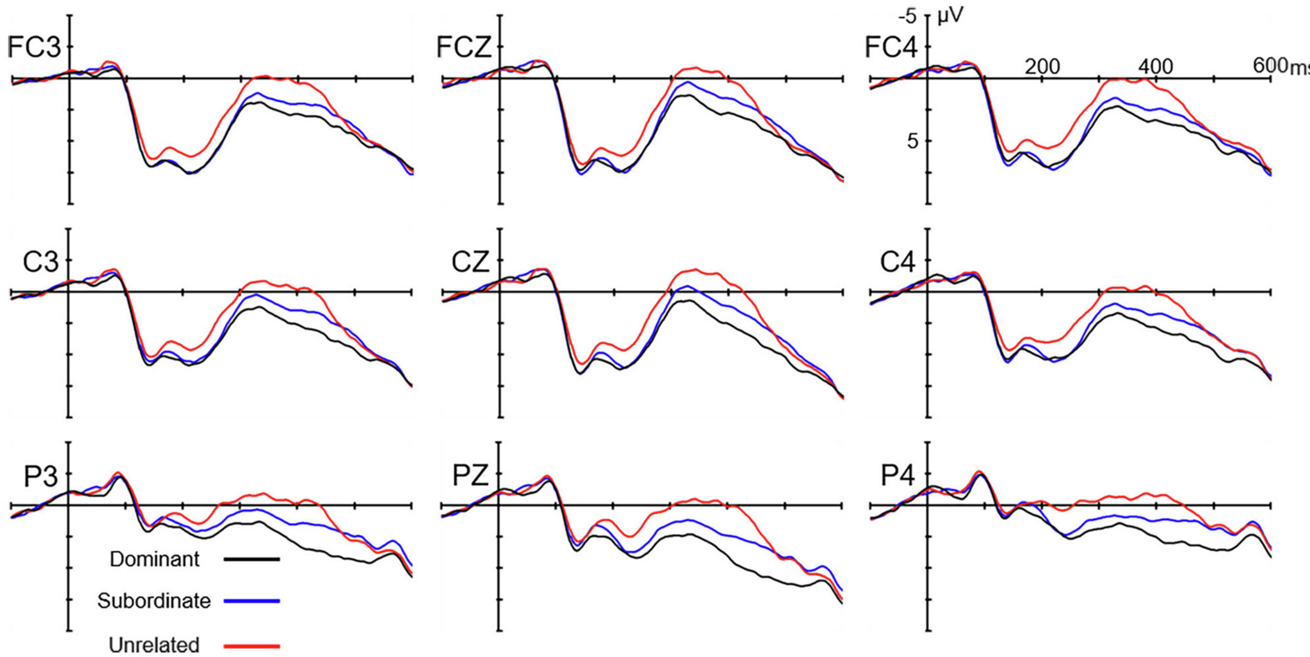

Fig. 1. Grand average ERPs for dominant targets in the three priming conditions at representative scalp electrode sites.

N400 time window (300–500 ms)

There were significant main effects of Target Type ($F_{1,25}$ = 4.65, p = .041, η_p^2 = .157) and Prime Type ($F_{2,50}$ = 18.77, p < .001, η_p^2 = .429). There was a significant two-way interaction between Target Type and Hemisphere ($F_{1,25}$ = 10.12, p = .004, η_p^2 = .288), which was attributed to stronger Target Type effect in the right hemisphere. There was also a significant two-way interaction between Prime Type and Site ($F_{4,100}$ = 4.46, p = .014, η_p^2 = .151). Subsequent analyses indicated that the Prime Type effects were significant in all sites, but the effects were stronger in central and posterior sites, which was typical for N400. There was also a theoretically interesting two-way interaction between Target Type and Prime Type ($F_{2,50}$ = 10.21, p < .001, η_p^2 = .290), which would be elaborated below.

Further analyses were conducted separately for dominant and subordinate targets to better understand the significant two-way interaction between Prime Type and Target Type. For dominant targets (Fig. 1), there was a significant Prime Type main effect ($F_{2,50}$ = 21.03, p < .001, η_p^2 = .457). Pairwise comparisons indicated that the dominant primes led to smaller N400 than the subordinate primes (p = .004), which in turn led to smaller N400 than the unrelated primes (p = .022). For subordinate targets (Fig. 2), there was a significant Prime Type main effect ($F_{2,50}$ = 8.80, p = .001, η_p^2 = .260). Pairwise comparisons indicated that the subordinate primes led to smaller N400 than the dominant primes (p = .024) and the unrelated primes (p = .006). The dominant primes tended to produce smaller N400 than the unrelated primes, but the difference failed to reach statistical significance (p = .466). Overall, the results suggested that the same meaning primes produced stronger N400 priming than the different meaning primes.

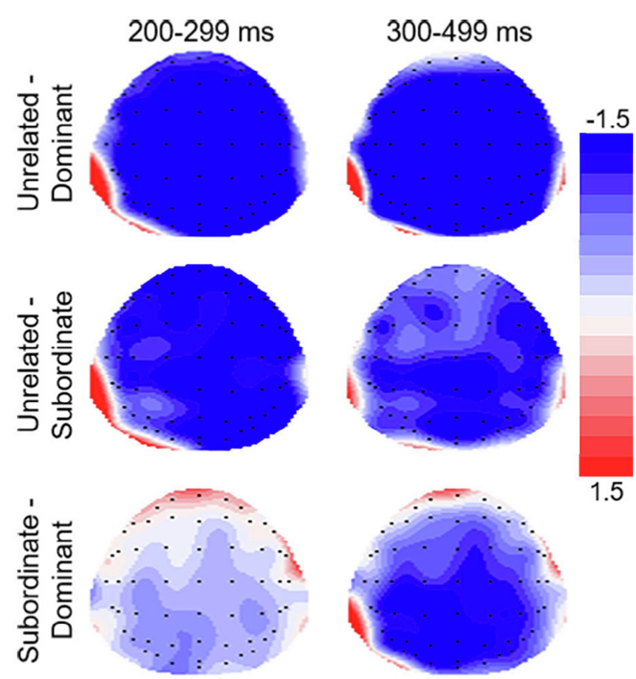

Fig. 2. Topographical maps that correspond to the difference waves across conditions and time windows for dominant targets.

DISCUSSION

This study examines the processing of ambiguous morphemes in the recognition of Chinese bimorphemic compound words. A masked priming lexical decision

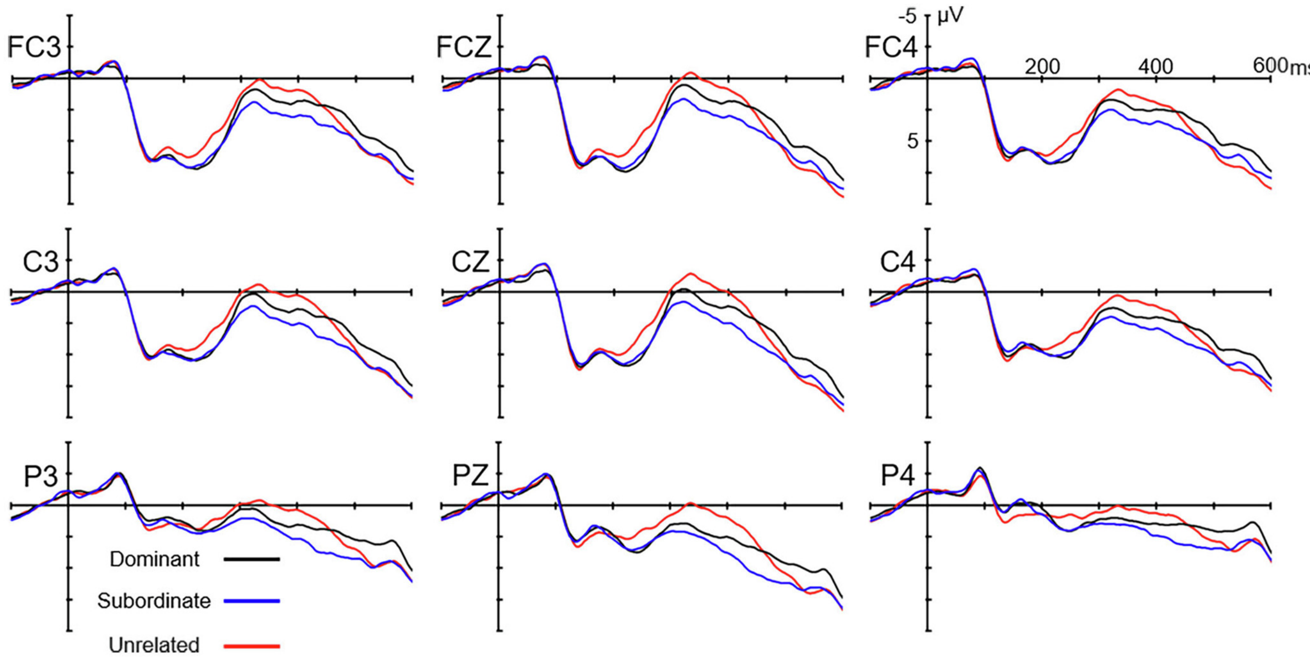

Fig. 3. Grand average ERPs for subordinate targets in the three priming conditions at representative scalp electrode sites.

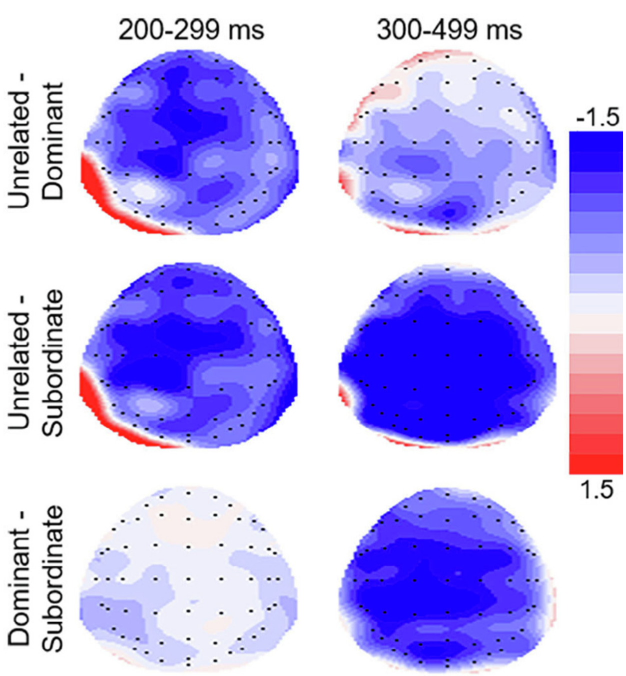

Fig. 4. Topographical maps that correspond to the difference waves across conditions and time windows for subordinate targets.

experiment was conducted when both behavioral and ERP data were recorded. Behavioral results showed that, for both dominant and subordinate targets, facilitative priming was produced by both dominant and subordinate primes. Moreover, the strength of facilitation was larger when the ambiguous morphemes in primes and targets took the same meanings (i.e., dominant primes-dominant targets and subordinate primes-subordinate targets) than when they took different meanings (i.e., dominant primes-subordinate targets and subordinate primes-dominant targets). The N400 results were consistent with the behavioral results in suggesting that the priming effects were stronger in the same meaning than the different meaning conditions. However, in the N250 time window, meaning consistency between primes and targets did not modulate the strength of priming. Instead, in this early time window, both the dominant and subordinate primes produced comparable priming in the recognition of dominant targets, and no priming was observed in recognizing subordinate targets.

Before discussing the implications of the present findings, it is important to consider whether the results truly reflected morphological processing. As mentioned in the Materials session, it was impossible to control for word level semantic relatedness. However, for two reasons, we believed that this confounding unlikely had a huge impact on the results. First, there is evidence that lexical semantic priming did not occur under procedure similar to this study. For example, Rastle et al. (2000) showed that semantic priming (e.g., "cello-VIOLIN") was absent when the primes were presented for 43 ms. The priming effect became significant when the prime duration was lengthened to 72 ms or 230 ms. Similarly, Wu et al. (2017) included a semantic condition (e.g., "草地-lawn" and "公園-park") in the masked priming experiment and found no semantic priming on P200 or N400. Second, if semantic priming did occur, higher semantic relatedness should lead to stronger priming. Our rating test showed that the semantic relatedness was significantly higher for the consistent conditions (i.e., dominant prime-dominant target and subordinate prime-subordinate target) than the inconsistent and unrelated conditions, which did not differ between themselves. However, the ERP results showed that for dominant targets, the inconsistent subordinate primes produced significant N250 and N400 priming. Similarly, for subordinate targets, there was no N250 priming by the consistent subordinate primes. These patterns were not in line with the predictions based on lexical semantic relatedness.

Another issue that should be considered is inherent to the priming paradigm, which involves the sequential presentation of prime and target within a short interstimulus interval. While it provides an opportunity to examine how different characteristics of the prime are activated to influence target processing, the short interstimulus interval also results in temporal overlapping of the ERP responses to primes and targets. This matter has not been widely discussed, but it is an important one because the ERP priming effects on target processing (especially those on early components) may be attributed to differences in the prime ERPs that "spillover" to the target ERPs. In this study, there were three primes (dominant meaning, subordinate meaning, and unrelated) for each target. One reasonable prediction was that the dominant primes would themselves generate smaller N400 than the subordinate primes because the more frequently used dominant meanings should be processed more easily. It followed that the ERP signals of targets might also be smaller when they were preceded by dominant than subordinate primes if the prime ERPs really had a strong influence on target ERPs. This prediction was inconsistent with the absence of N250 priming for subordinate targets. Therefore, even though the temporal overlap between prime and target ERPs was a real issue, it likely played little roles to the results obtained in this study.

We believed the results of this study truly reflected morphological processing and will have important methodological and theoretical implications. One major motive of this study is to clarify the previous inconsistent results. The present behavioral and N400 results appear to be consistent with Zhou et al. (1999) in showing stronger priming effects when primes and targets shared ambiguous morphemes of the same meanings than different meanings. On the other hand, whether primes and targets shared the same morphemic meanings or not did not influence the strength of N250 priming, which agrees with Tsang et al. (2014). The difference in the early and late ERP components confirms that ERP recordings can provide the temporal details not available in behavioral indices like reaction times and accuracies. Moreover, it helps reconcile previous findings: Depending on materials and procedures, previous behavioral results might have reflected the patterns of different ERP components. For example, the primes were presented for 40 ms in Tsang et al. (2014) and 57 ms in Zhou et al. (1999), which might have made the two studies more likely to reflect the earlier and later ERP components, respectively. In addition, all targets in Tsang et al. (2014) took the dominant meanings. Given that only dominant targets would show N250 priming, it is reasonable that their results would more strongly reflect the N250 pattern (i.e., comparable priming by dominant and subordinate primes). Zhou et al. (1999) did not report the ratio of dominant and subordinate targets. Assuming that there were some subordinate targets, the "weight" of N250 priming would be reduced (because subordinate targets showed no N250 effects), leaving only a pattern consistent with the N400 priming (i.e., stronger priming by same meaning primes).

In addition to reconciling the inconsistency in previous behavioral studies, the present results contribute to understanding the processing of ambiguous morphemes. As mentioned in the introduction, although ambiguous morphemes can be found in different languages, only a few studies have examined their roles in word recognition. Indeed, the processing of ambiguous morphemes is not a trivial matter, because in principle, the needs to resolve morphemic ambiguity would make the morphological route of word recognition less efficient than the whole-word access route. Yet, the present results showed that morphemes still play a role in word recognition, as evidenced by significant priming effects by sharing ambiguous morphemes. The results could not be explained by sharing lexical orthography because N250 priming was found only for dominant targets and N400 priming was stronger for the same meaning condition. Similarly, as discussed above, sharing lexical semantics also could not explain the results. Overall, the results could only be explained by assuming that ambiguous morphemes were activated during word recognition, and such activation was modulated by the relative frequency of the intended meanings (dominant vs. subordinate).

The importance of separating the dominant and subordinate meanings of ambiguous morphemes was proposed by Tsang and Chen (2013a,b), who showed that the recognition of dominant meaning targets was facilitated by both the dominant and subordinate primes, while the recognition of subordinate targets was facilitated only by the same meaning subordinate primes. Based on these findings, the authors argued that morphemic ambiguity resolution resembled the process of lexical ambiguity resolution (Duffy et al., 1988), such that the dominant meanings had the priority to be activated even when the intended interpretations were the subordinate meanings. In contrast, the subordinate meanings would only be weakly activated when they were not the correct interpretations supported by context. Therefore, only the subordinate primes would activate the subordinate meanings strongly enough to facilitate the recognition of subordinate targets. The present results are mostly consistent with this view. As in Tsang and Chen, both the dominant and subordinate primes produced significant N250 and N400 priming in the recognition of dominant targets. However, for subordinate targets, even when they were preceded by the subordinate primes, significant priming was not observed until N400. The absence of subordinate target priming in the earlier N250 window suggested that the dominant and subordinate meanings might not be activated simultaneously. It probably took longer time to activate the subordinate meanings than the dominant meanings because of the higher baseline activation of dominant meanings due to a higher frequency of usage. Tsang and Chen might have failed to reveal such early difference because of the limitation in behavioral measures, which "summarized" the processes reflected by N250 and N400. Again, this indicates that ERP recording is a valuable tool in understanding the temporal dynamics of morphological processing.

This study also has important implications on the debate about early morpho-semantic activation. According to the form-then-meaning account, morphemic meanings become activated at a later stage after decomposition has been triggered by morphemic form (Rastle and Davis, 2008). In contrast, the form-with-meaning account argues that morphemic meanings are immediately available when a word is segmented into the constituent morphemes (Taft and Nguyen-Hoan, 2010). Previous studies usually examined the two accounts by manipulating semantic transparency in masked priming experiments. As compared to the unrelated or form-sharing (e.g., "brothel-BROTH") control conditions, priming effects were typically found in both the transparent (e.g., "farmer-FARM") and opaque/pseudocomplex (e.g., "corner-CORN") conditions. The presence of masked priming in the opaque/pseudocomplex condition indicates that surface morphological form alone is sufficient to trigger morphological decomposition, because the meanings of the constituent morphemes are unrelated to the meanings of opaque/pseudocomplex words. However, it remains inconclusive whether morphemic meanings are also activated early. Some studies found that transparent and opaque primes produced comparable masked priming effects, even when morpheme meanings contributed to transparent word meanings (e.g., Lavric et al., 2007; Rastle et al., 2004). However, others showed that transparent primes did produce significantly stronger priming than the opaque primes (e.g., Feldman et al., 2009; Morris et al., 2007).

Although it is unclear why different results were obtained in previous studies, the present results are obviously more in line with the form-with-meaning account. Recall that according to the form-then-meaning account, it was expected that sharing ambiguous morphemes would produce N250 priming irrespective of whether morpheme meanings were shared between primes and targets. This prediction was not supported by the ERP data. In contrast, the form-with-meaning account assumed that morpheme meanings were rapidly available. We originally predicted that N250 priming would be stronger in the dominant prime-dominant target and subordinate prime-subordinate-target conditions. This was only partly supported because there was no significant priming at all for subordinate targets. However, the difference between processing dominant and subordinate targets by itself was supportive to the presence of morpho-semantic effects in N250. Indeed, this finding suggests that N250 is not a just an index of orthographic processing, but is sensitive to morpheme meanings too. More generally, this study shows that the examination of ambiguous morphemes can contribute to clarifying key issues in morphological processing. Besides comparing the dominant and subordinate meanings, other properties of ambiguous morphemes such as productivity (how many words are formed by each meaning) and degree of bias (the difference in frequency between the dominant and subordinate meanings) also deserve attention in future studies.

The present findings about ambiguous morphemes and early morpho-semantic activation can easily be accommodated by the AUSTRAL model (Taft, 2006; Taft and Nguyen-Hoan, 2010). According to the model, morphemes are stored at an abstract layer of representations called lemma. When a morpheme is accessed through morphological decomposition, the corresponding lemma is activated. The lemmas are not just form-based representations, they also store information about the grammatical functions and meanings of the morphemes, which provide the foundation of early morpho-semantic activation when words are decomposed. Moreover, ambiguous morphemes have multiple lemma representations, each corresponding to a different meaning/function. The baseline activation level of these lemmas is determined by the relative frequency of use, such that the most frequently used dominant meaning will have the strongest baseline activation and thus can be activated above threshold most easily. Finally, the lemmas of the ambiguous morphemes are connected to the congruent context morphemes with excitatory link, and to the incongruent context morphemes with inhibitory links. For example, the "moon" lemma of the ambiguous morpheme "月" is connected to the lemma of "亮" ("bright") via excitatory link and the lemma of "末" ("end") via inhibitory link. These links ensure that the correct morphemic meanings can finally be retrieved and integrated with the context morphemes (e.g., "月末" will not be misinterpreted as "the end of the moon").

Based on the model, we interpreted the N250 priming effect as reflecting the initial activation of lemmas. Both the dominant meaning and subordinate meaning primes would initially activate the dominant meaning lemma because it had a higher baseline activation. Therefore, the processing of dominant targets would be facilitated by both dominant and subordinate primes in the N250 window, and there would be no priming for subordinate targets because the subordinate meaning lemma was not activated yet. The N400 priming effect was interpreted as reflecting a later stage of processing in which the activated lemmas were combined for lexical access. Given that the correct lemma had to be selected before the combination could occur and there was sufficient time for such selection in the N400 window, the priming effect would be stronger when primes and targets shared ambiguous morphemes of the same meanings (i.e., dominant prime-dominant target and subordinate prime-subordinate target).

One final caveat in understanding the present results is whether they reflect universal aspects of morphological processing or are Chinese-specific. There are several idiosyncratic properties of the Chinese morphological system that makes it distinct from other major languages in morphological research. First, morpheme (character) boundary, instead of word boundary, is explicitly marked by spaces in written Chinese. Therefore, morphemes are salient perceptual units that make decomposition relatively effortless and automatic. Second, in contrast to the complex morphological systems in languages like Hebrew and Finnish, Chinese morphology is very simple. Inflection and derivation are uncommon in Chinese. Instead, the primary word construction method in Chinese is compounding. Through formal instruction and daily use, native Chinese users are proficient in extracting and combining morpheme meanings. Indeed, morphological awareness is particularly important to reading development in Chinese (McBride-Chang et al., 2005). These properties might have strengthened the role of morphemes in word recognition, leading Chinese users to rapidly activate the morpheme meanings even when the morphemes involved are ambiguous.

On the other hand, as mentioned in the introduction, although morphemic ambiguity is not a popular topic in psycholinguistic research, a few studies did demonstrate the activation of ambiguous morphemes in other languages like English, Finnish and Spanish (Allen and Badecker, 1999; Badecker and Allen, 2002; Järvikivi et al., 2009; Taft and Nguyen-Hoan, 2010). Similarly, despite being controversial, some studies did obtain evidence of early morpho-semantic activation (Feldman et al., 2009; Morris et al., 2007). Therefore, the present results are not isolated from the broader literature. Given that ambiguous morphemes exist in various languages, relevant research will be important to develop more comprehensive theories of morphological processing. Future studies can examine how other properties of ambiguous morphemes influence processing, and ERP recording will be a particularly useful tool for this purpose.

CONFLICT OF INTEREST STATEMENT

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

ACKNOWLEDGEMENTS

This work was supported by Fundamental Research Funds for the Central Universities awarded to Y. Wu and General Research Grant (HKBU12606717) awarded to Y.-K. Tsang.

REFERENCES

Allen M, Badecker W (1999) Stem homograph inhibition and stem allomorphy: representing and processing inflected forms in a multilevel lexical system. J Mem Lang 41(1):105–123. https://doi.org/10.1006/jmla.1999.2639.

Badecker W, Allen M (2002) Morphological parsing and the perception of lexical identity: A masked priming study of stem homographs. J Mem Lang 47(1):125–144. https://doi.org/10.1006/jmla.2001.2838.

Beyersmann E, Iakimova G, Ziegler JC, Colé P (2014) Semantic processing during morphological priming: An ERP study. Brain Res 1579:45–55. https://doi.org/10.1016/j.brainres.2014.07.010.

Cai Q, Byrsbert M (2010) Subtlex-CH: Chinese word and character frequencies based on film subtitles. PLoS ONE 5(6). https://doi.org/10.1371/journal.pone.0010729.

Duffy SA, Morris RK, Rayner K (1988) Lexical ambiguity and fixation times in reading. J Mem Lang 27(4):429–446.

Feldman LB, O'Connor PA, del Prado Martín FM (2009) Early morphological processing is morphosemantic and not simply morpho-orthographic: A violation of form-then-meaning accounts of word recognition. Psychon Bull Rev 16(4):684–691.

Huang H-W, Lee C-Y, Tsai J-L, Lee C-L, Hung DL, Tzeng O-L (2006) Orthographic neighborhood effects in reading Chinese two-character words. NeuroReport 17(10):1061–1065.

Huang H-W, Lee C-Y, Tsai J-L, Tzeng O-L (2011) Sublexical ambiguity effect in reading Chinese disyllabic compounds. Brain Lang 117(2):77–87.

Huang HW, Lee CY (2018) Number of meanings and number of senses: An ERP study of sublexical ambiguities in reading Chinese disyllabic compounds. Front Psychol 9:324. https://doi.org/10.3389/fpsyg.2018.00324.

Järvikivi J, Pyykkönen P, Niemi J (2009) Exploiting degrees of inflectional ambiguity: stem form and the time course of morphological processing. J Exp Psychol Learn Mem Cogn 35 (1):221–237. https://doi.org/10.1037/a0014355.

Kuznetsova A, Brockhoff PB, Christensen RHB. (2013). Lmertest: tests for random and fixed effects for linear mixed effect models (lmer objects of lme4 package).

Lavric A, Clapp A, Rastle K (2007) ERP evidence of morphological analysis from orthography: A masked priming study. J Cognit Neurosci 19(5):866–877. https://doi.org/10.1162/jocn.2007.19.5.866.

Lavric A, Rastle K, Clapp A (2011) What do fully visible primes and brain potentials reveal about morphological decomposition? Psychophysiology 48(5):676–686. https://doi.org/10.1111/j.1469-8986.2010.01125.x.

Liu Y, Shu H, Li P (2007) Word naming and psycholinguistic norms: Chinese. Behav Res Methods 39(2):192–198. https://doi.org/10.3758/BF03193147.

Luck SJ, Gaspelin N (2017) How to get statistically significant effects in any ERP experiment (and why you shouldn't). Psychophysiology 54(1):146–157. https://doi.org/10.1111/psyp.12639.

Luke SG (2016) Evaluating significance in linear mixed-effects models in R. Behav Res 49(4):1494–1502. https://doi.org/10.3758/s13428-016-0809-y.

McBride-Chang C, Cho J-R, Liu H, Wagner RK, Shu H, Zhou A, et al. (2005) Changing models across cultures: associations of phonological awareness and morphological structure awareness with vocabulary and word recognition in second graders from Beijing, Hong Kong, Korea, and the United States. J Exp Child Psychol 92(2):140–160. https://doi.org/10.1016/j.jecp.2005.03.009.

Morris J, Frank T, Grainger J, Holcomb PJ (2007) Semantic transparency and masked morphological priming: An ERP investigation. Psychophysiology 44(4):506–521. https://doi.org/10.1111/j.1469-8986.2007.00538.x.

Morris J, Grainger J, Holcomb PJ (2008) An electrophysiological investigation of early effects of masked morphological priming. Lang Cogn Process 23(7):1021–1056. https://doi.org/10.1080/01690960802299386.

Rastle K, Davis MH, Marslen-Wilson WD, Tyler LK (2000) Morphological and semantic effects in visual word recognition: A time-course study. Lang Cogn Process 15(4-5):507–537. https://doi.org/10.1080/01690960050119689.

Rastle K, Davis MH, New B (2004) The broth in my brother's brothel: morpho-orthographic segmentation in visual word recognition. Psychon Bull Rev 11(6):1090–1098. https://doi.org/10.3758/BF03196742.

Rastle K, Davis MH (2008) Morphological decomposition based on the analysis of orthography. Lang Cogn Process 23(7–8):942–971. https://doi.org/10.1080/01690960802069730.

Taft M (2006) A localist-cum-distributed (LCD) framework for lexical processing. In: Andrews S, editor. From Inkmarks to ideas: current issues in lexical processing. Hove, UK: Psychology Press. p. 76–94.

Taft M, Nguyen-Hoan M (2010) A sticky stick? The locus of morphological representation in the lexicon. Lang Cogn Process 25(2):277–296. https://doi.org/10.1080/01690960903043261.

Tsang Y-K, Chen H-C (2013a) Early morphological processing is sensitive to morphemic meanings: Evidence from processing ambiguous morphemes. J Mem Lang 68(3):223–239. https://doi.org/10.1016/j.jml.2012.11.003.

Tsang YK, Chen HC (2013b) Morpho-semantic processing in word recognition: Evidence from balanced and biased ambiguous morphemes. J Exp Psychol Learn Mem Cogn 39(6):1990–2001. https://doi.org/10.1037/a0033701.

Tsang Y-K, Wong A-K, Huang J, Chen H-C (2014) Morpho-orthographic and morpho-semantic processing in word recognition and production: evidence from ambiguous morphemes. Lang Cogn Neurosci 29(5):543–560. https://doi.org/10.1080/01690965.2013.790554.

Wu Y, Tsang Y-K, Wong A-K, Chen H-C (2017) The processing of homographic morphemes in Chinese: an ERP study. Lang Cogn Neurosci 32(1):102–116. https://doi.org/10.1080/23273798.2016.1227857.

Zhou X, Marslen-Wilson W, Taft M, Shu H (1999) Morphology, orthography, and phonology reading Chinese compound words. Lang Cogn Process 14(5-6):525–565. https://doi.org/10.1080/016909699386185.

(Received 23 April 2020, Accepted 4 August 2020)
(Available online 11 August 2020)