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Effects of morphological complexity in left temporal cortex: An MEG study of reading Chinese disyllabic words

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ABSTRACT

This study aims to evaluate effects of word-internal variables on reading disyllabic Chinese words by manipulating (a) morphological complexity, defined as the number of morphemes and (b) structural complexity, defined as whether the two syllables relate to each other via the specifier-head-complement structure. In a visual lexical decision task, magnetoencephalography (MEG) was recorded during the reading of four types of Chinese disyllabic words: (1), disyllabic-monomorphemic (e.g., 蚯蚓 "*qiu yin*" earthworms), used as the control condition; (2) coordinative compounds (such as 花草 "*hua cao*" flower-grass: plants), which are double-headed, with meanings jointly derived from the two roots; (3) modifier-head compounds (such as 汽車 "*qi che*" gas-car: an automobile), which are right-headed, with the first root as the modifier; and (4) verb-object compounds (such as 開車 "*kai che*" operate-car: to drive a car), in which the first and second roots express an action and an object respectively. Our source analysis indicated that, at 200 m s, reading compounds revealed larger activity in left anterior temporal cortex than reading monomorphemic words, which might reflect composition of morphologically complex words during processing. From 300 to 400 m s, reading modifier-head compounds and verb-object compounds revealed larger activity in the left posterior temporal cortex than reading monomorphemic words, but there was no significant difference between reading coordinative compounds and reading monomorphemic words in this time window. These results indicate that morphological complexity and structural complexity substantially modulate activities in left temporal cortex during the reading of disyllabic words.

1. Introduction

Studies of word recognition have suggested that complex words are decomposed into constituents (e.g., stem and affix) at an early stage of processing and that the processing of word-internal structure substantially influences the recognition of complex words (Lewis, Solomyak, & Marantz, 2011; Rastle, Davis, & New, 2004; Solomyak & Marantz, 2010; Taft, 1979, 1981). For example, behavioral studies of recognizing derivational and inflectional words have explored the word-frequency effect, wherein high-

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frequency words are recognized more quickly than low-frequency words (Broadbent, 1967), and have indicated that lexical decision times of recognizing complex words is determined not only by the frequency of the word but also by the base frequency of the stem (Baayen, Dijkstra, & Schreuder, 1997; Stockall & Marantz, 2006; Taft & Forster, 1976, 1975).

In addition to the application of derivational and inflectional morphemes to form complex words, roots can be concatenated with other roots to form compound words. The roots in compound words are not arbitrarily ordered but follow language-specific constraints. For example, in English, the majority of compound words are arranged so the first root functions as the modifier and the second as the head (Levi, 1978). There are behavioral and neurophysiological studies providing evidence for morpheme-based processing of compound words (Fiorentino & Poeppel, 2007; Fiorentino, Naito-Billen, Bost, & Fund-Reznicek, 2014). Fiorentino and Poeppel (2007) conducted an experiment manipulating two factors: 1) *morphological complexity* (monomorphemic words vs. compound words), and 2) *word frequency* (high, medium, and low frequency). Based on responses times as participants made lexical decision, the results indicated that reading compounds generally elicited faster responses than reading monomorphemic words, regardless of word frequency. In the same study, their Experiment 2 demonstrated that M350 latency, an magnetoencaphalography (MEG) component that is associated with the initial activation of word representations prior to the behavioral response (Pylkkänen & Marantz, 2003), tracked the effect of morphological complexity in the way that was demonstrated in lexical decision times. These results seem to imply that compounds are obligatorily decomposed into morphemes, which are co-activated, and hence facilitate recognition of compounds.

In a study of Brooks and De Garcia (2015), MEG was recorded while participants performed a word naming task. The results demonstrated a morphological complexity effect localized to the left anterior temporal lobe (LATL). That is, there was larger activity in response to transparent compounds than to monomorphemic controls in the LATL from 250 to 470 m s after onsets of stimuli. This finding suggested that the LATL, which has been implicated as sensitive to composition in language in numerous studies (e.g., Bemis & Pylkkänen, 2013; Pylkkänen, Bemis, & Elorrieta, 2014; Flick et al., in press), is involved in composing representations of the constituent morphemes.

In addition to compositional operations, a recent MEG study on noun and verb phrases demonstrated that the relationality of concepts modulates activity in left superior temporal cortex and the left angular gyrus (Williams, Reddigari, & Pylkkanen, 2017). This raises the question whether a similar mechanism may be also involved in the processing of compound words. Many linguistic theories have sought to categorize different types of compounds based on their internal structure (Downing, 1977; Jackendoff, 2009; Levi, 1978). For example, while analyzing *modifier–head compounds* in English, Levi (1978) categorized twelve distinct relational structures, including *noun MADE OF modifier*, *noun FOR modifier*, *noun FROM modifier*, etc. For instance, a *snowball* is a kind of ball made of snow, and a *snowshovel* is a kind of tool for shoveling snow. Behavioral studies have indicated that integrating relations between morphemes affects the reading of compounds (Estes & Jones, 2009; Gagné & Spalding, 2009, 2004). Particularly, evidence from so-called relational priming suggests that accessing the relational information is involved in processing compound words. Gagné and Spalding (2009) conducted a sense/nonsense judgment task by presenting participants with modifier–head compounds alongside novel combinations of roots. In some cases, two consecutive trials might share the same relational structure. For example, a *snowfort* could be followed by a *snowball,* the target trial. These words belong to the same relational category (i.e. *noun MADE OF modifier*). In other cases, two consecutive trials had compounds with different relational categories. For example, *snowshovel*, which has the structure *noun FOR modifier,* was followed by a target trial with a different relational category (e.g. *snowball)*. The results showed a significant category effect of relational structure, even after potential influences of word frequency and base frequency had been partialled out. That is, targets (*snowball*) that followed words with the same relational category (*snowfort*) elicited faster responses than those following words with a different relational category (*snowshovel*). In a study of Ji and Gagné (2007), the relational priming effect was demonstrated in reading Chinese compounds. These findings indicate that the word-internal structure of a compound is accessed during compound recognition.

In summary, subtle differences in behavioral and neural measures have provided substantial evidence about processing of reading morphologically complex words. The most relevant background for the current work is that the LATL region appears to be modulated by the number of morphemes (Brooks & De Garcia, 2015) and that in general, accessing the specific compound-internal structure plays a role in recognition (Jia, Wang, Zhang, & Zhang, 2013). However, the neural bases of processing different compound structure are still unknown. To address this, we directly compared words contrasting in their internal structure during lexical decision. Specifically, we compared MEG activity during the reading of Chinese disyllabic-monomorphemic words (e.g., 蚯蚓/qiu yin/earthworms) to that elicited by compound words. Chinese compound words have a variety of substructures according to the linguistic features of the words, specifically depending on whether they are coordinative, modifier–head, verb–object, verb–resultative, or subject–predicate words (Chao, 1968; Li & Thompson, 1981; Liao, 2014). Several studies of Chinese compound recognition have focused only on modifier–head and coordinative compounds, because these structures are among the most common and are easy to identify (Chung, Tong, Liu, Mcbride-Chang, & Meng, 2010; Liu & Mcbride-Chang, 2010a, 2010b). To elucidate potential processes of retrieving representations of roots and accessing relational categories, we included three types of Chinese compounds (Fig. 1): modifier–head words (e.g., 汽車, "*qi che*", gas-car: an automobile), coordinative and verb-object compounds. By definition, coordinative compounds (e.g., 花草 "*hua cao*" flower-grass: plants) are double-headed, and their meanings are jointly derived from both constituent morphemes. Verb–object words (e.g., 開車 "*kai che*" operate-car: to drive a car) are left-headed, meaning that their first and second morphemes respectively express an action and its object.

Moreover, Fig. 1 shows that modifier-head words and verb-object words have a specifier-head-complement structure. On the other hand, monomorphic words and coordinative compounds do not have such structure. Many researchers maintain that morphological complexity and structural complexity are equivalent (Di Sciullo & Williams, 1987; Hale & Keyser, 1993). Disyllabic compounding is very productive in Chinese, and the syllabic structure of Chinese is relatively simple. Therefore, Chinese compound

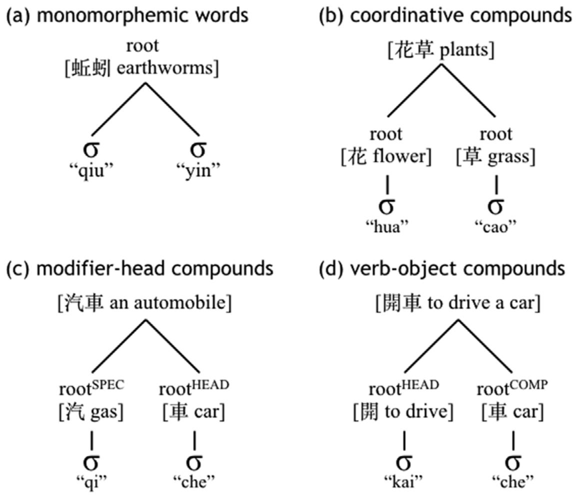

Fig. 1. Illustrations of four types of disyllabic words used in the present experiment. The internal structure of compounds is defined based on Liao (2014).

words are well-suited for answering the question of whether the neural effects of morphological complexity and structural complexity can be dissociated during lexical decision.

In addition to lateral temporal cortex, functional magnetic resonance imaging (fMRI) and MEG studies of visual word recognition have drawn attention to regions in the left ventral temporal cortex. For example, the visual word form (VWF) hypothesis argues that the activity in the anterior region of left occipitotemporal cortex is more sensitive to higher-level stimuli (e.g., frequent quadrigrams) than that in the posterior region (Mccandliss, Cohen, & Dehaene, 2003; Szwed et al., 2011; Vinckier et al., 2007). With their millisecond resolution, MEG studies have indicated that M170 activity in the left hemisphere, generated in left occipitotemporal cortex, is sensitive to the number of letters (Tarkiainen, Helenius, Hansen, Cornelissen, & Salmelin, 1999). Further, the left M170 is positively associated with the transition probability between suffix and stem (Solomyak & Marantz, 2010). For reading disyllabic Chinese words, there is a clear clue to the boundaries between constituents of syllables. Zhou, Marslen-Wilson, Taft, and Shu (1999) reported findings from masked priming experiments, which demonstrated significant levels of response time priming for morphologically overlapped prime-target pairs, and that the morphological priming effects cannot be reduced to semantic or form-based priming. Accordingly, we predict that there might be no morphological complexity effect in reading disyllabic Chinese words in the time windows corresponding to M170.

After the initial orthographic processing, reading compounds involves retrieving lexical representations of roots and accessing relational categories. MEG studies have suggested that the LATL is involved in basic phrasal composition (Bemis & Pylkkänen, 2013; Del Prato & Pylkkänen, 2014; Pylkkänen et al., 2014; Westerlund, Kastner, Al Kaabi, & Pylkkänen, 2015). Therefore, we question if the activity level in the LATL would differ when reading disyllabic words depending on the number of roots. That is, reading compounds might elicit larger LATL activity than reading monomorphemic words. On the other hand, studies have also indicated that the left posterior temporal lobe (LPTL) and the left inferior parietal cortex (IPC) are involved in integrating relations between words in phrases (Williams et al., 2017) and sentences (Grodzinsky & Friederici, 2006). If so, accessing the relational information in reading modifier-head and verb-object compounds might reveal large activity in LPTL and IPC.

2. Material and methods

2.1. Participants

Twelve Mandarin-speaking undergraduate or graduate students (age range 19–30, mean age 25.66) participated for money in this study. All participants were right-handed, and they did not have a history of neurological or psychological disorders. The current study was approved by the Human Subject Research Ethics Committee/Institutional Review Board of Academia Sinica, Taiwan. Written consent forms were obtained from all participants.

2.2. Stimuli

A list of 200 Chinese disyllabic words were selected as target words from the Academia Sinica Balanced Corpus (Huang & Chen, 1998). The corpus is based on more than five million words which are culled out from textbooks, newspapers, works of literature, popular works of fiction and nonfiction, and transcripts. Target words were selected by the following procedures. Although there is no database that exhaustively provides the morphological structure of each Chinese words, Chinese HowNet (Dong, 2000) provides morphological and semantic features of ten thousand polysyllabic words and phrases. There are 2227 disyllabic words in Chinese

Table 1
Means and standard deviations (in parentheses) of stimulus characteristics.

	monomorphic words	coordinative words	modifier-head words	verb-object words
word frequency[a]	0.91 (0.56)	1.55 (0.69)	1.36 (0.68)	1.46 (0.78)
frequency of the first character[a]	1.19 (0.63)	3.43 (0.71)	3.71 (0.74)	3.7 (0.68)
frequency of the second character[a]	1.29 (0.63)	3.13 (0.81)	3.53 (0.78)	3.69 (0.65)
number of strokes of the first character	13.16 (4.19)	10.18 (4.14)	8.57 (3.63)	10.66 (4.78)
number of strokes of the second character	12.68 (4.3)	11.73 (4.17)	10.98 (5.05)	10.76 (4.21)
orthographic neighborhood size of the first character	1.00 (0.00)	25.9 (25.54)	43.35 (36.95)	33.34 (31.16)
orthographic neighborhood size of the second character	1.00 (0.00)	15.24 (12.6)	33.96 (30.98)	39.4 (39.02)

[a] Log-transformed.

HowNet, of which 1234 are compound words included in the Academia Sinica Balanced Corpus. Among the 1234 compounds, there are 890 modifier-head compounds, 158 coordinative compounds, 123 verb-object compounds, 56 verb-resultatives, and 7 subject-predicate words. Searching for words without orthographic neighbors can efficiently identify disyllabic-monomorphemic Chinese words. Using this strategy, 168 disyllabic-monomorphemic words were found in the Academia Sinica Balanced Corpus. The target words were selected by matching the distribution in the log word frequency, log frequency of the first character, and log frequency of the second character between four types of words. Fifty words fitting this description were randomly selected for modifier-head, coordinative compounds, verb-object compounds, and disyllabic-monomorphemic words. Finally, target words were coded according to word frequency, number of strokes of the first characters and second characters, and the neighborhood size of the first characters and second characters (Table 1). In addition to target words, there were 120 filler words and 520 pseudowords which were created for the lexical decision task by concatenating two characters that do not occur in the word corpus.

2.3. Procedure

Prior to MEG acquisition, each subject's head shape was digitized, and head position indicator coils were used to localize the position of the subject's head inside the MEG helmet. The head-shape digitization and head position indicator locations were later used to co-register the MEG coordinate system to that of each subject's structural MR images.

Participants were given 20 practice trials before starting the experiment. Experimental trials (target words, fillers, and pseudowords) were randomly separated into ten test sessions. Visual stimuli were projected onto a screen above participants' heads while they lay in the magnetically shielded room that houses the MEG. Each trial began with a fixation point (" + ") that appeared on the screen for 200 m s, followed by a blank screen for 200 m s. Then, a fixation would appear on the screen for another 500 m s and was replaced by the stimuli. Participants were asked to respond to the stimulus by pressing one of two buttons to indicate whether or not they recognized the stimulus as a word. The stimulus remained on screen until participants pressed a button. After making a lexical decision response, the stimulus disappeared and a blank screen appeared for 1.6 s.

2.4. Data acquisition

MEG data were recorded continuously throughout the task by a 157-channel axial gradiometer whole-head MEG system (Kanazawa Institute of Technology, Kanazawa, Japan). A band-pass filter (0.3–100 Hz) was applied during the recording with a sampling frequency of 1 kHz. High-resolution T1-weighted MRI sequences were acquired for each participant using a Siemens MAGNETOM Skyra 3T scanner (Siemens, Erlangen, Germany). The following parameters were used: TI = 1100 m s; TR = 2530 m s; TE = 3.3 m s; flip angle = 7°; 256 × 256 field of view; 192 slices in sagittal plane; 256 × 256 matrix, yielding acquired resolution = 1 mm.

2.5. Data processing

In off-line processes, MEG data were first noise reduced using the time-shift PCA algorithm (De Cheveigné & Simon, 2007). The continuous MEG data were then epoched with 100 m s pre-stimulus intervals and 900 m s post-stimulus intervals, and baseline corrected using the pre-stimulus data. Trials with amplitude variations larger than 1.5pT were excluded from averaging and subsequent analyses. The averaged rate of rejected trials was 7.4% (ranged from 0% to 11.5%). Each subject's MEG data were then averaged and low-pass filtered at 30 Hz. Subjects' structural MR images were processed in FreeSurfer (CorTechs Labs, La Jolla, CA and MGH/HMS/MIT Athinoula A. Martinos Center for Biomedical Imaging, Charleston, MA) to create a cortical reconstruction of each subject's brain. MNE toolbox (MGH/HMS/MIT Athinoula A. Martinos Center for Biomedical Imaging, Charleston, MA) was then used to calculate a cortically constrained L2 minimum-norm solution for each subject's MEG data with 5124 sources on each subject's cortical surface. The boundary-element model method was used to compute the forward solution, which estimates the resulting magnetic field at each MEG sensor by the activity at each of the 5124 sources. This forward solution was then employed to create the inverse solution, which identified the spatio-temporal distribution of activity over sources that best account for each subject's averaged MEG data. Only components of activation that were in the direction normal to cortical surface were retained in the minimum-norm solution, and then the resulting minimum-norm estimates were converted into a dynamic statistical parameter map

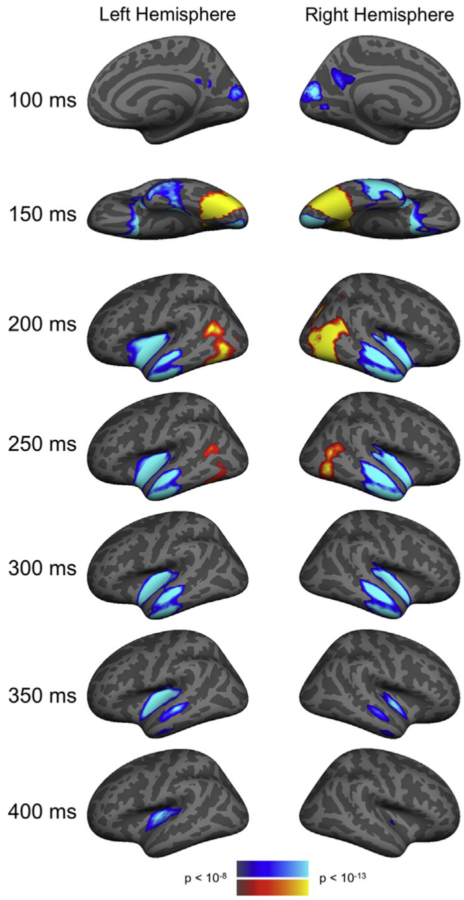

Fig. 2. Grand-averaged dSPM maps for each type of stimuli in both hemispheres shown at 50-ms intervals. Positive (red) values indicate current flowing outward from the cortical surface, whereas negative (blue) values indicate current flowing inward. Significance levels relative to empty-room noise estimates are indicated with color bars. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

(dSPM), which measured the noise-normalized activation at each source to avoid some of the inaccuracies of standard minimum-norm calculations (Dale et al., 2000). The noise-covariance matrix was estimated from the empty-room data recorded for 2 min in the experiment days. Each subjects' cortical surface was normalized onto a standard brain supported by FreeSurfer, and then all subjects' dSPM solutions were averaged together. Fig. 2 shows the averaged dSPM activity of both hemispheres. The significance of the modulation at each site was calculated with a F test (Dale et al., 2000), and all activity in the Fig. 2 was significant at $p < .00000001$. The positive (red) dSPM values indicate current flowing outward from the cortical surface, whereas the negative (blue) values indicate current flowing inward.

2.6. Regions of interests (ROIs)

Each participant's MR images were parcellated into anatomically based regions spanning the cortex (Fischl et al., 2002), based on the Desikan–Killiany gyral atlas (Desikan et al., 2006), using Freesurfer. Based on the findings of Brooks and De Garcia (2015) and Williams et al. (2017), ROIs were defined by anatomical labels in the left temporal lobe and bilateral IPC. The anterior and posterior areas of the left temporal lobe appear functionally distinctive, so we followed the methods of Brennan and Pylkkänen (2012) and divided the inferior, middle, and superior temporal gyri into anterior and posterior portions. Additionally, we also included the label of the left fusiform gyrus, the right fusiform gyrus, and left superior temporal sulcus (pSTS) which was in the posterior regions of the temporal cortex. In total, 11 regions were subjected to ROI analyses (shown in Fig. 3).

2.7. Statistical methods

The effect of word types was evaluated using the linear mixed model (LMM) over the single-trial data with the lme4 package in R. We estimated fixed effects of three contrasts including coordinative compounds vs. monomorphemic words, modifier-head compounds vs. monomorphemic words, and verb-object compounds vs. monomorphemic words. Analyzing the single-trial data allowed

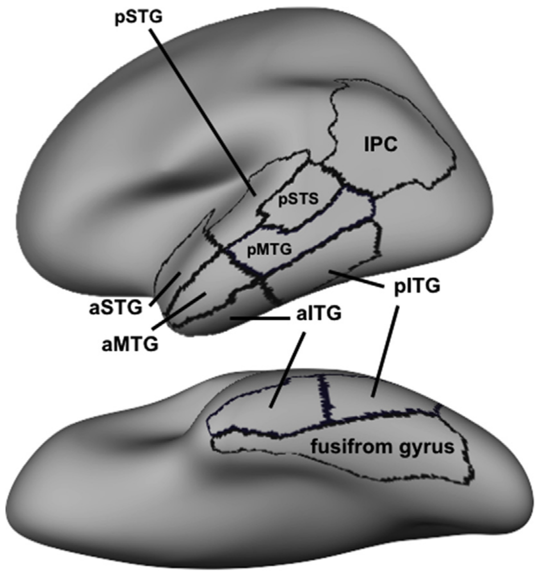

Fig. 3. Cortical regions in the left hemisphere used in our analysis were determined using an automated anatomical parcellation (Desikan et al., 2006). aSTG, anterior superior temporal gyrus; pSTG, posterior superor temporal gyrus; aMTG, anterior middle temporal gyrus; pMTG, posterior middle temporal gyrus; aITG, pITG, posterior inferior temporal gyrus; pSTS, posterior superior temporal sulcus; IPC, inferior parietal cortex.

incorporation of potentially confounding factors into the analyses. The LMM model included three contrasts of interest which were coded as a binary predictor set to 0 for monomorphemic words and 1 for compounds, along with several potential confounding variables which were also treated as fixed effects; these variables include word frequency (log-transformed), number of strokes of the first character, number of strokes of the second character, frequency of the first character (log-transformed), frequency of the second character (log-transformed), orthographic neighborhood size of the first characters, orthographic neighborhood size of the second characters, and trial order. The LMM model also included participants and items as crossed random effects.

The LMM model described above was fit per time-point for each ROI. The statistical significance of each contrast in each ROI was evaluated using non-parametric cluster-based analyses (Maris & Oostenveld, 2007) from 100 to 500 m s. This duration was defined to cover time windows of effects of morphological decomposition (Lewis et al., 2011) and semantic composition in previous studies (Pylkkänen et al., 2014).

In each ROI, the LMM model estimated t statistics for each contrast per time point. Then, for each contrast, time points with a absolute *t*-value larger than 1.64 (corresponding to $\alpha = 0.1$) were grouped into a set of clusters based on temporal adjacency; clusters shorter than 20 m s were discarded. This criterion could increase the sensitivity to weak and longer-lasting effects and did not affect the false alarm rate of the non-parametric statistical test (Maris & Oostenveld, 2007). We then formed a summary statistic describing each cluster by summing *t*-values. The statistical reliability of each cluster was tested by estimating the distribution of these cluster-level statistics from 1000 times permutation test (Maris & Oostenveld, 2007). The statistical significance of the cluster-level statistics was indicated by the Monte Carlo *p*-value for each contrast in each ROI. To correct for multiple comparisons across regions, *p*-values were corrected by using the False Discovery Rate (Benjamini & Yekutieli, 2001; Genovese, Lazar, & Nichols, 2002).

3. Results

3.1. Behavioral results

The same LMM model for ROI analysis was used to estimate effects of word types in response time. Fig. 4 shows the estimated response times for each word type. The results showed that reading compound words generally revealed faster response time than reading monomorphemic words, regardless the types of internal structure (coordinative compounds vs. monomorphemic words: $beta = -205.36$, $S.E. = 84.32$, $t = -2.43$, $p < .05$; modifier-head compounds vs. monomorphemic words: $beta = -228.05$, $S.E. = 95.21$, $t = -2.39$, $p < .05$; verb-object compounds vs. monomorphemic words: $beta = -284.55$, $S.E. = 95.66$, $t = -2.97$, $p < .01$).

3.2. The dynamic statistical parametric maps (dSPM) for reading Chinese disyllabic words

The grand-averaged dSPM maps (Fig. 2) indicated an early activity in the medial occipital regions (~80 m s) which was followed by the activities in bilateral occipitotemporal cortex around 170 m s. At around 200 m s, the activity extended to the anterior temporal lobes and the inferior parietal cortex. From 200 to 400 m s, there was a long-lasting increase of negative activity in the left superior temporal cortex.

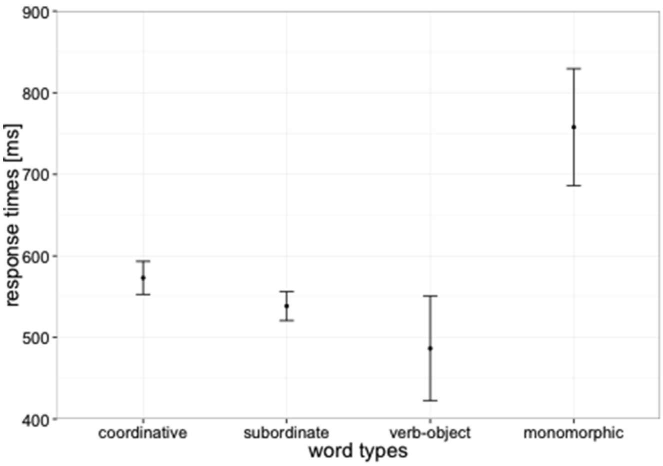

Fig. 4. Main effect of word types on response times. Partial effects based on LMM estimates are plotted in dots. Error bars are 95% confidence intervals.

3.3. Results of ROI analyses

Table 2 summarizes the results of cluster-level statistics. The contrast between monomorphemic and coordinative compounds only revealed a significant cluster in aITG. Fig. 5 indicates that reading coordinative compounds yielded larger aITG activity than reading monomorphemic words at 200–235 m s. The contrast between monomorphemic and modifier-head compounds was significant in two clusters in the anterior temporal cortex (aITG, 199–238 m s; aMTG, 197–239 m s) and in a cluster in pMTG (268–351 m s). The results indicated that reading modifier-head compounds generally generated larger activity than reading monomorphemic words. Finally, the contrast between monomorphemic and verb-object compounds was significant in a cluster in aITG (308–363 m s) and in two clusters in the posterior temporal cortex (pMTG, 288–354 m s; pSTG, 203–237 m s). The results suggested that reading verb-object compounds involved larger activities than reading monomorphemic words.

In addition to ROIs in the left temporal cortex, the contrast between monomorphemic and modifier-head compounds was significant in two clusters in the left IPC (207–246 m s) and the right IPC (430–450 m s). Finally, the contrast between monomorphemic and verb-object compounds was significant in two clusters in both IPC (left IPC, 223–247 m s; right IPC, 430–450 m s).

4. Discussion

Previous studies on Chinese word recognition have demonstrated that the activation and integration of morphemes of compound words depend on a wide variety of factors including lexical frequency, semantic transparency, and compound-internal structure (for a review, see Myers, 2006). The present study aimed to explore the role of compound-internal structure in processing. We investigated the neural correlates of reading Chinese disyllabic words to address whether sub-regions of the left temporal cortex would show sensitivity to different aspects of word-internal structure. In order to achieve this, MEG responses to various types of compounds were

Table 2
Summary of region of interest analysis. Cluster *p*-values are corrected for multiple comparisons across time and regions. Only effects with $p < .05$ (FDR corrected) are shown. MW, monomorphic words; CW, coordinative words; MH, modifier-head words; VO, verb-object words.

Region	Contrast	Times (ms)	Cluster statistic	Cluster *p*-value (FDR corrected)
aITG (LH)	CW vs MW	200–235	87.95	0.029
	MH vs MW	199–238	98.78	0.036
	VO vs MW	196–244	118.07	0.026
aMTG (LH)	MH vs MW	197–239	87.90	0.036
	VO vs MW	190–243	104.01	0.040
aSTG (LH)	VO vs MW	167–202	72.12	0.040
pITG (LH)	VO vs MW	316–356	77.14	0.040
pMTG (LH)	MH vs MW	268–351	153.73	0.036
	VO vs MW	288–354	134.23	0.040
pSTG (LH)	VO vs MW	203–237	72.36	0.040
pSTS (LH)	VO vs MW	388–416	58.36	0.040
IPC (LH)	MH vs MW	207–246	84.9	0.036
	VO vs MW	223–247	52.0	0.040
IPC (RH)	MH vs MW	328–367	79.8	0.036
	VO vs MW	329–375	100.64	0.040

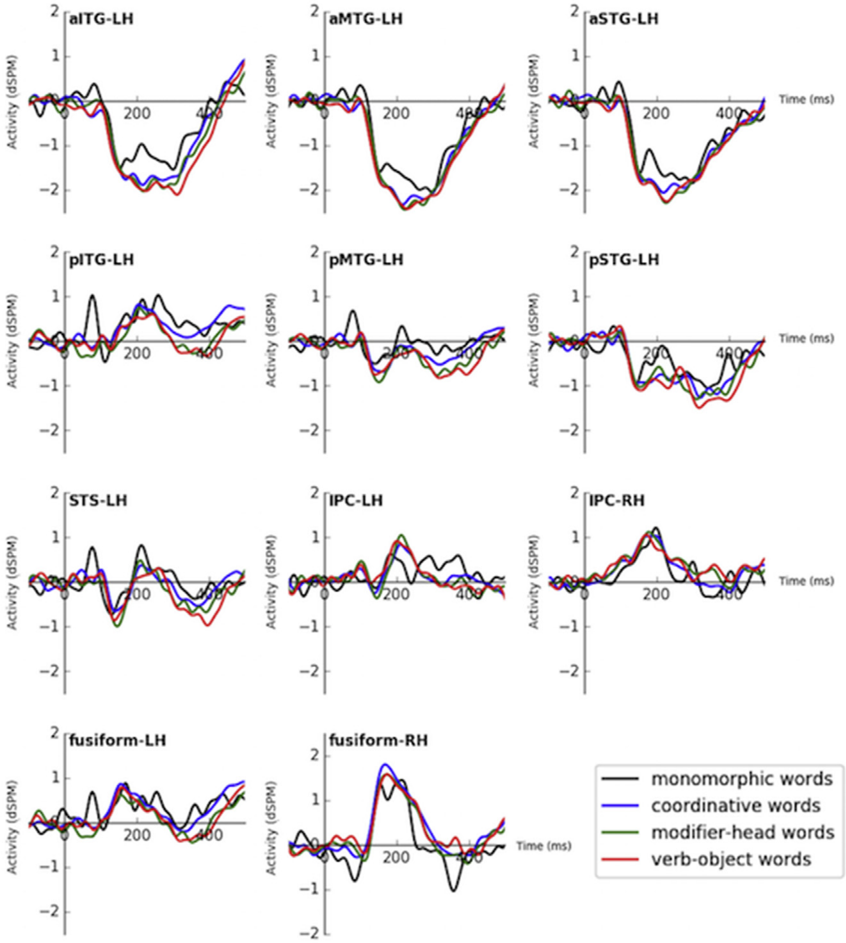

Fig. 5. LMM estimated activities in ROIs for each word type.

compared to that of disyllabic-monomorphemic words. Our behavioral results demonstrated that reading compounds generally revealed faster response times than reading disyllabic-monomorphemic words. The result of the facilitative effect of morphological complexity replicate the finding in Fiorentino and Poeppel (2007) and Fiorentino et al. (2014), which also showed faster response times for compounds than matched monomorphemic words. These results support the notion that compound words is recognized after morphological constituents of that word is parsed, and that morpheme combination is not costly in the lexical decision (for a comprehensive discussion, see Fiorentino & Poeppel, 2007).

Prior studies have provided evidence about the brain mechanisms of composing roots (Brooks & De Garcia, 2015) and intergrating relational roles of concepts (Frankland & Greene, 2015). The present results provide new evidence for different aspects of compositional processes during word recognition and allow for a detailed hypothesis about their relative timing and contributions. The present MEG data seemed to illuminate two different processes, one after another, underpinning the processing of Chinese disyllabic words, consistent with the putative neural correlates of morphological and relational processes. Based on the assumption that complex words are obligatorily decomposed into morphemes during word recognition (Fiorentino & Poeppel, 2007; Lewis et al., 2011; Solomyak & Marantz, 2009; Taft, 1979), the LATL activity at 200 m s might indicated the composition of roots in reading compounds, as all types of disyllabic compounds revealed larger LATL activity than disyllabic-monomorphemic words did. Studies of combinatory processing and word production have also indicated similar functions in the LATL (Pylkkänen et al., 2014). For example, fMRI studies suggest that the LATL yields larger activity in response to complex phrases than that to simple phrases or meaningless lists of words (Brennan et al., 2012; Stowe et al., 1998). An MEG study of word production demonstrated that both comprehension and production of adjective-noun combinations require combining lexical representations at around 200 m s after the onset of stimuli, and the LATL might be the corresponding mechanism of combinatorial operations (Pylkkänen et al., 2014). Therefore, in reading compound words, the LATL might handle the process of combining lexical representations of roots.

In addition, the present results in LPTL and IPC demonstrated that these regions might be associated with interpreting the internal structure of compound words. That is, the LPTL/IPC generated more activity for verb–object words and modifier–head words than for monomorphemic words, and LPTL activities were not different between reading coordinative words and reading monomorphic words. If the LATL increases for all compound words were due to the presence of two roots, the pattern of LPTL/IPC activities seems to reflect linguistic features that are present in verb–object words and modifier–head words but not in coordinative words. A recent fMRI study suggests that the superior temporal cortex has separated regions that are correspond to register contents of different sentence roles, such as agents, verbs, and patients (Frankland & Greene, 2015). In addition, Williams et al. (2017) suggest that functions of LPTL and IPC include extracting argument structure information from lexical items. Therefore, the results might lend support to that both verb–object words and modifier–head words have relational structures, and coordinative compound words do not. In coordinative compound words, the two component characters were equally important and are fused together to convey the whole-word meaning. On the other hand, the specifier-head-complement structure, which is absent in coordinative compound words, might be integrated with roots of verb–object words and modifier–head words. Therefore, results of LPTL and IPC activities during reading verb–object words and modifier–head words might reflect composing the internal structure of the compound word.

The effect of relational structures in the present MEG data is consistent with others who have suggested this effect is related to N400 activity in word recognition. Specifically, the effect of relational structures was found in LPTL activity during 300–400 m s, which were similar to the idiosyncratic properties of N400 (Federmeier & Kutas, 2011; Lau, Phillips, & Poeppel, 2008). Some studies have indicated that information of relational structures affect word recognition. For example, by recoding ERPs in recognizing modifier-head compounds of German, Koester, Gunter, and Wagner (2007) observed that integrating constituents of compounds was accompanied a large N400 activity. Furthermore, a behavioral study indicated that reading coordinative compounds revealed less semantic priming effects than reading modifier-head compounds (Liu & Mcbride-Chang, 2010a). Taken together, these results imply that relational structures play a substantial role in accessing lexical representations of compound words across languages.

In conclusion, by comparing MEG activity in response to reading disyllabic-monomorphemic words with that of reading disyllabic compound words, this study demonstrates that three sub-regions in the left temporal lobe show effects of morphological complexity. LATL activity reflected composing representations of roots at around 200 m s. After the morphological complexity effects in LATL, LPTL and IPC activity reflected a substantial step of integrating roots via the relational structures. These results represent a morpheme-based view of how the human brain handles the rich morphological information included in compound words.

Declarations of interest

None.

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