Morphological Decomposition in Chinese Compound Word Recognition: Electrophysiological Evidence

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Abstract

The present study examined the effect of both morphological complexity and semantic transparency in Chinese compound word recognition. Using a visual lexical decision task, our electrophysiological results showed that transparent and opaque compounds induced stronger Left Anterior Negativity (LAN) than monomorphemic words. This result suggests that Chinese compounds might be decomposed into their constituent morphemes at the lemma level, whereas monomorphemic words are accessed as a whole-word lemma directly from the form level. In addition, transparent and opaque compounds produced a similar N400 as each other, suggesting that transparency did not show an effect on the involvement of constituent morphemes during access to the whole-word lemma. Two behavioral experiments additionally showed similar patterns to the EEG results. These findings support morphological decomposition for compounds at the lemma level as proposed by the full-parsing model, and no evidence is found to support the role of transparency during Chinese compound word recognition.

Key Words: Chinese compound word, morphological complexity, morphological decomposition, semantic transparency, EEG

1. Introduction

The ability to automatically decompose compound words (hereafter, compounds) into constituent morphemes is an important aspect of fluent reading (e.g., Coch, Bares, & Landers, 2013; Zou, Packard, Xia, Liu, & Shu, 2019). Compounding is the most important method of Chinese word formation, and Chinese two-character compounds account for 73.6% of Chinese vocabulary, as opposed to only a few hundred two-character monomorphemic words (Li & Su, 2021; Tse et al., 2017). Therefore, it is particularly important to investigate whether or not Chinese compounds are decomposed during reading by adult native speakers.

A Chinese two-character compound is generated by two morphemes, each of which has an independent meaning associated with the whole word (e.g., *公园*, */gong1-yuan2/*, "park"; literally "public-garden"). In contrast, a two-character monomorphemic word consists of only one morpheme, which includes two sub-types: "binding" words (Taft & Zhu, 1995) where neither of the internal characters is a meaningful unit in its own right (e.g., *玻璃*, */bo1li0/*, "glass"), and "pseudomorphological" words (Lavric, Elchlepp, & Rastle, 2012) where the internal characters are meaningful in their own right but are in no way semantically related to the whole word (e.g., *沙发*, */sha1fa1/*, "sofa"; literally "sand-launch"). The difference in morphological complexity between compounds and monomorphemic words provides a window into examining whether or not Chinese compounds are decomposed on a morphological basis during visual word recognition. To our knowledge, no studies have revealed the neural correlates for morphological decomposition in Chinese compound recognition in contrast to monomorphemic words.

Another key factor regarding the processing of compounds is the extent to which a compound word is semantically related to its constituents. For some words, the relationship is highly transparent (e.g., *公园*), while for others, it is quite opaque (e.g., *海关*, */hai3-guan1/*, "customs";

literally "sea-shut off"). Previous EEG studies have suggested that opaque compounds are processed as a single unit whereas transparent compounds are fully decomposed, based on the assumption that the meanings of constituent morphemes in opaque compounds need to be inhibited during access to the whole-word meaning (e.g., Koester, Gunter, & Wagner, 2007; MacGregor & Shtyrov, 2013). However, for morphologically productive languages such as German and Hebrew, some studies have found that transparency plays little role in the processing of compounds (Eulitz & Smolka, 2021; Plaut & Gonnerman, 2000; Smolka & Libben, 2017). Given the pervasiveness of compounding in Chinese, it can be seen as a morphologically productive language, and that makes it well-suited for an examination of whether compounds are processed independent of transparency. Therefore, our EEG and behavioral experiments include an investigation into the electrophysiological and behavioral differences between transparent and opaque compounds in Chinese during visual word recognition.

1.1. Morphological complexity of compounds

Two different theoretical models have been proposed to account for whether compounds are recognized through a direct whole-word access or decomposed into their internal constituent morphemes. One is the full-parsing model, whereby each morpheme of all types of compounds has its own representation unit in addition to the whole-word representation (e.g., Taft, 2003; Taft & Forster, 1975; Taft & Nguyen-Hoan, 2010). According to the more recent instantiations of this model, both transparent and opaque compounds are fully decomposed at a level that mediates between form and meaning, namely, a "lemma" level. The other is the dual-route model, in which a decomposition route or a direct whole-word access route may be invoked for different compound types. For example, opaque compounds in alphabetic languages are recognized via a direct whole-word access, whereas the recognition of transparent compounds involves decomposition into their constituent morphemes (e.g., Koester et al., 2007; MacGregor & Shtyrov, 2013; Sandra, 1990; Zwitserlood, 1994).

Two previous EEG studies with an alphabetic language have investigated whether compounds are decomposed, using monomorphemic words as a baseline (El Yagoubi et al., 2008; Fiorentino, Naito-Billen, Bost, & Fund-Reznicek, 2014). El Yagoubi et al. (2008) examined the processing of Italian noun-noun compounds by Italian native speakers using a visual lexical decision task and found that compounds induced a larger left anterior negativity (LAN) than monomorphemic words. Similarly, Fiorentino et al. (2014) revealed that visually presented English compounds produced larger negative waves than monomorphemic words in the 275–400 ms window. It is worth noting that the negative waves occurred bilaterally and midline in the posterior electrodes, which is not the classic LAN located in the left anterior region of the scalp. Nevertheless, both studies argued that the LAN or the negative waves reflect the morphological decomposition of compounds as supposed by the full-parsing model, which suggests access to the morphological constituents of compounds. However, El Yagoubi et al. (2008) only used transparent compounds and did not include any opaque ones. The full-parsing model differs from the dual-route model in that opaque compounds are processed via the activation of their internal morphemes in the same way that transparent compounds are. Therefore, further research is needed to compare whether there is a difference in LAN between the processing of opaque compounds and monomorphemic words in order to examine whether a decomposition route exists for opaque compounds.

Another EEG study by Güemes, Gattei, and Wainselboim (2019) investigated the LAN effect between transparent and opaque compounds in Spanish, but did not include monomorphemic words. Comparing transparent agentives (i.e., verb + patients, e.g., *abrelatas,* literally "can-opener") and transparent locatives (i.e., name for a place indexed by a verb and noun, e.g., *guardarropas,* "wardrobe"; literally "keep-clothes") with opaque metaphoricals (i.e., meaning constructed through metaphor, e.g., *rascacielos*, "skyscraper"; literally "scratch-skies"), this study found that both types of transparent compounds produced a stronger LAN than opaque compounds at 200-350 ms during a visual lexical decision task. Based on this finding, the authors argue that transparent compounds are morphologically decomposed whereas opaque compounds are processed via direct whole-word access, which supports a dual-route model. However, the stronger LAN for transparent compounds was distributed throughout the whole scalp rather than only left anterior region where LAN typically occurs. In addition, due to the lack of monomorphemic words, the study cannot tell us whether opaque compounds are processed differently from monomorphemic words where there is presumably direct whole-word access.

With regards to Chinese compounds, the internal characters are physically separated from each other, and the spatial distance between them is exactly the same as that of monomorphemic words. In normal reading, it is not possible to know which two characters should be processed together prior to accessing the lexical information. Thus, all Chinese two-character word recognition proceeds character by character at the form level. Nevertheless, a difference in word recognition between compounds and monomorphemic words might occur at the lemma level, namely, whether or not the lemmas corresponding to its internal characters directly activate the lemma for the whole compound. Furthermore, monomorphemic words can be distinguished from compounds during word recognition when readers recognize that their individual characters do not have an independent meaning associated with the whole word. Taken together, the process of morphological decomposition in Chinese compounds seems to be sensitive to morpheme meaning, even though the visual form features are conducive to decomposition at the form level.

There are only two reported Chinese language studies that have compared compounds with monomorphemic words ("binding" words in particular). Using a visual lexical decision task, Cui, Haikio, Zhang, Zheng, and Hyona (2017) revealed that the insertion of extra spaces between the two component characters had an inhibitory effect on the processing of monomorphemic words while facilitating the processing of compounds for Chinese native speakers. Using the boundary paradigm in sentence reading, an eye-tracking study by Cui et al. (2013) found a parafoveal-on-foveal effect for monomorphemic words, but not for compounds, which indicates that the prior processing of the parafoveal character reduced the fixation durations on the foveal character during reading monomorphemic words. Both studies suggest that the processing of compounds is more inclined towards a morphological decomposition route, compared to that of monomorphemic words. However, only transparent compounds were included in both studies, so opaque compounds are needed to test whether a dual-route model can be applied to Chinese compounds.

In addition to studies that compare compounds and monomorphemic words, previous EEG studies on Chinese have used various paradigms and materials (e.g., whole-word priming or morpheme priming, reversed compounds, etc.) to investigate whether Chinese compounds are decomposed. These studies provide consistent evidence for the activation of morphemes within compounds (Chung, Tong, Liu, McBride-Chang, & Meng, 2010; Du, Hu, Fang, & Zhang, 2013; Gao et al., 2022; Lo, McBride, Ho, & Maurer, 2019; Tong, Chung, & McBride, 2014; Tsang & Chen, 2013; Tsang & Zou, 2022; Wu, Tsang, Wong, & Chen, 2017; Zou et al., 2019), which contradicts a whole-word access model. However, we have found no research that has investigated whether transparent and opaque compounds in Chinese induce a larger LAN that indexes morphological decomposition, compared with monomorphemic words.

1.2. Semantic transparency of compounds

Two opposing theoretical viewpoints have been proposed regarding whether semantic transparency has an impact on the combinatorial process of constituent morphemes for compounds. One view is that there would be a larger semantic conflict for opaque as opposed to transparent compounds while computing a compositional meaning from their constituent morphemes during access to the whole-word meaning (Koester et al., 2007). This viewpoint has been supported by a recent study by Güemes et al. (2022), who revealed that opaque metaphoricals induced a greater N400 than transparent agentives in Spanish, under either a whole-word or separated-by-space presentation mode in a visual lexical decision task. In addition, Güemes et al. (2019) found that P600 component in 550-750 ms was elicited for opaque as opposed to transparent compounds. The N400 and P600 components generally serve as an index of morpheme-based semantic analysis during visual word recognition (Bai et al., 2008; Coch et al., 2013; Du et al., 2013; Koester et al., 2007). All these findings provide evidence that word-internal semantic composition is engaged with more effort for opaque compounds due to the difficulty in constructing the metaphorical meaning of the whole word.

The other theoretical view holds that for a morphologically rich language, the semantic composition of the internal morphemes of compounds occurs regardless of transparency. Smolka and colleagues conducted a series of studies on German which, unlike other alphabetic languages (e.g., English, French, etc.), is a morphologically rich language. Using overt visual, auditory, and cross-modal priming paradigms (Günther, Smolka, & Marelli, 2019; Smolka, Gondan, & Rosler, 2015; Smolka, Komlosi, & Rosler, 2009; Smolka & Libben, 2017; Smolka, Libben, & Dressler, 2019; Smolka, Preller, & Eulitz, 2014), their behavioural studies found the same priming effects for transparent and opaque derivatives. For example, transparent derivatives facilitated recognition of their base verbs (e.g., *zerbrechen-brechen*, “break into pieces”- “break”), but opaque derivatives induced the same amount of facilitation (e.g., *verbrechen-brechen*, "commit a crime"-"break"). Furthermore, their EEG studies also showed no semantic transparency effect, indexed by no N400 difference between transparent and opaque words in an overt visual priming for German derivatives (Smolka et al., 2015), and in a non-word decision task without priming for German compounds (Eulitz & Smolka, 2021). Such a null effect of transparency has also been observed in two other morphologically rich languages, Hebrew (Bick, Goelman, & Frost, 2011) and Arabic (Boudelaa & Marslen-Wilson, 2004). Two priming studies on Basque also supported that the constituents of compounds were activated regardless of their semantic contribution to the whole-word meanings (Duñabeitia, Laka, Perea, & Carreiras, 2009; Duñabeitia, Perea, & Carreiras, 2007). According to Smolka and colleagues, all these convergent findings may be due to the highly productive word-formation system for morphologically rich languages, in which a single morpheme can be used to generate a large number of different words with new whole-word meanings, formulating a large morphological family. Thus, the productivity of German words drives the activation of constituent morphemes during visual word recognition, as well as strong semantic associations between whole words and their constituent morphemes, even for opaque words. In other words, the morphological structure of the language as a whole determines the role of transparency on the semantic interaction between the whole word and its internal morphemes (Plaut & Gonnerman, 2000).

Similar to German, the individual morphemes in the Chinese lexical system are highly productive creating a huge number of compound words. For example, the bound morpheme *馆 (/guan3/*, "a place for a specific function") can be used in many compounds, such as *饭馆* (*/fan4-guan3/*, "restaurant")、宾馆 (*/bin1-guan3/*, "hotel")、图书馆 (*/tu2shu1-guan3/*, "library"), etc. Due to the high productivity of morphemes, Chinese language is well suited to examine the role of morphemes in compound processing.

A few studies proposed that morphemic ambiguity prevents the occurrence of morphological decomposition especially for opaque words because it is very resource-demanding to find an appropriate morphemic meaning during whole word recognition (Packard, 1999, 2000). An EEG study on spoken Chinese compounds by Tsang, Zou, and Tse (2022) found that transparent compounds showed a smaller mismatch negativity (MMN) than pseudocompounds whereas opaque compounds had no difference in MMN from pseudocompounds (e.g., *村音*, */cun1-yin1/*, "village-music"). They argued that Chinese speakers process transparent compounds via a combinatorial route whereas they process opaque compounds by combining morphemes on the one hand while retrieving their holistic representations on the other in order to avoid incorrect interpretation of morphemic meanings. However, another possibility is that the serial presentation of two morphemes in the auditory modality makes it more likely that the first morpheme that is heard might activate its dominant meaning that is not related to the whole-word meaning of opaque compounds. If so, opaque compounds might induce a conflict between the meaning of the whole word and that of its constituent morphemes. This might be another reason for the null MMN effect for opaque compounds. Another EEG study by Bai et al. (2008), who also used an auditory mode of word presentation, found a larger N400 for opaque than transparent compounds during lexical decision. In contrast, the two morphemes of visually presented stimuli appear on the screen simultaneously, which would be conducive to whole word processing. Therefore, the findings with regards to morphological processing in an auditory mode are required to be fully investigated in a visual mode.

In addition, two behavioral megastudies of Chinese word recognition revealed a limited effect of transparency on Chinese compound processing. Tse et al. (2017) used a database of 18983 traditional two-character compounds during a visual lexical decision task, and a hierarchical multiple regression showed that transparency only explained 0.9% and 1.2% of the variance in the reaction times (RTs) and accuracy respectively beyond the effects of character strokes and frequency measures, though it was significant. An EEG megastudy of 1017 words by Tsang and Zou (2022) analyzed two time-windows (300-400 ms and 400-500 ms) similar to that of the N400 during a go/no-go lexical decision task. Results only showed the effect of transparency for the second character during the first time-window, but no effects of transparency for the second character during the second time-window and for the first character during both time windows. In the two above studies, we found that the selection of compounds was quite liberal, including binding words, pseudomorphological words, and many other extremely opaque compounds. This might be one reason for the presence of a weak transparency effect. Future studies should consider to use a conservative threshold to select compounds, especially whose constituent morphemes are either directly or metaphorically related to whole words in meaning.

On the other hand, semantic transparency might play little role in compound processing. This was supported by Tsang and Chen (2014)[1] and Momenian, Cham, Amini, Radman, and Weekes (2021), who found no effect of semantic transparency for Chinese compounds on the magnitude of priming in RTs during a visual lexical decision task. In addition, a cross-modal priming study on opaque words by Huang, Tsang, Xiao, and Wang (2020) found that constituent morphemes are still activated in Chinese even if they conflict with the whole-word meaning. The argument was that morphological decomposition is in most cases effective in recognizing the whole word even if it might generate errors for opaque words. According to Smolka and colleagues (Eulitz & Smolka, 2021; Smolka & Libben, 2017), however, another possible explanation might

[1] For opaque words, Tsang and Chen (2014) used pseudomorphological words (e.g., *雷达*, */lei21da2/*, “radar”; literally “thunder-arrive”).

be that semantic transparency no longer plays a role for a morphologically productive language. In summary, previous studies are still inconclusive and the explanations are relatively speculative on the role of transparency during word recognition.

1.3. The Present Study

Our EEG experiment on Chinese is the first to involve both transparent and opaque compounds, along with monomorphemic words as a baseline in the same design. Using LAN as an indicator of the effect of morphological complexity, Experiment 1 investigated whether both types of compounds are processed via a direct whole-word access or a decomposed route at the lemma level. We propose that, if both transparent and opaque compounds induce a larger LAN in contrast to monomorphemic words, then it would seem that both types of compounds are decomposed into their morpheme lemmas, whereas monomorphemic words are accessed directly through their whole-word lemma. If only transparent compounds produce a larger LAN but opaque compounds have no greater LAN compared to monomorphemic words, then it would seem that transparent compounds are decomposed whereas opaque compounds are not. According to the previous findings on LAN in alphabetic languages (El Yagoubi et al., 2008; Fiorentino et al., 2014) and the morpheme-level characteristic of Chinese compounds, we hypothesize that both transparent and opaque compounds in Chinese are decomposed via the activation of constituent morphemes.

Past research is inconsistent with regard to whether opaque compounds induced larger N400 than transparent compounds during semantic composition of constituent morphemes (Bai et al., 2008; Güemes et al., 2022). As in German, morphemes in Chinese are highly productive in creating compounds. Following the findings of Smolka and colleagues (e.g., Eulitz & Smolka, 2021; Smolka et al., 2015), in Experiment 1 we predict that opaque compounds will not differ in

N400 from transparent compounds in a visual lexical decision task.

2. Experiment 1

2.1. Materials and methods

2.1.1. Participants

Thirty-seven native Chinese speakers participated in this experiment, all of whom were undergraduates or postgraduates from the Beijing Language and Culture University. They included 20 males and 17 females, ages ranging from 18 to 30 years (average age: 22 years). All participants were judged to be right-handed by the Edinburgh Handedness Inventory (Oldfield, 1971). The participants had normal or corrected-to-normal vision and had no history of brain injury or neurological disease. The study was approved by the Ethics Committee of Language Acquisition and Cognitive Neuroscience Lab, at the Beijing Language and Culture University. The participants had signed the consent form before the experiment, and they were remunerated after the experiment.

2.1.2. Materials

Three different types of real words were used in the experiment: transparent, opaque, and monomorphemic (see Table 1). They were all composed of two Chinese characters. Transparent and opaque words were all compound words, which had two stems with independent meaning for each word. Semantic transparency refers to the degree to which each of the two morphemes within a word is semantically related to the whole word (e.g., Tse et al., 2017). Fifteen undergraduate students who were not participants in the experiment scored the semantic transparency between the individual morpheme and the corresponding Chinese compound word on a 7-point scale (1 = irrelevant, 7 = very relevant), and the average of the two morpheme scores was the semantic transparency of the compound word. The transparent compounds (e.g., *公园*, */gong1-yuan2/*, "park"; literally "public-garden") selected in this experiment all scored from 3.53 to 6.03 (*M* = 4.26), and the opaque compounds (e.g., *海关*, */hai3-guan1/*, "customs"; literally "sea-shut off") all scored from 2.13 to 3.16 (*M* = 2.80). The whole-word meaning of the opaque compounds could be potentially inferred indirectly from their internal morphemes by means of metaphor. Monomorphemic words (e.g., *沙发*, */sha1fa1/,* "sofa") were included in addition to the compound words. Two experts majoring in linguistics were asked to evaluate whether they agreed with our pre-selected list of 95 possible monomorphemic words based on the definition of the binding words and the pseudomorphological words mentioned above. The inter-rater agreement was 82%. We selected the words from those that were identified as monomorphemic words by both of the experts.

Insert Table 1 near here

Participants were presented with 52 transparent, 52 opaque, and 52 monomorphemic words during the experiment[2]. The three types of stimuli were matched in terms of the number of strokes and word frequency (both ps > .05 for the one-way ANOVA analysis). Transparent and opaque compounds were also matched in terms of character frequency, orthographic neighborhood size (i.e., the number of word neighbors sharing the same character), number of meanings for a given

[2] There were 156 transparent compounds used for the experiment, which were randomly divided into three sets, each comprising 52 transparent compounds. Each participant was randomly assigned to one of the three sets. This was done for another study that is not reported here, in which the individual morphemes of the transparent compounds were used to create two types of non-words. The three sets of transparent compounds were required so as to ensure that the same morpheme was not repeated across transparent compounds and two types of non-words.

character, and conditional probability of the second character given the first[3] (all *p*s > .05 for independent t tests). The number of character meanings was obtained from the Megastudy of Lexical Decision in Simplified Chinese (MELD-SCH) (Tsang et al., 2018). The remaining measures were obtained from the Chinese Lexical Database (Sun, Hendrix, Ma, & Baayen, 2018). Half of each type of stimuli were concrete words and half were abstract. Word concreteness was rated by two experts majoring in linguistics, and inconsistent judgements were agreed upon by both experts during a second check. In addition, we only selected three parts of speech for the three types of words: nouns, verbs, and adjectives. All compounds had a modifying-structure (e.g., *公园*, "public-garden") or a governing-structure (e.g., *海关*, "sea-shut off") between the two internal morphemes. All compounds were comprised of free or bound morphemes. The boundedness of a morpheme was determined by two experts majoring in linguistics, depending on whether the morpheme could stand alone simultaneously as a real word. The inter-rater agreement was 76%. We only selected morphemes with consistently rated results. Finally, we managed to achieve a comparable ratio across the three types of words in terms of part of speech, and between transparent and opaque compounds in terms of morphological structure and morphological boundness. The means of the above variables are shown in Table 2, and the word list and lexical characteristics of these words are provided in the Supplementary Materials (Table S1).

The morphological decomposability of the whole words was assessed through ratings. Morphological decomposability refers to the extent to which a word can be decomposed into smaller meaningful units associated with the whole word. A group of 15 university students rated decomposability on a 7-point scale (1 = low, 7 = high) for all the compounds and monomorphemic

[3] Compared with compounds, the character frequency of monomorphemic words was lower, the neighborhood size smaller, the number of character meanings smaller, and the conditional probability larger (all *ps* < .05). We assume that these differences between monomorphemic and compound words are determined by the holistic versus decomposed nature of the words themselves.

words used in the present study, and the result of the paired sample *t* test showed a significant difference ($p < .05$), in which the decomposability of compounds (M = 3.51) was higher than that of monomorphemic words (M = 2.73).

Insert Table 2 near here

Finally, we also used 156 non-words as fillers to ensure the same proportion of real words and non-real words. We re-combined the initial character of one word and the final character of another word into a meaningless non-word (e.g., *陆话*, */lu4-hua4/*, “land-words”, was generated by the recombination of the words, *笑话*, */xiao4-hua4/*, “joke” and *陆地*, */lu4-di4/*, “land”). In order to avoid the repetition effect of the same character, the average number of occurrences of the same character in the experiment was limited to 1.33.

2.1.3. Procedure

The participants conducted the experiment at the Language Acquisition and Cognitive Neuroscience Lab under dim lighting and a quiet environment. They were seated approximately 60 cm in front of a 19.5-inch Dell LCD monitor, with the stimuli being presented using E-Prime 2.0. Before the experiment, there was a practice session ensuring that the participants understood the task.

This experiment used a visual lexical decision task, in which the participants were asked to judge whether the pairs of characters visually presented on the screen were real words or not. During the experiment, instructions were first displayed on the screen, and then they pressed the ‘space’ key to enter the formal experiment. For each trial, a fixation ‘+’ was presented at the centre of the screen for 500 ms, followed by a word/non-word for 1000 ms in white colour against a black background, in 50 pt *Heiti* font. In order to avoid the artifacts produced by response-related hand movements, participants were not asked to make responses on this screen, so the RTs were not recorded. After the word had disappeared, '??' appeared on the screen, which reminded participants to respond accurately during this time window. Once the participants had pressed a button, or 2000 ms later, a blank screen of random 700-1100 ms was presented and participants could blink at this screen. In order to balance the button response of the left and right hands, for the first half of the blocks, the 'F' key was pressed for real words, and 'J' was pressed for non-real words; for the second half of the blocks, 'J' was pressed for real words and 'F' was pressed for non-real words.

Each participant received 312 trials, with half requiring 'yes' responses and half 'no' responses. All trials were randomly divided into six blocks with 52 trials in each block. In addition, trials were pseudo-randomized within the block, making sure that the same type of response consecutively appeared no more than three times. The experimental time for each block was about 2.5 minutes, with a one-minute rest between blocks, and the total experiment was completed in about 20 minutes.

2.1.4. EEG recording and ERP processing

The EEG data were collected using the NeuroScan SynAmps system (http://www.neuroscan.com). The Quik-cap was based on the extended version of the international 10-20 system embedded with 60 Ag/AgCl electrodes. Two horizontal electrooculogram (EOG) electrodes were attached 1 cm away from the outer canthi of both eyes, and the two vertical EOG electrodes were attached 1 cm upper and lower away from the left eye. During EEG recording, the left mastoid (M1) was used for reference, and the impedance of all electrodes was less than 5 KΩ. The sampling rate was 1000 Hz, and the filter bandwidth was 0.05–100 Hz.

The EEG data were pre-processed with EEGLAB 2020. First, the sampling rate was reduced to 500 Hz, followed by 0.05 Hz high-pass filtering and then 40 Hz low-pass filtering, and the 50 Hz line noise was also removed using the *Cleanline* package in EEGLAB. The M1 was re-referenced to the average of the bilateral mastoids (M1, M2). After EEG data pre-processing, the epochs were extracted ranging from 200 ms before to 600 ms after stimulus onset. Independent component analysis (ICA) was then used to filter out the artifacts from the EEG signal, mainly removing the ICA components such as EOG (electrooculography) and EMG (electromyography). In addition, the epochs with EEG amplitudes exceeding the baseline (-200 ms ~ 0) ± 75 μV were rejected, accounting for 3.9% of all correct trials. Furthermore, all epochs were corrected using the baseline of -200 ms to the stimulus onset, and then the ERP data were generated by averaging the epochs of correct trials under each stimulus condition. Finally, the average number of trials used for the EEG signal was 49 transparent compounds, 49 opaque compounds, and 50 monomorphemic words, respectively.

2.1.5. Data analysis

Error rates were analysed by means of the mixed-effects logistic model[4] among transparent, opaque, and monomorphemic words. In terms of the EEG data, six regions of interests (ROIs) in the lateral electrodes with six electrodes each were defined: left anterior (F1, F3, F5, FC1, FC3, FC5), right anterior (F2, F4, F6, FC2, FC4, FC6), left central (C1, C3, C5, CP1, CP3, CP5), right central (C2, C4, C6, CP2, CP4, CP6), left posterior (P1, P3, P5, PO3, PO5, O1), and right posterior (P2, P4, P6, PO4, PO6, O2). In addition, three ROIs in the midline electrodes were defined: midline anterior (FZ, FCZ), midline central (CZ, CPZ), and midline posterior (PZ, POZ). Based on visual inspection of the grand average waveforms of ERPs and previous relevant studies on the time windows of LAN and N400 (e.g., El Yagoubi et al., 2008), 275–450 ms was selected as the window

[4] See the model details in Experiment 2. Data files for one participant were missing, so there were 36 participants for the error rate analysis.

for statistical analysis of mean ERP amplitudes.

Using SPSS 26.0, we conducted a 3 (word types: transparent, opaque, monomorphemic) * 3 (region: anterior, central, posterior) * 2 (hemisphere: left, right) repeated measures ANOVA for lateral electrodes. In addition, we carried out a 3 (word types: transparent, opaque, monomorphemic) * 3 (region: anterior, central, posterior) repeated measures ANOVA for midline electrodes. Simple main effects of word types were then performed at each region and both hemispheres. Post hoc comparisons were adjusted by Bonferroni correction, and ANOVAs were adjusted by Greenhouse-Geisser correction when Mauchly' s test of sphericity was not satisfied. This study reported unadjusted degrees of freedom, adjusted p-values, F-values, and effect sizes. The significance level was set at $\alpha = 0.05$.

Using JASP 0.16.4 (https://jasp-stats.org), we also conducted Bayesian repeated-measures ANOVA with the same data and factors as the ANOVA above. This was done to determine whether non-significant results convincingly support the null hypothesis. Bayes factors (BF10) are reported, which indicate the likelihood of ratio of the alternative over the null hypothesis. A BF10 of 3-10 is typically considered a moderate effect in favor of the alternative hypothesis, while a BF10 of 0.33-0.1 or < 0.1 is considered moderate or strong evidence for the null hypothesis, respectively (Goss-Sampson, van Doorn, & Wagenmakers, 2020).

2.2. Results and Discussion

The mixed-effects logistic model with error rates as dependant variable showed that the effect of word type was not significant, z = 1.550, $p = .461$, BF10 = 0.615. Chinese speakers incorrectly identified the transparent (M = 0.5%, SD = 7.3%), opaque (M = 0.9%, SD = 9.2%), and monomorphemic words (M = 1.6%, SD = 12.6%) to the same degree.

Lateral electrodes. Although no significant main effects of word type, F (2, 72) = 0.055, p

= .946, BF10 = 0.011, and hemisphere, F (1, 36) = 0.082, p = .776, BF10 < 0.001, repeated-measures ANOVA found a significant word type * region * hemisphere three-way interaction, F (4, 144) = 2.885, p = .025, η_p^2 = .074, BF10 = 0.009. The simple main effects of word type at each of the six ROIs revealed that the left anterior electrodes had a significant main effect of word type, F (2, 35) = 5.206, p = .010, η_p^2 = .229, BF10 = 9.182, but no effect for right anterior, F (2, 35) = 0.465, p = .632, BF10 = 0.109, left central, F (2, 35) = 1.032, p = .367, BF10 = 0.216, right central, F (2, 35) = 0.512, p = .604, BF10 = 0.146, left posterior, F (2, 35) = 2.107, p = 0.137, BF10 = 0.576, and right posterior electrodes, F (2, 35) = 2.481, p = .098, BF10 = 0.263. Post-hoc multiple comparisons for the left anterior electrodes showed that there were significant differences between transparent compounds and monomorphemic words (p = .030, BF10 = 4.199), and between opaque compounds and monomorphemic words (p = .014, BF10 = 7.885), but no difference between transparent and opaque compounds (p = .987, BF10 = 0.278). Specifically, both transparent and opaque compounds induced larger negative amplitudes than monomorphemic words, while transparent compounds had similar amplitudes to opaque compounds[5] (see Figure 1). Bayesian analysis provided results consistent with the frequentist analysis for the significant effects between compounds and monomorphemic words at the left anterior region, and more importantly, for the null effects between transparent and opaque compounds at all six ROIs.

According to Guajardo and Wicha (2014) and Molinaro, Barber, and Carreiras (2011), topographical differences could represent the recruitment of different neural sources, and thus help in disentangling the linguistic processing at a neurocognitive level. LAN and N400 are typically located in different scalp distributions within approximately the same time window. Specifically,

[5] See Table S2 in the Supplementary Materials for the linear mixed-effect model results when transparency is treated as a continuum. The results also showed no significant effect of transparency in terms of all the lateral and midline electrodes.

the N400 generally occurs more posteriorly than the LAN, and the LAN occurs at the left hemisphere as its name reflects (Friederici, 1995, 2017). Based on that, we will discuss the LAN and N400 effect individually.

According to previous studies (El Yagoubi et al., 2008; Güemes et al., 2019), we identified the ERP component at the left anterior region as the LAN, which reflects the occurrence of morphologically decomposition. In our study, both transparent and opaque compounds produced a larger LAN than monomorphemic words, while transparent compounds had a similar LAN to opaque compounds, suggesting transparent and opaque compounds are morphologically decomposed. In addition, in accordance with previous studies (Bai et al., 2008; Coch et al., 2013; Du et al., 2013; Kutas & Federmeier, 2011), we identified the ERP component at the bilateral central and posterior regions as the N400, which reflects the process of semantic composition between constituent morphemes. In our study, transparent compounds had a similar N400 to opaque compounds. Considering that the interpretation of the ERP components should be based on the design, the results of LAN/N400 are defined based on the stimuli that invoke them (morphological complexity or semantic transparency, respectively).

Insert Figure 1 near here

Midline electrodes. Although the main effect of word type was non-significant, F (2, 72) = 1.090, p = .342, BF10 = 0.733, repeated-measures ANOVA found that the main effect of region was significant, F (2, 72) = 5.069, p = .022, η_p^2 = .123, BF10 = 7.147, as was the word type * region interaction, F (4, 144) = 3.776, p = .012, η_p^2 = .095, BF10 = 2.933. Simple main effects of word type revealed that it was significant in the midline anterior electrodes, F (2, 35) = 5.124, p

= .011, η_p^2 = .227, BF10 = 3.896, but neither significant in the midline central, F (2, 35) = 0.645, p = .531, BF10 = 0.129 nor posterior electrodes, F (2, 35) = 0.500, p = .611, BF10 = 0.122. Post-hoc multiple comparisons in the midline anterior electrodes showed that there were significant differences between transparent compounds and monomorphemic words (p = .015, BF10 = 7.764), and between opaque compounds and monomorphemic words (p = .044, BF10 = 3.021), but no difference between transparent and opaque compounds (p > .999, BF10 = 0.203). Specifically, both frequentist and Bayesian analysis revealed that both transparent and opaque compounds produced a larger LAN than monomorphemic words, while transparent compounds had a similar LAN to opaque compounds for the left anterior region. As with the lateral electrodes, no N400 effect was found between transparent and opaque compounds in the midline central and posterior regions (see Figure 1).

3. Experiment 2

In Experiment 1, the RTs were not recorded due to the fact that the button presses were made 1000 ms after the presentation of visual words. This was done to avoid artifacts of the EEG signals produced by response-related hand movements. Therefore, we conducted an additional behavioral experiment (Experiment 2a) using the same materials to Experiment 1, with the button presses being made once the visual word appeared on the screen, hence providing the RT data that was missing from Experiment 1. In addition, the MELD-SCH by Tsang et al. (2018) provides the RT data for simplified Chinese compounds. With the help of this database, in Experiment 2b we collected transparency data based on a large word list of compounds, and examined the effect of transparency on the RTs. Another advantage of the behavioral data in Experiment 2a and 2b is that the transparency scores of the first and the second characters can be treated as two continuous variables. This is difference from Experiment 1, in which transparent or opaque compounds were treated as a categorical variable since the EEG data needs to be analyzed using the average amplitude of all trials for each word type. Similar to results of Experiment 1, we predict that transparent or opaque compounds are processed differently from monomorphemic words (Experiment 2a), and the error rates or RTs are not affected by the transparency scores of compounds (Experiment 2a and 2b).

3.1. Experiment 2a

3.1.1. Participants

Another 34 native Chinese speakers participated in this behavioral experiment, all of whom were undergraduates or postgraduates from the Beijing Language and Culture University. They included 17 males and 17 females, ages ranging from 18 to 27 years (average age: 22 years). The participants had normal or corrected-to-normal vision. The participants had signed the consent form before the experiment, and they were remunerated after the experiment.

3.1.2. Materials and procedure

Experiment 2a used the same stimuli and procedures as described in Experiment 1 except that participants were asked to respond as quickly and accurately as possible once the visual word appeared on the screen. They had a maximal time window of 2000 ms to make their responses for lexical decision. In addition, the ratings of transparency on the 7-point scale were conducted by the same participants who attended the lexical decision task in Experiment 2a about three days after they completed the lexical decision task.

3.1.3. Data analysis

Prior to formal analysis, the RTs beyond three *SD*s of the mean within each participant were considered outliers and removed. Linear or logistic mixed-effects models were conducted to analyze the RTs or error rates data respectively in R4.2.1 (http://www.r-project.org) using the *lme4* package 1.1-31 (Bates, Machler, Bolker, & Walker, 2015). First, our mixed-effects models treated transparent, opaque and monomorphemic words as a categorical variable, which were dummy coded with monomorphemic words as the reference level. Second, for the mixed-effects models with only transparent and opaque compounds we treated the semantic transparency scores of the first and the second character as two continuous variables. A series of covariates were all continuous variables, including number of strokes, character frequency, orthographic neighborhood size, number of character meanings for the first and the second character separately, as well as the whole word frequency and conditional probability of the second character given the first. To reduce the problem of multicollinearity, the transparency scores and all covariates were centralized at their means. Frequency, orthographic neighborhood size, and the number of character meanings were natural log transformed before their centralization. To achieve normality, RTs were natural log transformed.

Models were fitted using a maximum likelihood technique with word type or the transparency scores as fixed effects. Random effects included random intercepts for participants and items, and by-participant random slopes for word type or the transparency scores. This was done in order to keep a maximal random-effects structure justified by the design (Barr, Levy, Scheepers, & Tily, 2013). The *p* values for the linear mixed-effects models were estimated based on the *t* distribution using Satterthwaite's method in the *lmerTest* package 3.1-3, and FDR corrected where appropriate. The variance inflation factors (VIF) were estimated using the *car* package, and the results showed all VIFs were less than 4, which were acceptable while assessing the multicollinearity.

Using JASP 0.16.4, Bayesian linear or logistic mixed-effects models were also implemented to validify the null effect of transparency. The 95% credible intervals (*CrI*) based on the posterior densities were reported. For each independent variable, if its 95% *CrI* included zero, it would be considered as reliable that this variable had no effect on the dependent variable (Gelman et al., 2013; Yi, Man, & Maie, 2022).

3.1.4. Results and Discussion

With regards to word type as a categorical variable, results showed that there were significant differences between compounds and monomorphemic words in terms of both the error rates and RTs (all *p*s < .05). Specifically, Chinese speakers incorrectly identified monomorphemic words (M = 5.0%, SD = 21.8%) more than transparent (M = 2.1%, SD = 14.3%) and opaque compounds (M = 2.8%, SD = 16.4%), and also responded more slowly to monomorphemic words (M = 617, SD = 147) than transparent (M = 584, SD = 145) and opaque (M = 594, SD = 146) compounds [6]. The result of error rates in Experiment 2a differed from that in Experiment 1, probably due to the response delays in Experiment 1, which required participants to respond 1000 ms after the visual word was presented. The statistics of the mixed-effects models were reported in the Supplementary Materials (Table S3).

With regards to transparency as a continuous variable, results showed that the transparency effects of the first and second characters were not significant in terms of either error rates ($\beta 1$ = -0.118, p = .416; $\beta 2$ = 0.076, p = .599) or RTs ($\beta 1$ = 0.002, p = .528; $\beta 2$ = -0.004, p = .218). According to the results of Bayesian analysis, the 95% CrIs of the transparency effects for the first and second character included zero in terms of either the error rates (*CrI1* = [-0.303, 0.174], *CrI2* = [-0.191, 0.353]) or RTs (*CrI1* = [-0.004, 0.007], *CrI2* = [-0.009, 0.003]), indicating that the null

[6] With regards to the two sub-types of monomorphemic words, the mixed-effects model results showed that there were no differences in error rates and RTs between binding words and pseudomorphological words, but pseduomorphological words differed from transparent or opaque compounds. In addition, the opacity of pseudomorphogical words is fundamentally different from that of opaque compounds in that the latter have metaphorical meaning of the semantic composition between morphemes. Therefore, we did not distinguish the two sub-types of monomorphemic words in the following analysis. See Table S6, S7, and S8 for the statistics in the Supplementary Materials.

effect of transparency was reliable (see Figure 2 upper panel). Effects of covariates were reported in the Supplementary Materials (Table S4). To sum up, the above results revealed that Chinese compounds were processed differently from monomorphemic words, and the processing of compounds themselves was not affected by transparency. Experiment 2a used the transparency scores as a continuum, and the findings are consistent to the EEG results in Experiment 1 with transparency as a categorical variable.

3.2. Experiment 2b

3.2.1. Materials and procedure

The word list of 1343 compounds for Experiment 2b was obtained by the following two steps. First, we used a pool of approximately 5000 words from the *New HSK Chinese Proficiency Test Syllabus Level 6* and selected all two-character words from it. Second, two linguistic experts rated these two-character words based on whether they were compounds and whether they belonged to any of the governing, modifying or coordinate structures. The inter-rater agreement was 85%. We selected 1343 compounds that two experts agreed on. Fifteen university students rated transparency of the first and second character separately on a 7-point scale (1 = opaque, 7 = transparent) for the word list. In addition, the corresponding RT data to the above compounds were obtained from the MELD-SCH by Tsang et al. (2018). The raw RTs were transformed into standardized RTs (zRT) for each word. In all, there were 1059 words without missing RT data that could be used for further analysis.

3.2.2. Data analysis

Using the same models of Tse et al. (2017), analysis of correlation and hierarchical multiple regression was performed in SPSS 26 to examine the effect of transparency on zRTs and error rates. In Step 1, the number of strokes for each of the two characters were first entered as two predictors.

In Step 2, three frequency-related predictors were entered using the context diversity subtitle frequency for whole words and constituent characters from Cai and Brysbaert (2010). Finally, semantic transparency for each of the two characters were entered in Step 3. The frequency measures were natural log transformed and all predictors were centralized at their means, in order to reduce the problem of multicollinearity. The model showed all VIFs were less than 1.5. The standardized regression coefficients (β), R^2 change and *p* value were reported. In addition, Bayesian linear regression was performed in JASP 0.16.4 to support the null hypothesis, and BF10 was reported.

3.2.3. Results and Discussion

The correlational results showed that the transparency scores for neither the first nor the second character were correlated with either error rates ($r1$ = .006, p = .839; $r2$ = .048, p = .112) or zRTs ($r1$ = -.027, p = .383; $r2$ = .020, p = .515). Moreover, results of the hierarchical multiple regression model showed no significant effects of transparency for the first or second character on both the error rates ($\beta1$ = .013, p = .690, BF10 = 0.077; $\beta2$ = .053, p = .097, BF10 = 0.067) and zRTs ($\beta1$ = -.023, p = .446, BF10 = 0.077; $\beta2$ = -.004, p = .900, BF10 = 0.067). The R^2 change in Step 3 also showed that transparency did not account for any variance in the error rates (.003) and zRTs (< .001) beyond the effects induced by the number of strokes and frequency measures. The effects of variables in the first two steps are reported in the Supplementary Materials (Table S5).

Insert Figure 2 near here

To sum up, the correlation and regression results did not show a transparency effect during Chinese compound processing (see Figure 2 lower panel), a finding that contradicts the limited transparency effect revealed by Tse et al. (2017) and Tsang and Zou (2022). This may be because our study adopted a conservative threshold to select Chinese compounds, especially those whose constituent characters are directly or metaphorically associated with whole-word meanings. The findings of Experiment 2b are consistent with those in Experiment 1 and 2a, in which no evidence is found to support the transparency effect.

4. General Discussion

Our EEG and behavioral study investigated the effects of morphological complexity and semantic transparency on the processing of Chinese two-character compounds. During a visual lexical decision task, transparent and opaque compounds were compared using monomorphemic words as a baseline. With regards to the EEG results, we found that both transparent and opaque compounds induced a larger LAN in the left anterior region during a time window of 275-450 ms than monomorphemic words, while there was no difference between transparent and opaque compounds. In the same time window, transparent and opaque compounds showed no difference in N400 in the central and posterior regions of the brain scalp. With regards to the behavioral results, we found a similar pattern to the EEG results. In particular, responses to both transparent and opaque compounds were faster and more accurate than those to monomorphemic words, and the speed and accuracy of processing compounds was unaffected by transparency.

4.1. Morphological decomposition of compounds: Evidence from LAN

Our study is the first to report a difference in LAN between compounds and monomorphemic words in Chinese during visual word recognition, suggesting that Chinese compounds are morphologically decomposed while monomorphemic words are processed as a whole word. A two-character monomorphemic word cannot be split into smaller meaningful units associated with the whole word. Therefore, the individual characters of a monomorphemic word have no corresponding lemmas that are semantically related with the whole word, and the whole-word lemma is activated directly from its constituent characters at the form level. In contrast, compounds are decomposed in the sense that the two internal morphemes are represented at the lemma level and the whole-word lemma for a compound word is activated through the lemmas for its constituent morphemes (see Figure 3). Thus, the difference between monomorphemic words and compounds is ascribed to the lemma level. Such a finding provides additional evidence for morphological decomposition to the LAN effect of morphological complexity in Italian by El Yagoubi et al. (2008) and in English by Fiorentino et al. (2014).

Note that, in addition to the whole-word lemma of a compound word being activated through the individual lemmas of its characters, it is possible that the whole-word lemma is activated in parallel directly from the individual character representations. However, the advantage of mediation through the individual lemmas is that they will, by definition, be of higher frequency than the whole word and, therefore, activated more quickly. As such, the direct pathway would rarely succeed over the mediated pathway in activating the whole-word lemma if the two pathways are working in parallel (see Taft, 2023 for a similar argument in relation to derivationally complex words).

Insert Figure 3 near here

In contrast to previous EEG studies that only included transparent compounds (El Yagoubi et al., 2008) or did not distinguish between transparent and opaque compounds (Fiorentino et al., 2014), our study examined LAN for transparent and opaque compounds and, finding no difference, suggested that both types of compounds are decomposed on a morphological basis. This finding is inconsistent with the study on Spanish compounds by Güemes et al. (2019) that revealed a larger LAN for transparent as opposed to opaque compounds, but in line with the EEG study on Chinese compounds by Tsang et al. (2022) that revealed the occurrence of a decompositional route not only for transparent but also opaque compounds. However, our study did not find a holistic route for opaque compounds as demonstrated by Tsang et al. (2022). Instead, the LAN difference between opaque compounds and monomorphemic words in our study suggests that opaque compounds are not processed using a direct whole-word pathway in the same way that monomorphemic words are. In addition, our findings are in line with previous EEG studies that have demonstrated the activation of morphemes (e.g., Chung et al., 2010; Du et al., 2013; Tsang & Zou, 2022; Wu et al., 2017; Zou et al., 2019).

Consistent with two behavioral and eye-tracking studies on Chinese transparent compounds (Cui et al., 2017; Cui et al., 2013), our behavioral results on both error rates and RTs additionally provide evidence for morphological decomposition of opaque compounds. Another piece of evidence is the subjective assessment of morphological decomposability for the words by native speakers in our study, in which the compounds were judged to be more fully decomposable than monomorphemic words. In all, our data suggest a decomposed route for Chinese compound word recognition. The two-character compounds account up to 72% of Chinese vocabulary, and a finite number of individual morphemes can be combined to produce a massive number of compounds. Given that the individual morphemes are nearly always more frequent than the whole word itself (Xu & Taft, 2015), the advantage of a decomposition route for compounds lies in the ease of activating the lemmas for the individual morphemes, making it easier to activate the whole-word lemma than it would if it were activated without any mediation of morphemes. Taken together, our findings support a full-parsing model during visual word recognition, where opaque compounds also involve the activation of their constituent morphemes as it is for transparent compounds.

Finally, the LAN in our study occurred only in the left anterior region. This reflects more of a typical ERP component indexing morphological processing than the negative waves observed in the Fiorentino et al. (2014) study which occurred bilaterally and at midline posterior electrodes, and the LAN observed by Güemes et al. (2019) which occurred throughout the whole scalp. In addition, compounds with different structures were used in our study, which provides more evidence for morphological decomposition beyond the noun-noun compounds tested by El Yagoubi et al. (2008) in Italian.

4.2. The link between whole word and constituent morphemes: Null transparency effect in N400

Our study did not observe any difference in N400 between transparent and opaque compounds, and the error rates and RTs of processing compound were not affected by transparency during visual word recognition. These findings are in line with behavioral and EEG studies in German, a morphologically rich language, conducted by Smolka and colleagues (Eulitz & Smolka, 2021; Günther et al., 2019; Smolka et al., 2015; Smolka et al., 2009; Smolka & Libben, 2017; Smolka et al., 2019; Smolka et al., 2014), and the priming study for Chinese compounds by Tsang and Chen (2014), Huang et al. (2020) and Momenian et al. (2021). However, our findings are inconsistent with previous EEG studies of other alphabetic languages, such as those examining English compounds (Davis, Libben, & Segalowitz, 2019; MacGregor & Shtyrov, 2013; Sandra, 1990) and Spanish compounds (Güemes et al., 2022), which assumed that the larger N400 for opaque than transparent compounds was due to the fact that the compositional process of their internal morphemes interfered with the access to whole-word meaning. However, it is unlikely even for a transparent compound to be semantically composed on the fly. It is not always possible to know exactly what the semantic relationship is between the constituent morphemes. For example, "daydream" is a transparent compound, but its meaning as "a dream happening during the day" or "a dream about the day" cannot be known without accessing a whole-word representation that is associated with the correct meaning. According to the full parsing model, both a whole word and its constituent morphemes for compounds have their own lemmas. Based on that, rather than referring to such a compositional phase, our study focused on the semantic transparency effect for compounds depending on whether there is a facilitatory or inhibitory relationship between the whole-word lemma and the individual morpheme lemmas (Taft, 2003, 2023; Xu & Taft, 2015). Following the explanation of Smolka and colleagues, the high productivity of morphemes in Chinese compounds leads to strong semantic associations between a whole word and its morpheme at the lemma level. For opaque compounds, the link between the morpheme lemmas and the whole-word lemma is also positive and represents a metaphorical relationship. For this reason, it seems that there is no competition between whole words and their constituent morphemes during the process of activating the whole-word representation.

This theoretical explanation is supported by the connectionist view that the role of morphemes depends on the systematicity of morphological structure in the language as a whole (Plaut & Gonnerman, 2000), as in root languages such as Hebrew (Boudelaa & Marslen-Wilson, 2004) and Arabic (Bick et al., 2011), and in Basque (Duñabeitia et al., 2009; Duñabeitia et al., 2007). This morphological structure leads to lexical creativity in Chinese, and the strong semantic associations between whole words and constituent morphemes extend beyond transparent compounds to opaque compounds in morphologically productive languages. In addition to the three types of real words used in the data analysis, we analyzed the N400 induced by the non-words and found that they produced a larger N400 than compounds. This is consistent with the nonexistence of a whole-word lemma for non-words or difficulties in composing two unrelated morphemes or characters (e.g., *陆话*, */lu4-hua4/*, “land-words”), hence reinforcing the validity of the N400 results obtained for the compounds. In sum, the finding of a lack of difference in N400 related to transparency in Chinese compounds provides new evidence that semantic transparency in morphologically productive languages has a very weak effect on visual word recognition. On the other hand, there is another possibility that the effect of transparency cannot be detected in a visual word recognition task or in the N400, and future studies may consider using the recognition memory paradigm to test whether language users can equally recognize the constituents of a transparent or opaque compound.

The lack of a semantic transparency effect in our study is not consistent with the studies of auditory compounds in Chinese by Bai et al. (2008) and Tsang et al. (2022), which revealed a different N400 or MMN pattern between opaque and transparent compounds. This may be due to differences in presentation modes. In auditory presentation, the two morphemes serially appear over time. The first morpheme that is heard might activate multiple meanings or a dominant meaning of this morpheme. Before the second morpheme arrives, there is time for the activation of the first morpheme to go up to the semantic level and feed activation from the dominant meaning back down to the whole-word lemmas. Therefore, the lemma corresponding to a transparent compound will be activated more strongly than a lemma corresponding to the opaque compound. This would lead to a larger semantic conflict for opaque compounds during the interaction between constituent morphemes and their whole-word lemmas. In contrast, our study used visually presented stimuli where both morphemes are presented simultaneously on the screen, and this may induce the activation of the morphemes with one of their multiple meanings that is closely associated with the whole word. Future studies might visually present two morphemes separated by spaces or in two consecutive screens, which might then induce the occurrence of similar mental processes to that under auditory mode. We predict that this would lead to a larger N400 for opaque than transparent compounds as well.

5. Conclusions

In summary, our study supports a full-parsing model at the lemma level for Chinese compound processing. In this model, both the whole word and constituent morphemes for compounds have their own lemmas that are hierarchically organized. In other words, Chinese compounds are decomposed into their constituent morphemes at the lemma level, whereas the whole-word lemma for a monomorphemic word is directly activated from the form level. In addition, the process of whole-word access and its interaction with internal morphemes for compounds are unaffected by semantic transparency. This is due to the fact that high productivity of morphemes in Chinese compounds yields strong semantic associations between the whole word and their constituent morphemes, even for opaque compounds. Taken together, our findings support a full-parsing model during visual Chinese compound recognition.

As a final note, binding and pseudomorphological words were not distinguished, with both being categorized as monomorphemic. Logically, the comparison between pseudomorphological words and opaque compounds might be able to shed light on the role of morphemes during the access to the whole word, since both have constituents that are free-standing characters. Given the far greater semantic conflict between constituent characters and the whole word for the pseudomorphological words, though, future studies might explore whether they can produce a larger N400 than for opaque compounds.

CRediT authorship contribution statement

Yanjun Wei: Conceptualization, Methodology, Software, Formal analysis, Resources, Data curation, Writing - original draft, Visualization, Supervision, Project administration, Funding acquisition.

Ying Niu: Methodology, Software, Formal analysis, Investigation, Data curation, Writing - original draft.

Marcus Taft: Conceptualization, Methodology, Writing – Review & Editing, Supervision.

Manuel Carreiras: Conceptualization, Methodology, Writing – Review & Editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data accessibility

The behavioral data are available at https://doi.org/10.7910/DVN/WPIEZQ, Harvard Dataverse, V3.

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Figure 1. Panel A: Grand average ERPs at the nine Regions of Interests (ROIs) for the left-hemisphere, right-hemisphere and midline electrodes across the transparent compounds (Trans), opaque compounds (Opaq), and monomorphemic (Mono) words. Negative is plotted downwards. The rectangular boxes at the left and midline anterior electrodes indicate the Left Anterior Negativity (LAN). Panel B: Scalp topographies for three types of words within 275-450 ms time window, and for the three contrasts of "Trans minus Mono", "Opaq minus Mono", and "Opaq minus Trans".

Figure 2. The scatterplots for the relationship between the transparency of the first (C1) or the second (C2) character and the RTs in Experiment 2a and 2b. The scatterplots for Experiment 2a are based on the transparency scores and the RTs of the 208 compounds.

Figure 3. The demonstration of the representation of a whole word and its constituent morphemes at the lemma level during visual word recognition for the transparent compounds, opaque compounds, and monomorphemic words. The spelling in two slashes indicates the pronunciation in Chinese transcription system.