Word structure tunes electrophysiological and hemodynamic responses in the frontal cortex

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Abstract

As a morphological impoverished language, how does word structure impact Chinese lexical processing in the brain? To address this issue, the current study examined the temporal signatures and localizations in the human brain for morphological priming effect (compound/derivation constitute priming vs. non-morphological priming) and word structure modulation (derivation vs. compound) in light of EEG-fNIRS fusion. Whilst morphological priming effect was manifested in behavioral performance and left prefrontal hemodynamic responses, word structure effect was prominent drawing on behavioral, ERP, and fNIRS data. Chinese derivations elicited greater activation in the frontal cortex and engaged more distributed network than lexicalized compounds. The results were interpreted by the differing connection patterns between constitute morphemes within a given word structure from spreading activation perspective. Together, Chinese word structure effect showed a distinct pattern from the dual-route mechanism in alphabetic languages. Meanwhile, the current study for the first time identified dissociable behavioral and neurophysiological responses of Chinese derivations and coordinate compounds.

Keyword: morphological priming, word structure, derivation, compound, EEG-fNIRS

Introduction

In linguistics, morphology concerns not only how words are formed, but also how they are inter-connected with each other in the arguable mental lexicon (Levelt, 1993; Treisman, 1960). With developments in experimental psychology and neurosciences, psycholinguistic and neurolinguistic approaches in studying morphology in the human mind/brain have provided accumulating evidence for sub-lexical information processing and morphological structure processing. For instance, a key issue pertaining to morphological processing in the past five decades discussed about whether words are stored and processed in a full-listing or full-parsing manner for morphologically complex words (De Grauwe, Lemhöfer, Willems, & Schriefers, 2014; Frost, Kugler, Deutsch, & Forster, 2005; Fei Gao, Wang, Zhao, & Yuan, 2021), which yet has not reached consensus (Jiang, 2018; Schiller & Lieber, 2020). Importantly, irrespective of whether decomposition is an obligatory process of word recognition, the way how morphemes/lexemes are connected to establish a new word has been recognized to significantly modulate lexical access. This paper therefore looks at this crucial component of morphology, that is, morphological structure processing in the brain, which received increasingly critical attention in recent years.

To shed light on the sub-types of morphological structures, there have been extensive studies examining the representations of inflectional and derivational words in alphabetical languages drawing on behavioral, electrophysiological, and neuro-imaging techniques (Bölte, Jansma, Zilverstand, & Zwitserlood, 2009; Carrasco-Ortiz & Frenck-Mestre, 2014; Grainger & Beyersmann, 2020; Leminen, Smolka, Dunabeitia, & Pliatsikas, 2019; Whiting, Marslen-Wilson, & Shtyrov, 2013). Inflections are used upon word forms to mark grammatical changes like gender, number, voice and tense, whose meanings remain unchanged. In contrast, derivations are realized by attaching affixes (prefixes, infixes, and suffixes) to base word, thus establishing new word form, meaning, and even grammatical category. For example, "*walks*" in "*Tom walks to school every day*" is an inflection marking third-person singular verb in present tense, while "*walker*" is a noun derived from the verb "*walk*". Specifically, Newman, Ullman, Pancheva, Waligura, and Neville (2007) compared the event-related potential (ERP) responses to regular/irregular past tense of English verbs, phrase structure, and lexical semantics in sentential contexts. Irregular past tense elicited significant left-lateralized anterior negativities (LANs), probably indexing a rule-based computation on morphology, while significant P600 effects identified from regular and irregular violations might suggest a controlled processing for lexicalized linguistic items (e.g., irregular forms like *ran*). This pattern was replicated in a recent Swedish study (Schremm, Novén, Horne, & Roll, 2019) and elaborated in a so-called dual-access model (Baayen, Dijkstra, & Schreuder, 1997; Bozic & Marslen‐Wilson, 2010; Marslen-Wilson & Tyler, 2007) highlighting the neurocognitive signatures for morphological complexity. In this dual system, the processing of regular inflections in English might selectively engage the left fronto-temporal network, which is sensitive to rule-based decomposition and combination. On the contrary, the bilateral subsystem and broader brain regions are employed in reading derivational words and highly lexicalized forms, which is neuro-biologically specified for whole-word, storage-based sound-to-meaning mapping.

Compared to the numerous studies on inflections and derivations, however, the investigations into compound processing and the sub-structures of compounding are very scarce. Compounding deals with the process of concatenating different lexical constitutes (words/lexemes), so as to create new lexical items, which might constitute a fundamental mechanism of morphological productivity for most languages (Libben, 2014; Libben, Gagné, & Dressler, 2020). The majority of existing studies focused on how constitute frequency (e.g., Andrews, Miller, & Rayner, 2004), semantic transparency (e.g., Brooks & Cid de Garcia, 2015; Libben, Gibson, Yoon, & Sandra, 2003; Smolka & Libben, 2017), and constitute headedness (e.g., Libben et al., 2003; Marelli & Luzzatti, 2012) would impact lexical access and morphological parsing in compound word recognition (Leminen et al., 2019). What remains unclear is the extent to which word structure from a lexical view (i.e., the grammatical and semantic relations between lexical constitutes) would modulate the representation and processing of compound words. Insights from conventional descriptive linguistics (see review by Olsen, 2012) suggested a variety of compound structures, partially based on syntactic relations yet mostly on semantics, including apposition (e.g., *woman doctor*), subject/object + action (e.g., *sunrise*), and purpose (e.g., *wineglass*), among others (Jespersen, 1914). Drawing on a syntactic lens instead, existing psycholinguistic studies on compound processing exclusively focused on "modifier-head" (e.g., teacup, pineapple) structure (Brooks & Cid de Garcia, 2015; Smolka & Libben, 2017). Even though a couple of studies mentioned the existence of coordinative structure in English, or so-called "dual compounds"/ "copulative type" (e.g., *singer-songwriter*, *architect-sculptor*, *in-and-out*), which is primarily a hyphenated combination (Chung, Tong, Liu, McBride-Chang, & Meng, 2010; Libben, 2014; Olsen, 2012), there was neither a single study examining the neural basis of this structure, nor comparisons with other compounding structures. The rather inadequate evidence on this issue may be attributable to the relative impoverished compounding system of English words.

On the other hand, Chinese language is categorized as one without much inflection (see the debate about Chinese inflection from Dai, 1997), which is in striking contrast to alphabetical languages. In light of structuralism linguistics (e.g., B. Huang & Liao, 2011), Chinese vocabulary is classified into four categories in terms of word structure, that is, mono-morphemic word (e.g., *葡萄*, pu2-tao, "grape"), derivation (prefixed and suffixed), reduplication (e.g., *媽媽*, ma1-ma1, mom-mom, "mother"), and compound, among which compound words constitute the greatest portion (more than 70%). According to a survey through modern Chinese dictionary (Cao, 2003), the majority of multi-morphemic words in colloquial dataset is compound words (83.02%), followed by derivations (14.51%). In particular, there are five sub-structures of compounds, including modification (54%, e.g., *黑板*, hei1-ban3, black-board, "black-board"), coordination (26%, e.g., *花草*, hua1-cao3, flower-grass, "plant"), verb-object (18%, e.g., *吃飯*, chi1-fan4, eat-food, "to eat"), verb-resultative (2%, e.g., *長大*, zhang3-da4, grow-up, "grow up"), and subject-predicate (1%, e.g., *晚安*, wan3-an1, night-safe, "good night") (statistics from Su, 2016). The seminal work concerning Chinese word structure effect on morphological decomposition revealed that compounding structure (coordination vs. modifier) would modulate the constitute frequency effect in word recognition (B. Zhang & Peng, 1992). Specifically, the frequency of both constitutes in coordinative structure impacted the reaction time (RT) to target

words, while for modifier structure, RT was only related to the constitute on the final position. This study shed light on the decomposition mechanism of Chinese compound words, which is also mediated by morphological structures. Both behavioral and neuro-imaging studies since then have accumulated ample evidence for the morphemic effect of Chinese word reading in the human brain. For instance, ambiguity and polysemant at the constitute morpheme level would significantly affect the representation of disyllabic compound words (e.g., C. Y. Huang, Lee, Huang, & Chou, 2011; H. W. Huang, Lee, Tsai, & Tzeng, 2011; L. Liu et al., 2013; Tsang, Wong, Huang, & Chen, 2013; Wu, Duan, Zhao, & Tsang, 2020; Zhao, Wu, Tsang, Sui, & Zhu, 2021; Zou, Packard, Xia, Liu, & Shu, 2015, 2019). Besides morphemic effect, morpheme relations were also investigated in terms of semantic/thematic (Ji & Gagné, 2007; Jia, Wang, Zhang, & Zhang, 2013; Li & Xu, 2021; Pan & Jared, 2020; Z. Xu & Liu, 2019) and grammatical aspects. As this paper focuses on morphological structure processing, we primarily reviewed studies pertaining to the grammatical relations between constitute morphemes within a word in the following part.

Existing behavioral and electrophysiological studies mostly concentrated on subordinate and coordinate compounding structures and their corresponding representational difference in mental lexicon. Drawing on a compounding production task, P. D. Liu and McBride-Chang (2010b) compared Chinese third graders' word production performance with four compounding structures. Their results reveled that subordinate and coordinate structures were easier to produce than subject–predicate and verb–object structures, whose difficulty was found proportional to their distributional characteristics in language units (Laudanna & Burani, 1995). Following studies further differentiated subordinate and coordinate structures by employing various paradigms. For instance, subordinate structure was harder to recognize than coordination in a priming lexical decision task, where semantic relatedness and structural consistency between primes and targets were manipulated (P. D. Liu & McBride-Chang, 2010a). In subordinate condition, same structures facilitated the semantic priming effect, while the coordinate structures manifested the opposite pattern. On the other hand, subordinate structures were found to significantly boost literacy performance in memorizing compound words (D. Liu, 2016, 2017), relative to coordinative structures. D. Liu (2016) attributed this difference to the strengths of constitute connections within a compound word in light of the spreading activation theory (Collins & Loftus, 1975) and further proposed the independent representation of morphological structure in mental lexicon (D. Liu, 2017). Both of the two constitute morphemes in a coordinate structure contribute equally to the whole word meaning (e.g., 风雨, feng1yu3, wind-rain, "storm"), whose inter-connection are relatively weaker than the modifier-head relation in subordinate structure. It therefore requires more cognitive efforts to combine the lexical constitutes for coordinate structures. Importantly, there might exist a morphological structure layer in mental lexicon (D. Liu, 2017), in addition to morpheme and word layers in mental lexicon, which is originally proposed by the interactive activation model (Taft, 1994). At this specific layer for word structures, both the semantic and syntactic connections between lexical constitutes would be activated. Given the relative weak semantic connections in coordinate structure relative to subordinate structure, its corresponding morphological effect might be dampened.

However, the differing patterns between coordinate and subordinate structures from P. D. Liu and McBride-Chang (2010a) were not replicated in Cui et al. (2018) and Chung et al. (2010). The inconsistency was thought to result from the prolonged stimulus onset asynchrony (SOA=200 ms) in P. D. Liu and McBride-Chang (2010a). In Chung et al.'s ERP study using only coordinate compounds, morphological structure effect was null in behavioral data, yet manifested in the frontal P250 effect (220-300 ms time windows). Structural priming elicited greater P250 than distinct structure pairs, which might indicate a word structure facilitation and top-down processing at the early stage of lexical access (Hill, Strube, Roesch-Ely, & Weisbrod, 2002). The discrepancy calls for further examinations concerning the morphological structure effect in coordinate compounds.

Only a handful of neuro-imaging studies quantified the brain changes associated with Chinese morphological processing (F. Gao et al., under review; Ip, Hsu, Arredondo, Tardif, & Kovelman, 2017; Ip et al., 2019; Zou et al., 2015). They identified that both the left frontal and temporal cortex are involved in processing Chinese morphology, yet failed to differentiate various structures (i.e., mixed with different sub-structures of compounding and derivations). To our knowledge, there is only one imaging study which tried to disassociate the brain responses of various sub-structures of Chinese compound words (Hsu, Pylkkänen, & Lee, 2019). Hsu and colleges examined the Chinese morphological complexity effect (mono-morphemic vs. multi-morphemic) and compounding structural effect (subordinate, coordinate, and verb-object) by using lexical decision task and magnetoencephalography (MEG) technique. Compound words generated greater brain activations at an early stage (200 ms) in the left temporal cortex. In the later time window of 300-400 ms, however, there was a null effect in coordinate structure compared to baseline (mono-morphemic word), while both subordinate and verb-object structures generated greater responses in the posterior part of the left temporal region. The authors attributed the absence of coordinate structure effect in the left temporal cortex to the idea that coordinate compound words might lack a specifier-head-complement relational structures as manifested in subordinate and verb-object words. Instead, the two component morphemes make equal contributions to the whole-word meaning, resulting in a rather loose connection. However, this study failed to include the frontal cortex as a region of interest (ROI) in brain activation analysis, while related studies revealed that the left frontal cortex is also a crucial hub for Chinese morphological processing (F. Gao et al., under review; Ip et al., 2017). This indicates a need to examine the role of frontal cortex in processing different compound sub-types.

Taken together, the neurobiological basis of differing Chinese compound structures is still poorly understood, with respect to both temporal signatures and localizations in the human brain. Specially, much uncertainty still exists about the neural reality of coordinate structure effect. Importantly, no previous study has investigated the brain representations of Chinese derivation words, even though they constitute the second largest proportion of Chinese vocabulary. The present study therefore aims at exploring whether Chinese derivations employ the similar cognitive resources as compound words and examining the root priming effects from derivations and compounds in relation to semantic controls (non-morphological relationship). Masked priming is used to elicit early and automatic morphological parsing (Fiorentino, Naito-Billen, Bost, & Fund-Reznicek, 2014) in a visual lexical decision task. Electroencephalogram (EEG)

and functional near-infrared spectroscopy (fNIRS) were recorded simultaneously to depict both temporal signatures and spatial activations in the brain, as the latter one would somewhat compensate for the relatively poor spatial resolution of EEG. The research questions are raised as follows: What are the temporal and spatial specifications in the human brain for morphological priming effect (compound/derivation constitute priming vs. non-morphological priming) in Chinese word reading? Does Chinese derivational word reading employ the same neural resources as Chinese compound words (derivation vs. compound)?

Materials and Methods

Participants

Thirty Mandarin Chinese native speakers (mean age: 22.2 ± 3.2 years old; 15 female) were recruited as paid volunteers from the University of Macau campus. They were registered university students from various majors. All participants were righthanded and reported no neurological illness or mental disorder, with normal or corrected-to-normal vision. All materials and procedures were approved by the Institutional Review Board at the University of Macau. Written consent form was obtained from each participant prior to the experiment.

Stimuli

Thirty-six disyllabic Chinese compound words with coordinate structures and 36 disyllabic derivational words with suffixes (e.g., 儿/er/, 民/min2/) were selected as target words. In masked priming task (Lavric, Clapp, & Rastle, 2007), these words were primed by their corresponding constitute morpheme on the head position. Another 36 disyllabic compound words with four lexical structures (subordinate: 22, coordinate: 8, verb–object: 5, noun-complement: 1) were selected as control group, completed with a semantically related Chinese character as the prime. In control group, prime character and constitutes of target word are distinct at both orthographic and phonological levels and yielded no morphological relationship. Twelve Chinese native speakers were invited to rate the semantic relatedness between the prime and target among derivation, compound and control materials with a 0-7 Likert scale. The averaged semantic relatedness from each group was above five, indicating a high semantic transparency and consistency among groups. Three lists are matched regarding word frequency, character frequency, and the number of strokes (Table 1).

One hundred and eight disyllabic Chinese non-words were selected from MELD-SCH dataset (Tsang et al., 2018). The non-words yielded a pronounceable meaningless string and are primed by a distinct character. They worked as fillers to balance the yes/no responses.

Table 1. Stimulus statistics across three lexical conditions

	Prime	Frequency	Stroke Number	Target	Frequency	Stroke Number	Cloze Probability	Semantic Relatedness
Derivational word	网/wang3/, net	94 (145)	8.3 (2.3)	网民/wang3 min2/, netizen	8 (32)	15.3 (3.8)	0.07 (0.12)	5.2 (0.9)
Compound word	花/hua1/, flower	83 (109)	8.6 (3.1)	花草/hua2 cao3/, plant	7 (10)	16.9 (4.6)	0.12 (0.19)	5.4 (0.9)
Non-morphological	脏/zang1/, dirty	356 (1076)	8.8 (2.8)	污水/wu1 shui3/, dirty water	34 (79)	17.8 (4.5)	/	5.3 (0.5)

Procedure

The visual lexical decision task was adapted from the morphological priming paradigm with a short stimulus-onset asynchrony (SOA) (Chung et al., 2010) and employed a masked priming technique (Lavric et al., 2007). E-prime was used to program for all materials and procedures (Figure 1). Participants would first see a white fixation in the screen center for 300 ms, followed by a blank of 200 ms. A series of asterisks acting as mask were presented for 300 ms, which then would be replaced by the prime (57 ms). After the prime disappears, participants would read the target and decide whether the presented character string is a real Chinese word or not by pressing the corresponding buttons labelled as “yes” or “no” in the keyboard as quickly as possible. If they fail to react within three seconds, it would be marked as wrong automatically by the software. After the response, there would be blank jittered from one to four seconds (P. Zhang, Zhang, Peng, Song, & Bai, 2016). Primes were presented with Italic *Kaiti* typeface and size of 40, while targets showed up with bold *SimHei* at 40. Ten practice trails with correctness feedback were provided before the formal testing.

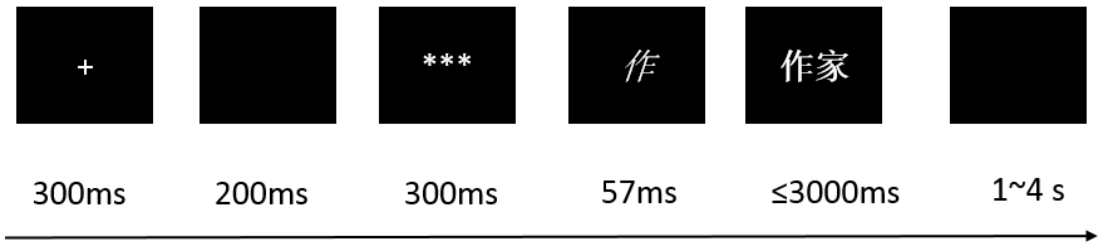

Figure 1. Schematic procedure of the lexical decision task. Participants need to decide whether the target is a real word or not once they read the character string. The stimulus-onset asynchrony (SOA) between prime and target is set at 57 ms in light of the previous study (Chung et al., 2010). “*作*” denotes “write” and “*作家*” stands for “writer”.

EEG recording and analysis

EEG and fNIRS data were collected simultaneously using an EasyCap (Brain Products, Munich, Germany), which was connected to Brain Products EEG system and NIRScout system (NIRx Medizintechinik GmbH, Berlin, Germany). For EEG acquisition, 32 electrodes were arranged

based on the international 10/20 system. EEG data was digitized at 500 Hz with a bandpass filter of 0.03-70 Hz. During the online acquisition, the left mastoid electrode was used as a reference and impedance of all electrodes was kept below 20 kΩ.

For offline analysis in EEGLAB v2021.0, continuous EEG data was firstly re-refenced to the grand average of all channels and filtered with a band pass of 1-30 Hz. Bad channels were interpolated by averaging the spherical electrodes, which took up less than 3% of all the channels. Then epochs lasting from 158 ms before the target onset to 1000 ms afterwards were extracted. Eye movement components were removed from the segmented data by the Independent Component Analysis (ICA) algorithm and ICLabel plugin (Pion-Tonachini, Kreutz-Delgado, & Makeig, 2019). Bad epochs were further removed by visual inspection.

The averaged amplitudes of selected electrodes were computed and compared in the time windows of P250 (220-300 ms) and N400 (300-500 ms), in light of the previous study (Chung et al., 2010). Specifically, AFF5h, FC1, FCz, FC2, and FC6 from the bilateral and midline sites of frontal cortex were used for P250 analysis, while centro-parietal electrodes CPP5h, CP1, CP2, and CP6 were employed for examining N400 effects.

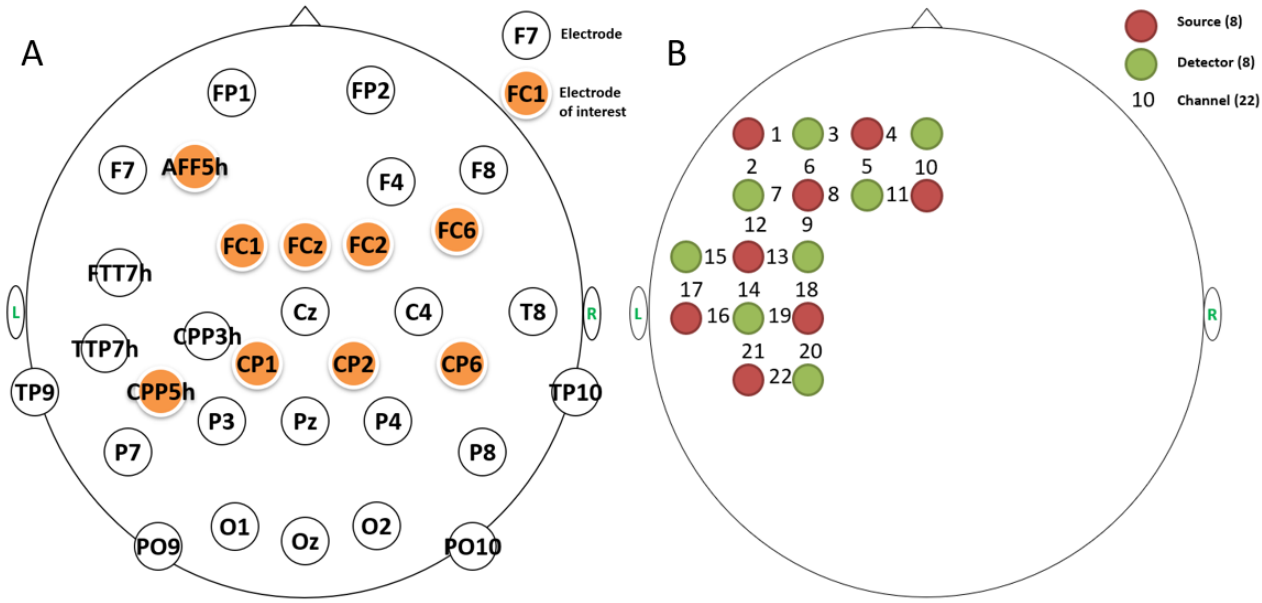

Figure 2. The layout of fused EEG-fNIRS setup. (A) There were 32 electrodes in total, nine of which (in orange) were used for further ERP analysis. (B) Eight sources and 8 detectors generated 22 fNIRS channels, covering the frontal and temporal regions of the left hemisphere.

Optical signal recording and analysis

Eight sources and 8 detectors were placed in the left frontal and temporal cortex (P. Zhang et al., 2016), thus forming 22 fNIRS channels (Figure 2B, 5A). Each source transmitted LED lights at the wavelength of 760 nm and 850 nm. The distance between source and detector was maintained at 3 cm. Optical signals were sampled at 7.81 Hz. The MNI coordinates of optodes and channels were obtained from their spatial information at the international 10/20 system,

which were then imported to NIRS_SPM (Ye, Tak, Jang, Jung, & Jang, 2009) to generate anatomical label and percentage of overlap.

The pre-processing of fNIRS data was performed with nirsLAB (Y. Xu, Graber, Schmitz, & Barbour, 2014). Data from one participate was missing due to device breakdown, leaving 29 participants for formal fNIRS analysis. Epochs were extracted during the time course of -1-13 s, which was time-locked to prime onset. Motion artifacts were removed from the raw data by the built-in algorithm, which were subsequently filtered with a band pass of 0.01-0.2 Hz. Hemodynamic states were then computed in the light of the modified Beer-Lambert Law. Oxygenated hemoglobin (HbO) and deoxygenated hemoglobin (HbR) changes were modeled in the Level 1 module of statistical parametric mapping with the canonical HRF function. As a result, general linear model (GLM) coefficients (beta values) were obtained across all priming conditions from each participant.

Results

Behavioral results

The mean of overall accuracy rate (ACC) of all participants was 95.26%, indicating that participants well engaged the task. Repeated-measures analyses of variance (ANOVA) were conducted on reaction time (RT) and ACC, respectively. There was a significant priming effect for RT data, $F(2,58)=34.085$, $p<0.001$, partial $\eta^2=0.540$. Multiple comparisons revealed that reaction time to derivational priming (712+121 ms) was significantly longer than compound constitute priming (625+82 ms) and non-morphological priming (636+99 ms) (ps<0.001), while there is no significant difference between compound and non-morphological priming ($p>0.05$).

Likewise, the priming effect was reliable with ACC data, $F(2,58)=37.873$, $p<0.01$, partial $\eta^2=0.566$. Derivational priming (89.87+6.19%) obtained significantly lower accuracy than those of compound (98.8+2.31%) and non-morphological (97.1+3.03%) cases (ps<0.001). Meanwhile, the ACC of non-morphological priming was significantly lower than compound ($p<0.01$). The behavioral results were visualized in Figure 3.

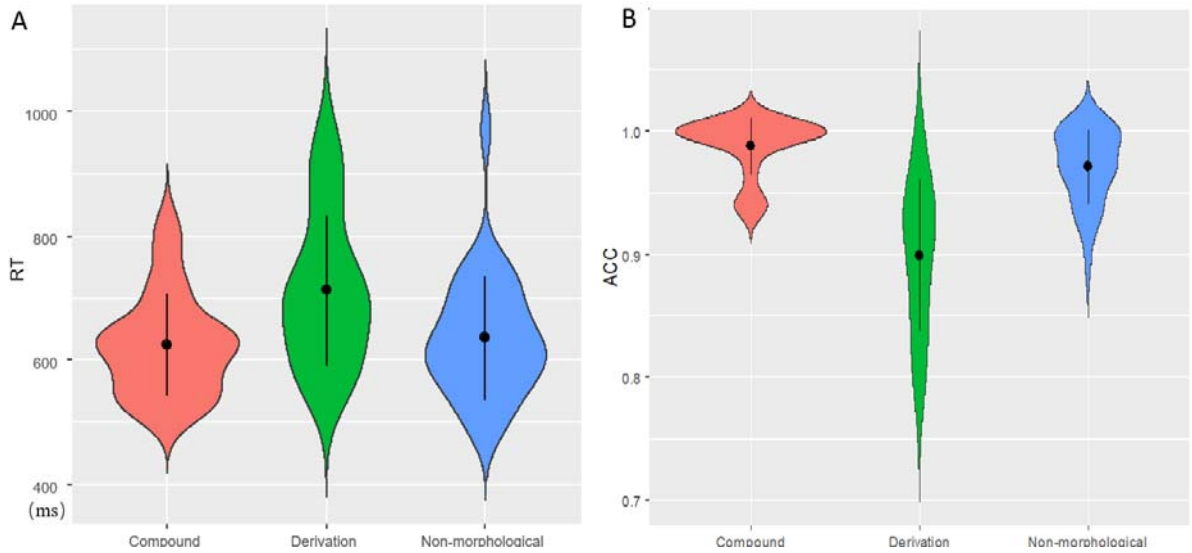

Figure 3. Violin plots of behavioral results. Black points denote means, and error bars represent standard deviations. (A) Reaction time comparisons. (B) Accuracy difference across three conditions.

ERP results

The P250 modulations were examined during the time window of 220-300 ms after target word onset in bilateral and midline sites of the frontal region (Chung et al., 2010). Two-way repeated-measures ANOVA was performed with priming type and hemisphere (left: AFF5h, FC1; right: FC2, FC6) as independent variables at the bilateral sites. There was no significant priming condition effect, $F(2,58)=2.169$, $p=0.131$, partial $\eta^2=0.07$. Yet a reliable main effect of hemisphere was found, $F(1,29)=0.252$, $p<0.05$, partial $\eta^2=0.153$. The right hemisphere (2.55±0.31 μV) revoked greater P250 activities than the left one (1.92±0.30 μV). There was also a significant interaction between priming type and hemisphere. Simple effects tests reveled that non-morphological condition (2.10±0.33 μV) elicited significantly higher P250 than compound cases (1.54±0.37 μV) over the left hemisphere, while derivational priming (2.97±0.37 μV) generated greater positivity than compound cases (2.27±0.34 μV) along the right hemisphere. No other comparisons reached statistical difference. Likewise, the effect of priming type was examined at the midline electrode (FCz) of the frontal cortex, while no reliable difference was detected, $F(2, 58)=1.262$, $p=0.289$, partial $\eta^2=0.042$.

Based on the visual inspection of grand-average ERP and topographies (Figure 4A, 4B), as well as previous study (Chung et al., 2010), N400 effect was examined in the time windows of 300-500 ms with priming type and hemisphere (left: CPP5h, CP1; right: CP2, CP6) as factors. Significantly more negative-going amplitudes were detected in the left hemisphere (0.295±0.268 μV) than in the right one (1.756±0.278 μV), $F(1,29)=40.433$, $p<0.001$. partial $\eta^2=0.582$. No other significant main effect or interaction was found.

To further differentiate the neural consequences of different word structures, the priming effect were evaluated by comparing the difference waves between the two priming conditions, namely, the P250 and N400 amplitudes of compound minus that of control and derivation minus control,

respectively (Figure 4C). Derivational structure effect (derivation minus control, 0.279±0.350 μV) elicited greater P250 responses than compounding structures (-0.354±0.250 μV) (*p*s<0.05) in both hemispheres. Interestingly, P250 in the right hemisphere (0.206±0.294 μV) was statistically higher than the left hemisphere (-0.280±0.261 μV) ($p<0.05$). The P250 patterns in the midline were consistent with bilateral sites. With regards to N400 component, the results remained unchanged.

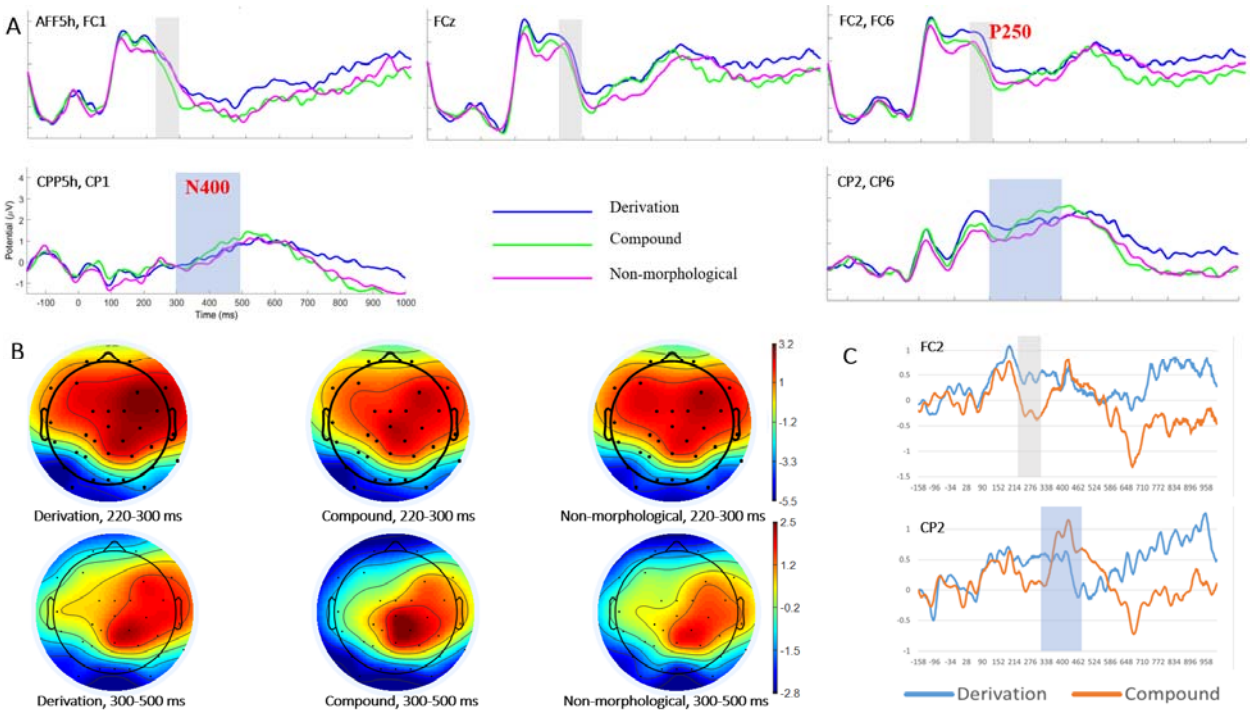

Figure 4. Visualization of ERP results. (A) Grand average ERPs over the frontal electrodes (the first row) highlighting P250 components (in grew shades), and centro-parietal sites (the second row) manifesting N400 activities (in blue shades). (B) Topographies of P250 (the first row) and N400 (the second row) across three conditions. (C) Difference waves for Derivation vs. Control (in blue), and Compound vs. Control at FC2 and CP2, respectively. The time windows of P250 and N400 were shaded in grey and blue, respectively.

fNIRS results

Although both HbO and HbR beta values were obtained from the GLM estimations, the present study only analyzed HbO signals to examine the priming condition effect (He, Wang, Li, & Yuan, 2017; Hu et al., 2018). Firstly, HbO beta values were compared across three conditions by repeated-measures ANOVA channel by channel, among which Channel 6 in the frontopolar area showed a significant condition effect, $F(2, 56)=3.162$, $p<0.05$, partial $\eta^2=0.101$. Pairwise comparisons were then conducted between Derivation vs. Compound, Derivation vs. Non-morphological, and Compound vs. Non-morphological. Table 2 summarized significant ($p<0.05$) and marginal significant ($0.05<p<0.1$) results when *p* values were not corrected. Specifically, the left frontal cortex including the pre-motor and supplementary motor cortex (channels 5, 6, 8.

11 ,18) elicited enhanced activation from non-morphological condition to compound words. Meanwhile, compound produced greater frontal cortex activities than derivations, as manifested in channel 10. Related brain activation patterns were visualized in Figure 5B and 5C.

Furthermore, pure word structure effect (derivation/compound minus non-morphological) was examined. The results of t tests were plotted in Figure 5D. Only channel 10 reached a marginal significance (p=0.057), where compounds evoked greater activation than derivations.

Table 2. Comparison results of significant and marginal significant channels and their corresponding spatial information

CH#	MNI coordinates			BA	Anatomical label	Overlap	Comparisons	*t*	*p* (uncorrected)	*p* (FDR corrected)
	x	y	z							
5	-21	67	53	9	Dorsolateral prefrontal cortex	0.8178	Compound > Non-morphological	2.42	0.02	0.07
6	-44	67	27	10	Frontopolar area	0.95455	Compound > Non-morphological	2.84	0.01	0.02
8	-41	58	47	9	Dorsolateral prefrontal cortex	0.88688	Compound > Non-morphological	1.93	0.06	0.19
10	0	73	49	9	Dorsolateral prefrontal cortex	0.75591	Derivation > Compound	-1.99	0.06	0.16
11	-15	61	61	8	Includes Frontal eye fields	0.77686	Compound > Non-morphological	2.07	0.05	0.14
18	-67	6	58	6	Pre-Motor and Supplementary Motor Cortex	0.92913	Compound > Non-morphological	1.74	0.09	0.28

*CH#: channel number, BA: Brodmann area, FDR: false discovery rate

Correlational results

The associations between electrophysiological responses and brain activation were examined by calculating the Pearson correlation coefficients between P250 amplitudes and HbO beta weights. Specifically, mean amplitudes of FP1, F7, AFF5h, FC1, FCz and activation values on CH5, CH6, CH8, CH10, CH11 were used to depict brain activities in the left frontal cortex, respectively, while the temporal responses were evaluated from FTT7h, TTP7h, CPP5h, CPP3h, CP1, and CH15, CH16, CH17, CH21, CH22. According to the matrixes of correlation coefficients, P250 could well predict the temporal activation in derivation reading (Figure 6A and 6B), which implicates a broad semantic network. More importantly, both frontal and temporal ROIs (Figure 6C and 6D) showed close associations between P250 and hemodynamic responses in derivation vs. compound contrast.

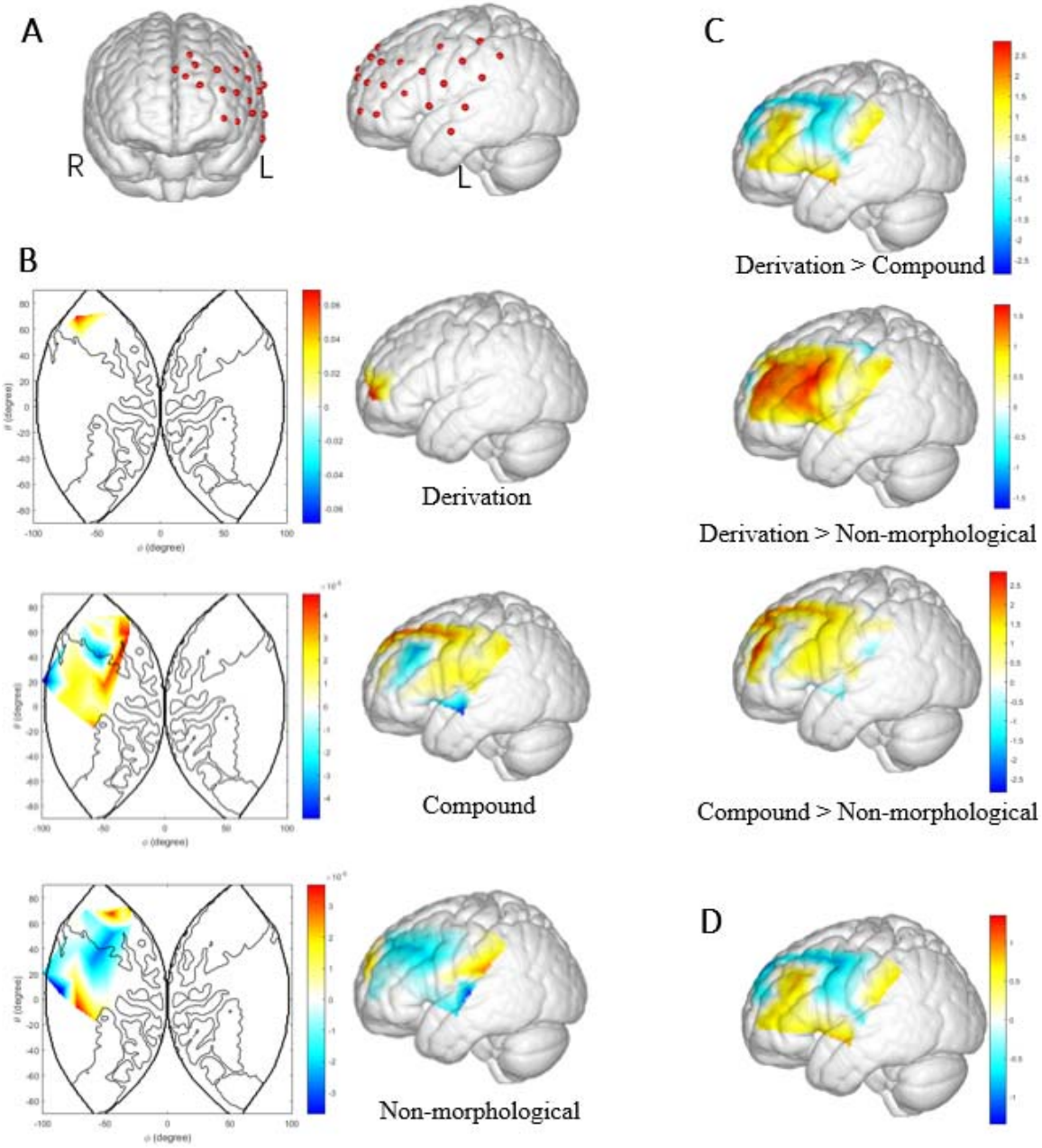

Figure 5. Configuration of fNIRS layout and activation maps. (A) fNIRS layout covering the frontal and temporal cortex of the left hemisphere, from the frontal and the views, respectively. (B) Brain activation patterns in reading words across three conditions based on HbO beta values. (C) T maps of three pairwise comparisons. (D) Activation difference of Derivation vs. Control (in blue), and Compound vs. Control.

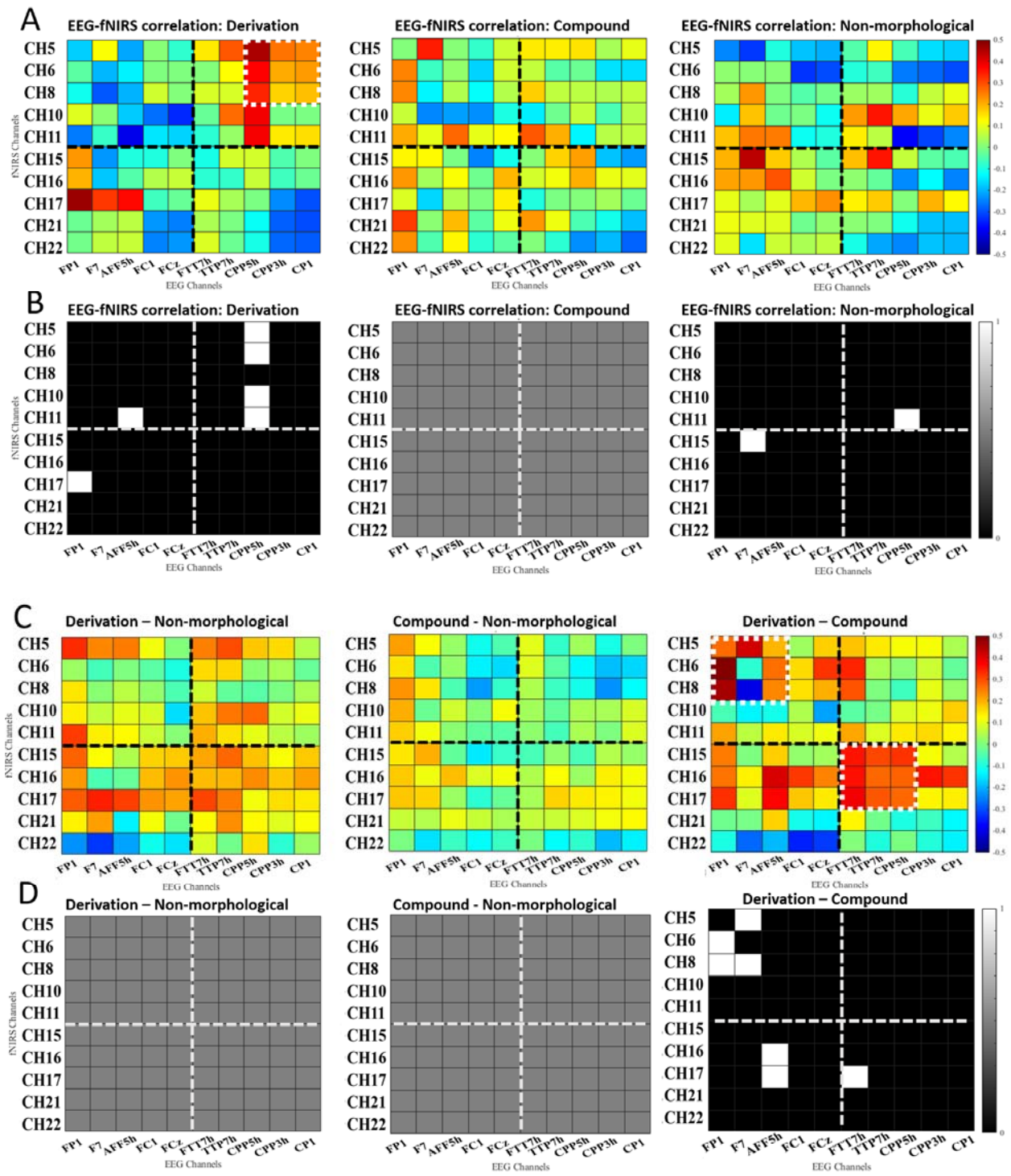

Figure 6. Correlation coefficient matrixes between electrophysiological responses (ERP data) and brain activation (fNIRS data). Dashed line represents the division of frontal (ERP: FP1, F7, AFF5h, FC1, FCz; fNIRS: CH5, CH6, CH8, CH10, CH11) and temporal regions (ERP: FTT7h, TTP7h, CPP5h, CPP3h, CP1; fNIRS: CH15, CH16, CH17, CH21, CH22). (A) Correlations between ERP and fNIRS data among representative probes across three conditions. Brighter color stands for stronger correlation. The white square with dashed outline represents region of interest. (B) Binary maps of the correlation results across three conditions. The white squares denote a significant correlation between bi-modal data (p<0.05). (C) Correlations between ERP and fNIRS data among

representative probes across three comparisons. (D) Binary maps of the correlation results across three comparisons (p<0.05).

Discussion

The current study examined both morphological priming effect (compound/derivation constitute priming vs. non-morphological priming) and word structure effect (derivation vs. compound) by using a masked priming technique in a lexical decision task. The analysis of behavioral performance revealed a morphological structure facilitation for coordinate compounds, which exhibited statistically higher accuracy and relatively shorter reaction time than non-morphological pairs. This pattern extended the findings from Chung et al. (2010) by suggesting that coordinate structure priming effect could not only be elicited from word pairs sharing the same structure, but also in coordinate words which are primed by their first roots, conditional on a short SOA (57 ms). Nevertheless, this morphological facilitation was not in line with P. D. Liu and McBride-Chang (2010a) and Cui et al. (2018). The discrepancy could be attributed to the relatively longer SOA and different task demands, where the former used 200 ms for SOA and the latter asked participants to respond to both primes and targets in a self-paced manner. The current findings therefore implicate that Chinese coordinate structure effect might be sensitive to SOAs and index an automatic and short-lived activation of morphological information at an early stage of lexical access (P. D. Liu & McBride-Chang, 2010a). Yet, the present study failed to detect any morphological priming effect for Chinese derivations. As there is no previous study examining the psychological reality of Chinese derivations, and morphological structure effect is somehow weak in behavioral patterns due to technical limitation (Chung et al., 2010; Cui et al., 2018), we will rely more on ERP and imaging data to advance understandings into this word structure.

With respect to word structure effect, both reaction time and accuracy data revealed that derivations might be harder to recognize than coordinate structures in constitute priming conditions. This finding is somewhat consistent with the coordinate vs. subordinate structure contrast identified in semantic priming paradigm (P. D. Liu & McBride-Chang, 2010a). Both subordinate structure (e.g., *黑板*, black-board, “blackboard”) and derivation (e.g., *作家*, writing-expert, “writer”) employed a modifier-head relation, whereas the suffix in derivation (i.e., *家* in *作家*) has been delexicalized in grammaticalization process. As a result, the suffix is loosely attached to the base form and productive in deriving new word forms (e.g., *画家*, “painter”; *艺家*, “artist”; *音家*, “musician”). In contrast, the inter-connection between the constitutes within a coordinate structure is relatively stronger than the base-suffix association in a derivation, even not as strong as those of subordinate compounds (D. Liu, 2016). Therefore, the word structure effect identified in the current behavioral results shed light on the spreading activation account, where the strengths between constitutes within a morphological complex word would determine the cognitive efforts needed in word recognition.

The ERP data revealed a prominent word structure effect on the frontal P250. Difference wave analyses showed that derivations elicited significantly greater bilateral negativities in the time window of 220-300 ms, compared to coordinate compounds, while the right hemisphere tends to

be more significant. The frontal P250 effect was previously found in the comparison between word pairs of different semantic relatedness (Hill et al., 2002) and structure consistency (Chung et al., 2010). Importantly, this early component was sensitive to SOA, as it was only present in a short SOA of 150 ms/57 ms, yet not in 700-ms condition, which indexes the automatic access in lexical processing. Existing MEG studies (Cavalli et al., 2016) also associated this early time window with a decomposition and parsing operation in morphological processing. As such, relative to coordinate compounds, greater P250 amplitudes found in derivations of the current study would indicate more cognitive resource consumption in morphological parsing, which confirmed the behavioral patterns. By virtue of the spreading activation account, all concepts (i.e., word roots in the current case) are stored as nodes and connected with each other by different weights. With the input of prime, not only the corresponding morphemes but also the candidate morpheme, with which it could make up new words, would be activated, followed by the re-combination of two morphemes. Yet, the inter-constitute connection across word structures is different. For instance, compared to subordinate structures, both constitutes in coordinate structure contribute equally to the whole word, manifesting a rather loose connection (D. Liu, 2016). The current P250 effects further suggest that Chinese derivations and compounds could be discriminated in the frontal cortex in light of their differing constitute relationships, as facilitated by spreading activation.

In addition to P250 effects, Chung et al. (2010) also reported a classic N400 semantic priming effect mediated by semantic relatedness between primes and targets, which was absent in the current study. According to the grand-average brainwaves and topographies, there was a N400-like component, which was widely distributed in the centro-parietal cortex. Yet, the comparison between three conditions did not reach any statistical difference. It was because the current study did not manipulate the semantics, as the semantic associations between primes and targets were generally comparable by measuring and matching semantic transparency. The frontal P250 effect could therefore be attributed to a relatively purer word structure modulation.

Brain activation obtained from fNIRS data provided robust evidence on morphological priming effect in compound word recognition, which was not statistically reliable in reaction time. Coordinate compounds elicited enhanced activation than the controls in the left frontal network, including dorsolateral prefrontal cortex (DLPFC) and frontopolar area. This pattern identified in the left frontal cortex from the current study is roughly consistent with previous fMRI results associated with morphological processing for children and/or with auditory stimuli. For instance, word pairs sharing morphemic information (e.g., *高温-高空*, high temperature-high sky) showed the highest activation in the left inferior frontal gyrus (IFG) across all lexical conditions in an explicit auditory morphological judgment task (Zou et al., 2015). This implicates an important role of the left IFG in morphological processing across alphabetic languages (Bozic, Marslen-Wilson, Stamatakis, Davis, & Tyler, 2007; Lehtonen, Vorobyev, Hugdahl, Tuokkola, & Laine, 2006) and Chinese. In a recent bilingual children study (Ip et al., 2017), Chinese-English bilingual children elicited greater activation in the IFG in auditory English morphological task (e.g., re-jump), compared to Chinese compound morphology task (e.g., *病花*, sick-flower) This pattern was similar to monolingual English children, further highlighting the role of left frontal cortex in morphological processing. Compared to fMRI, fNIRS is relatively limited in spatial

resolution, which might cause the current study's failure to localize subtle changes in exact IFG. Yet, the left frontal cortex (mostly DLPFC) still showed manifested activations in morphological priming conditions. Importantly, the current findings could justify previous fMRI results with data from print reading among adult population. Taken together, we may infer that the left frontal cortex implicates a core area for morphological processing across language modalities and literacy stages.

Whilst this study did not include as many word structures, it did partially substantiate a word structure effect between Chinese derivations and coordinate compounds, which made an original contribution to the field. Even though the contrast between the two structures only reached a statistically marginal significance, correlational analysis on derivation vs. compound difference revealed a good coherence between frontal P250 values and hemodynamic responses in the left frontal area. Derivations generated stronger activation than compounds, given the rather loose connections between roots and suffixes, which might demand more efforts in constitute meaning access and re-composition. The fNIRS data is overall consistent with ERP results and further validate the word structure effect in the frontal cortex.

Nevertheless, unlike previous MEG and fMRI studies (Hsu et al., 2019; Ip et al., 2019), the current study did not detect exact temporal engagement neither in morphological processing nor in word structure differentiation. Yet, ERP-fNIRS correlations showed that P250 in temporal cortex could well predict brain activations in the corresponding regions. Meanwhile, the electrophysiological responses in the left temporal region were closely associated with frontal activations. Whilst we highlighted the role of the left frontal cortex in word structure discrimination, the temporal areas should not be neglected. Future studies could address this region by using fMRI technique and functional connectivity analysis.

Finally, the current findings did not apply to the dual-route theory in morphological rich language (Baayen et al., 1997; Bozic & Marslen‐Wilson, 2010). According to this theory, the recognition of regular inflections and rule-based word units requires online computation mechanism and employ the left fronto-temporal cortex. In contrast, storage-based and highly lexicalized items engage broader bilateral brain regions, which is less time-costly. However, Chinese is a language lacking morphological inflection. Instead, compounding is the dominant structure of Chinese morphology and implicates a storage-based representation. Even though the proportion of derivations is much smaller than compounds, they are highly productive given the adhesiveness of affixes. By comparing the two word structures with differing lexicalization extents, the current study found that Chinese derivations might employ broader brain networks in bilateral fronto-temporal cortex, while compounds were mostly manifested in the left frontal regions and indexes a storage-based mechanism. This brain pattern might be attributable to the connection strength between constitutes across different word structures in light of spreading activation theory.

Together, this study examined both morphological priming effect and word structure effect by using EEG-fNINS simultaneous data. Specifically, we found prominent word structure effect in the frontal cortex. Chinese derivations elicited greater activation in this area and engaged more distributed network than lexicalized compounds, as manifested by both electrophysiological and

hemodynamic responses. As a morphologically impoverished language, Chinese word structure effect showed a distinct pattern from the dual-route mechanism in alphabetic languages. Future research needs to be done to examine this hypothesis by including more morphological structures and using more nuanced imaging technique.

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