

ERP evidence for the online processing of rhythmic pattern during Chinese sentence reading

Yingyi Luo^a, Xiaolin Zhou^{a,b,c,d,*}

^a Center for Brain and Cognitive Sciences and Department of Psychology, Peking University, Beijing 100871, China

^b Key Laboratory of Machine Perception, Ministry of Education, Peking University, Beijing 100871, China

^c Key Laboratory of Computational Linguistics, Ministry of Education, Peking University, Beijing 100871, China

^d Learning and Cognition Laboratory, Capital Normal University, Beijing 100037, China

ARTICLE INFO

Article history:

Received 15 March 2009

Revised 29 September 2009

Accepted 5 October 2009

Available online 13 October 2009

Keywords:

Prosody

Rhythmic pattern

Sentence reading

ERP

N400

Posterior positivity

Late positivity

P800

ABSTRACT

Prosodic information has been found to have immediate impact upon spoken sentence comprehension. However, it is not clear to what extent such information could constrain neuro-cognitive processes in silent reading. In this event-related potential (ERP) study, we investigate whether a particular prosodic constraint in Chinese, the rhythmic pattern of the verb–noun combination, affects sentence reading and whether neural markers of rhythmic pattern processing are similar to those of prosodic processing in the spoken domain. In Chinese, the rhythmic pattern refers to the combination of words with different lengths, with some combinations (e.g., the [2 + 1] pattern; numbers in brackets stand for the number of syllables of the verb and of the noun respectively) disallowed and some combinations (e.g., [1 + 1] or [2 + 2]) preferred. We manipulated the well-formedness of rhythmic pattern as well as the semantic congruency between the verb and the noun and we visually presented sentences, segment by segment, to readers who were required to make acceptability judgment to each sentence. In two experiments in which the verb and the noun were presented either separately or as one segment, we found that the abnormal rhythmic pattern evoked an N400-like effect in the 400- to 600-ms time window and a late positivity effect in semantically congruent sentences; however, the abnormal rhythmic pattern elicited a posterior positivity effect in the 300- to 600-ms time window in semantically incongruent sentences. These findings suggest that information concerning rhythmic pattern is used rapidly and interactively to constrain semantic access/integration during Chinese sentence reading.

© 2009 Elsevier Inc. All rights reserved.

Introduction

Prosody, which comprises phonological properties such as intonation, stress and rhythmic pattern, is important to spoken language processing. Functionally, prosody can be broadly categorized into affective prosody and linguistic prosody. While the former is crucial for the recognition of emotional meaning conveyed through utterance (Besson et al., 2002; Mitchell et al., 2003; Pell, 2006; Wildgruber et al., 2005), the latter may function at different linguistic levels, from lexical processing (Böcker et al., 1999; Christophe et al., 2003; Cutler and Otake, 1999; Li et al., 2008a,b) to phrasal/sentence parsing (Frazier et al., 2006; Fodor, 2002; Jun, 2003; Steinhauer et al., 1999; Strelnikov et al., 2006) to formation of information structure in discourse (Birch and Clifton, 1995; Bock and Mazzella, 1983; Dahan et al., 2002; Li et al., 2008b). A number of event-related potential (ERP) studies have been conducted to investigate neural dynamics of prosodic processing in spoken language comprehension (e.g. Eckstein

and Friederici, 2005, 2006; Magne et al., 2007; Mietz et al., 2008; Pannekamp et al., 2005; Schön et al., 2004; Steinhauer et al., 1999). However, little is known to what extent prosodic information constrains neuro-cognitive processes of written language processing. In this study, we focus on a particular type of prosodic constraint in Chinese, the rhythmic pattern of the verb–noun combination, and investigate to what extent this information is activated in silent sentence reading and interacts with the semantic access/integration process. Before we give a linguistic description to rhythmic pattern in Chinese and introduce our experimental manipulations, we briefly summarize previous ERP findings regarding prosodic processing in spoken language comprehension.

ERP correlates of prosodic processing in spoken language processing

Reflected as variations of acoustic parameters, prosody is a salient feature of spoken language. Earlier studies demonstrate the immediate use of prosodic cues in sentence parsing by uncovering a specific ERP component, closure positive shift (CPS; Steinhauer et al., 1999). It was found that, relative to sentences without clear prosodic boundary, boundary cues (including pause and pitch variation in preceding

* Corresponding author. Department of Psychology, Peking University, Beijing 100871, China. Fax: +86 10 6276 1081.

E-mail address: xz104@pku.edu.cn (X. Zhou).

words) elicited a positive-going waveform (Pannekamp et al., 2005). Later studies revealed that the final word with intonation mistakenly signaling the continuation of a sentence elicited a right anterior negativity in the 300- to 500-ms time window (Eckstein and Friederici, 2005); the penultimate word intonated to signal the end of the sentence elicited a broadly distributed negativity in the same time window (Eckstein and Friederici, 2006) or a centro-parietal negativity in a later, 600- to 900-ms time window (Eckstein and Friederici, 2005). A late positivity (named as P800) was also reported for incongruent intonation that induced modality mismatch between the ending and the initial constituents of a sentence (Astésano et al., 2004). In particular, Magne et al. (2007) lengthened the second syllables of trisyllabic French words and asked listeners to make semantic or prosodic judgment to sentences containing these words. They found an N400-like negativity and the P800 in the prosodic judgment task but only the N400 effect in the semantic judgment task for the incongruent lengthening. It is suggested that these ERP effects reflect specific linguistic functions of prosody, such as lexical access/integration (Eckstein and Friederici, 2005; Magne et al., 2007) or judgment of the correctness of speech act (Astésano et al., 2004).

ERP studies have also documented the interaction between the prosodic process and the syntactic process, which takes place in either the earlier or the later stage of lexical or prosodic processing. In Eckstein and Friederici (2006), the critical word at the penultimate position in the sentence carried a suffix consistent/inconsistent with the word category it should be and this word was either normally intonated or mistakenly intonated to signal the ending of the sentence. An early negativity in 200–400 ms time-locked to the suffix onset was found at the left temporal scalp locations for syntactic violation but at bilateral temporal scalp locations for the combination of syntactic and prosodic violations. Eckstein and Friederici (2005) manipulated the congruency between prosody and syntax at two different positions (penultimate vs. final word) in a sentence and asked participants to make grammatical judgment to the sentence. In prosodically incongruent sentences, critical words were presented at the penultimate with the closure signal (e.g., the downturn of intonation) or at the final without the closure signal. In syntactically incongruent sentences, words at the two positions were reversed or verbs at the final position were simply dropped. At the penultimate position, prosodic incongruence resulted in a late centro-parietal negativity in the 650- to 850-ms time window, but only for grammatical sentences, not for syntactically incorrect sentences. At the sentence-final position, in addition to a right anterior negativity for the mismatching prosodic feature, a P600 was found for both prosodic and syntactic violations and this P600 was larger for the combination of violations. Similarly, prosodic boundary cues interact with the syntactic process in syntactic parsing. Steinhauer et al. (1999) added an incorrect boundary cue to the position before a noun phrase (NP) which would be wrongly interpreted as a direct object of the following intransitive verb (in German). A central N400 effect and a parietal P600 effect were observed on the verb, suggesting that the prosodic cue was used to drive the syntactic parsing. Kerkhofs et al. (2007) also showed that the CPS elicited by a prosodic break was reduced when this prosodic break was coincided with a syntactic break expected on the basis of contextually induced parsing of an ambiguous syntactic structure.

ERP evidence also shows the interaction between prosodic and semantic processing in spoken sentence comprehension. Astésano et al. (2004) manipulated the prosodic and semantic congruency between the sentence-ending critical verb and its preceding noun phrase and observed a centro-parietal N400 effect for semantic incongruency in both semantic and prosodic judgment tasks and a left temporo-parietal positivity (P800) for prosodic incongruency in the prosodic judgment task. Moreover this P800 effect was larger for semantically incongruent sentences than for semantically congruent sentence, suggesting an interaction between the semantic and

prosodic processes at a late stage and modulation of this interaction by the task demand. Magne et al. (2007) also manipulated the semantic congruency and the length of the second syllable of sentence-final French trisyllabic words. The prosodic incongruency elicited an N400 effect in both semantically congruent and incongruent sentences and in both semantic and prosodic judgment tasks. A P800 effect was also obtained in both types of sentences in the prosodic judgment task, although not in the semantic judgment task.

Related to semantic processing, the processing of information structure has also been found to be constrained by prosodic information. Magne et al. (2005) manipulated the accentuation of critical words in answers to questions and found that incorrect accentuation elicited a sustained positivity effect for words in the middle of sentences but a sustained negativity effect for words at the end of sentences. Li et al. (2008b) manipulated the information state of critical words such that the old information was given with words that had appeared in the preceding context and the new information was given with novel words. This manipulation was crossed with the manipulation of the accentuation of the critical words, which were either accentuated or not. The authors found that new information elicited larger N400 responses than old information and both accented old words and accented novel words led to stronger N400 responses than the deaccented counterparts. The authors suggested that the N400 responses here reflect semantic integration load and accenting a word would increase this load and the amplitude of N400.

While prosodic information in the above studies on spoken language processing was conveyed through acoustic variations, prosodic information in the written language can be conveyed through punctuation. It was reported that the CPS elicited by prosodic boundaries in spoken language comprehension could be observed in silent reading when the implicit prosodic boundaries were cued by commas (Steinhauer, 2003; Steinhauer and Friederici, 2001). An N400 effect could also be elicited when stress was put on the subject rather than on the object in the second clause, inconsistent with the implicit, default stress on the object in the preceding clause in German (Stolterfoht et al., 2007). However, little is known whether other types of prosodic devices can affect the neuro-cognitive processes in silent sentence reading and to what extent the neural dynamics involved is similar to that in spoken sentence comprehension.

The present study

The main purpose of this study is to investigate to what extent prosodic constraints in Chinese play a role and interact with the semantic process in silent sentence reading. To this end, we focus on a particular type of prosodic constraint in Chinese, the rhythmic pattern of the verb–noun combination and examine whether the violation of this constraint would elicit a particular pattern of ERP responses.

In Chinese, the rhythmic pattern refers to the combination of words with different numbers of syllables. Most words in Chinese are monomorphemic, monosyllabic words or disyllabic compounds. In written form, these words are represented either by a single character or by two characters, with each character corresponding to a syllable and a morpheme (see Zhou et al., 1999 for descriptions). Linguistically, it has been known that some particular combinations of words, in terms of the number of syllables involved, are disallowed and some are preferred. For the verb–object noun combination (see Table 1), with a few exceptions, the [2 + 1] pattern (numbers in brackets stand for the number of syllables of the verb and of the noun, respectively) is abnormal and not acceptable, but the [1 + 1] or the [2 + 2] pattern is allowed, even though a pair of such words express the same meaning (Lu and Duanmu, 2002; Wang, 2002). As shown in the examples, the action “read” can be expressed in either a monosyllabic form “读, *du*” or a disyllabic form “阅读, *yuedu*”. Similarly, both “报, *bao*” and “报纸, *baozhi*” express the meaning of “newspaper”. To a native speaker of Mandarin Chinese, “阅读报, *yuedu bao*” sounds odd even though it has

Table 1

Exemplar verb–noun combinations in terms of [1 + 1], [1 + 2], [2 + 1] and [2 + 2] patterns, respectively.

[1 + 1]	[1 + 2]	*[2 + 1]	[2 + 2]	Translation
读-报 <u>dú</u> bao	读-报纸 <u>dú</u> baozhi	*阅读-报 yuèdú bao	阅读-报纸 yuèdú baozhi	to read newspaper
种-蒜 zhong suan	种-大蒜 zhong dasuan	*种植-蒜 zhongzhi suan	种植-大蒜 zhongzhi dasuan	to plant garlic

Verbs and object nouns are separated with a hyphen, with the verbs underlined. The pattern with “*” is abnormal.

the same meaning as “读报, *dubao*” or “阅读报纸, *yuèdú baozhi*”. Other combinations, like the modifier–noun structure or the verb–complement word structure, are constrained by their own rhythmic patterns (Lü, 1963; for a review, see Feng, 2000).

These phenomena are captured by a linguistic principle that characterizes the relationship between the rhythmic pattern and information focus, which is in turn determined by the syntactic structure of word combination (Zhou, 2006). It is assumed that syntactic constituents in a sentence are focus-marked according to the rule that the most deeply embedded constituent in a syntactic structure is assigned as the default focus (Cinque, 1993; Zhou, 2006). This focus marking then determines the prosodic prominence, which can be conveyed by word length in Chinese (Duanmu, 2007). In the case of verb–noun combination, the most deeply embedded object noun in the combination is assigned as the default focus. However, a monosyllabic noun in the [2 + 1] pattern cannot carry the focus due to its less prominence in word length, as compared with the disyllabic verb. The mismatch between focus marking and rhythmic pattern leads to the oddity of the [2 + 1] verb–noun combination (Lu and Duanmu, 2002; Zhou, 2006).

The existence of rhythmic constraints for the verb–noun combination allows us to investigate to what extent prosodic information can be activated and used to constrain the semantic (and the syntactic) processes in silent reading, in which such information is conveyed by neither acoustic cues nor by punctuations. Therefore, the first aim of this study is to examine whether the rhythmic pattern of the verb–noun combination plays a role in sentence reading and whether a violation of such rhythmic constraints would elicit ERP responses similar to those for the processing of prosodic information in spoken sentence comprehension. We manipulated the rhythmic pattern of the verb–noun combination, which was either in the canonical [1 + 1] format (i.e., a monosyllabic verb followed by a monosyllabic noun) or in the abnormal [2 + 1] format (i.e., a disyllabic verb followed by a monosyllabic noun). The second aim of this study is to investigate whether the processing of rhythmic pattern interacts with the semantic process during sentence reading. To this end, in addition to the above prosodic manipulation, we also manipulated the semantic congruency between the verb and the object noun by making the noun fitting or not fitting the selectional restrictions of the preceding verb. We crossed the semantic congruency with rhythmic pattern, yielding 4 types of sentences (see Table 2). These orthogonal manipulations would allow us to examine to what extent the prosodic process interacts with the semantic process during silent reading of Chinese sentences.

The semantic incongruency between the verb and the noun should elicit the typical N400 effect, as this effect has been observed not only in a large number of studies on Western languages (for a review, see Kutas and Federmeier, 2000) but also in ERP studies on Chinese (Jiang et al., 2009; Li et al., 2006, Ye et al., 2006, 2007). More importantly, if we assume that difficulty in prosodic processing would lead to difficulties in lexical access and/or in integrating the current word into sentence representation (Magne et al., 2007), we would expect to see an N400 effect for the violation of rhythmic constraint as well. Furthermore, a late positivity effect could be observed for this violation given that this

effect has been observed in several studies manipulating expectancy towards the prosodic properties of the upcoming word (e.g., Eckstein and Friederici, 2005; Astésano et al., 2004). This late positivity may reflect the difficulty or the reanalysis process in integrating the prosodically incongruent information into sentence representation.

Experiment 1

In this and the following experiments, sentences were presented segment by segment at the center of a computer screen. The critical difference between the two experiments was whether the critical verb and noun were presented as one segment (Experiment 1) or as two consecutively presented segments (Experiment 2). When presented as one segment (Experiment 1), the abnormal verb–noun combination (i.e., the [2 + 1] pattern) would have three characters on the screen, which was always longer than the normal verb–noun combination (i.e., the [1 + 1] pattern) which had two characters on the screen. The potential confound with word length was controlled in Experiment 2, in which the critical target was the one-character noun across all the experimental conditions. As we will see, the presentation mode had little impact upon the pattern of the ERP effects.

Method

Participants

Sixteen students (8 females, aged between 19 and 26 years) from Peking University participated in the experiment. They had normal or corrected-to-normal vision and had no history of neurological, psychiatric or cognitive disorders. They were native speakers of Mandarin Chinese and were right-handed according to the Chinese Handedness Questionnaire (Li, 1983). This study was approved by the Academic Committee of the Department of Psychology, Peking University.

Design and materials

The experiment had four conditions, each containing 36 sentences: semantically congruent with the acceptable [1 + 1] pattern (i.e., SEM+RHY+), semantically congruent with the abnormal [2 + 1] pattern (i.e., SEM+RHY−), semantically incongruent with the acceptable [1 + 1] pattern (i.e., SEM−RHY+) and semantically incongruent with the abnormal [2 + 1] pattern (i.e., SEM−RHY−). Each critical sentence was composed of a main subject noun (S), a verb (V1), an object noun (N2), a second verb (V2) and the object noun (N2) of the second verb. These constituents were structured as “S + (V1 + N1) + (V2 + N2)”, with the subject followed by two verb

Table 2

Conditions and exemplar sentences with approximate literal translations.

Condition	Example
SEM+RHY+	技术员 / 建议 / 村民 / [<u>种</u> 蒜]。 jishuyuan jianyi cunmin zhong suan.
SEM+RHY−	技术员 / 建议 / 村民 / [<u>种植</u> 蒜]。 jishuyuan jianyi cunmin zhongzhi suan. technician advise villagers [<u>plant</u> garlic]. The technician advised the villagers to plant garlic.
SEM−RHY+	老师 / 组织 / 学生 / [<u>读</u> 蒜]。 laoshi zuzhi xuesheng du suan.
SEM−RHY−	老师 / 组织 / 学生 / [<u>阅读</u> 蒜]。 laoshi zuzhi xuesheng yuedu suan. teacher organize students [<u>read</u> garlic]. The teacher organized the students to read garlic.

The critical words in brackets are underlined, with the first representing the critical verb and the second representing the critical noun. The critical words in brackets were presented as one segment in Experiment 1 and separately as two segments in Experiment 2. Sentences are segmented by “/” between two segments.

phrases. The subject of the critical second verb phrase (i.e., the verb–noun combination) was a personal noun denoted either by the main subject of the sentence (i.e., S) or by the main verb's object (i.e., N1). Table 2 gives the exemplar sentences of the four conditions.

Seventy-two pairs of critical verbs were selected, with one verb in each pair monosyllabic (e.g., 种, zhong, to plant) and one verb disyllabic (e.g., 种植, zhongzhi, to plant). The selection of the verbs was very stringent such that each pair of verbs were synonyms, expressing the same or similar meanings and having the same syntactic properties. They were combined with a monosyllabic noun which fit the selection restrictions of the verbs (e.g., 蒜, suan, garlic), forming the SEM+RHY+ and the SEM+RHY– conditions, respectively. The same monosyllabic noun were recombined with another pair of verbs, which were semantically incongruent with the noun, to form the SEM–RHY+ and the SEM–RHY– conditions, respectively (see Table 2).

A full Latin-square procedure in assigning stimuli into test versions would yield 4 lists, with each condition having only 18 sentences in each list. To increase the number of sentences in each condition viewed by each participant, we split the stimuli into two test versions, such that in each version there were 36 sentences from each condition. The same monosyllabic noun appeared twice in a list, once following a semantically congruent monosyllabic verb (i.e., the SEM+RHY– condition) and once following a semantically incongruent disyllabic verb (the SEM–RHY+ condition) or once following a semantically incongruent monosyllabic verb (the SEM–RHY+ condition) and once following a semantically congruent disyllabic verb (the SEM+RHY– condition). Consequently, the same noun would appear twice in a list, but with different verbs of different lengths. One hundred and eight filler sentences of various syntactic structures were added into each list and 18 of them had semantic mismatches between the verb and the object noun.

The semantically congruent sentences were assessed for their semantic acceptability and naturalness of expression. The 72 pairs of sentences in the SEM+RHY+ and SEM+RHY– conditions were split into two versions in a counter-balanced manner. A participant, who was not tested for the ERP experiment, was asked to rate one list in terms of semantic acceptability and another list in terms of naturalness of expression, while another participant was asked to do the opposite for the two lists. Twenty participants in total completed the assessment. A 5-point scale was used for each rating, with “1” representing that the sentence was semantically anomalous or the expression was unnatural and “5” representing that the sentence was semantically acceptable or that the meaning of the sentence was expressed in a conventional way. For semantic acceptability, sentences with abnormal rhythmic pattern (i.e., in the SEM+RHY– condition) were generally rated as acceptable (mean = 4.41, SD = 0.39), although this rating was slightly lower than the rating for sentences in the SEM+RHY+ condition (mean = 4.57, SD = 0.47), $t(71) = 2.67$, $p < 0.01$. For the naturalness of expression, sentence with abnormal rhythmic pattern (mean = 2.60, SD = 0.44) were rated far less natural than sentences in the SEM+RHY+ condition (mean = 4.26, SD = 0.51), $t(71) = 24.25$, $p < 0.001$.

Procedures

Sentences in each test list were pseudo-randomized, such that there were at least 50 sentences intervening between two critical sentences using the same monosyllabic noun or between two critical sentences using the paired monosyllabic or disyllabic verbs. Each sentence was displayed segment by segment, in white against black background, at the center of a computer screen. Each segment was presented for 400 ms with a 400-ms inter-stimulus interval (ISI) between the segments. However, the sentence-final critical segment (i.e., the verb–noun combination) was presented for 400 ms and the interval between this segment and the full stop sign (i.e., a small circle in Chinese) was 600 ms. A question mark was then presented after the full stop. The separate presentation of

the full stop was to avoid emphasizing the sentence-final position of the critical segment and hence to reduce the impact of potential sentence-final wrap-up processes upon the ERP responses to the critical segment.

Participants were randomly assigned to one of the two test lists. They were seated in a sound-attenuated, electrically shielded chamber with a viewing distance of approximately 1 m. They were instructed to read each sentence silently and to judge, by pressing a key on a joystick after seeing the question mark, whether the sentence was semantically acceptable or whether it was expressed in a natural way. They were explicitly told that “no” responses should be given to both nonsense sentences and unnatural sentences. Thus, the participants were conducting two judgment tasks at the same time. The assignment of the “yes” or “no” response to the left or right button was counter-balanced between participants. Participants accepted a practice block of 15 sentences before they were tested for the formal experiment. The entire session, including electrode application and removal, lasted about 2 h.

EEG recordings

EEGs were recorded using AC amplifiers (Neuroscan). An elastic cap (Electrocap International), equipped with 62 electrodes according to the International 10–20 system, was fixed to the participant's scalp. The electrodes were localized at the following positions: AF7, AF3, FP1, FP2, AF4, AF8, F7, F5, F3, F1, Fz, F2, F4, F6, F8, FT7, FC5, FC3, FC1, FCz, FC2, FC4, FC6, FT8, T7, C5, C3, C1, Cz, C2, C4, C6, T8, TP7, CP5, CP3, CP1, CPz, CP2, CP4, CP6, TP8, P7, P5, P3, P1, Pz, P2, P4, P6, P8, PO7, PO5, PO3, POz, PO4, PO6, PO8, O1, Oz and O2. EEGs on these electrodes were referenced online to the left mastoid and were rereferenced offline to the mean of the left and right mastoids. In order to detect horizontal eye movements and blinks, the vertical electrooculogram (VEOG) was monitored from electrodes located above and below the left eye and the horizontal EOG (HEOG) from electrodes located at the outer canthus of each eye. Electrode impedances were kept below 5 k Ω . The biosignals were amplified with a band pass from .05 to 70 Hz and digitized online at 500 Hz.

EEG analysis

ERPs were computed for each participant over an epoch from 200 ms before to 1000 ms after the onset of the critical segment, with the EEG activity in the 0- to 100-ms post-onset of the segment for baseline correction. Baseline correction with the EEG activity in the –200- to 0-ms post-onset of the segment was also performed and the same pattern of effects was obtained. The ERP responses and the statistic analyses reported in this experiment were based on the EEG data with a baseline correction of 0- to 100-ms post-onset of the segment. Epochs contaminated by blinks and other eye movement artifacts were excluded from averaging by the criterion of 70 μ V.

For EEG averaging, only trials with correct responses and without artifacts were included. On average, 31 trials in the SEM+RHY+, 30 trials in the SEM+RHY–, 33 trials in the SEM–RHY+ and 33 trials in the SEM–RHY– conditions were included in the statistical analyses, with at least 24 trials in each condition for each participant. Based on visual inspection of ERP waveforms and the time windows of potential effects, ERPs in the 200–300, 300–400, 400–600, 600–700 and 700–850 ms time windows were selected for statistical analyses. Repeated-measures ANOVA were performed separately for the midline and the lateral sites with respect to Sentence Type (two factors: SEM and RHY, each having two levels). For the midline analysis, the additional factor was Electrode, which had 6 levels: Fz, FCz, Cz, CPz, Pz and Oz. For the lateral analysis, the additional factors were Hemisphere (left and right) and Region (frontal, fronto-central, central, centro-parietal, parietal and occipital). Thus, lateral electrodes were organized into 12 regions of interest (ROIs), each having two or three representative electrodes: left frontal (F1, F3, F5), left fronto-

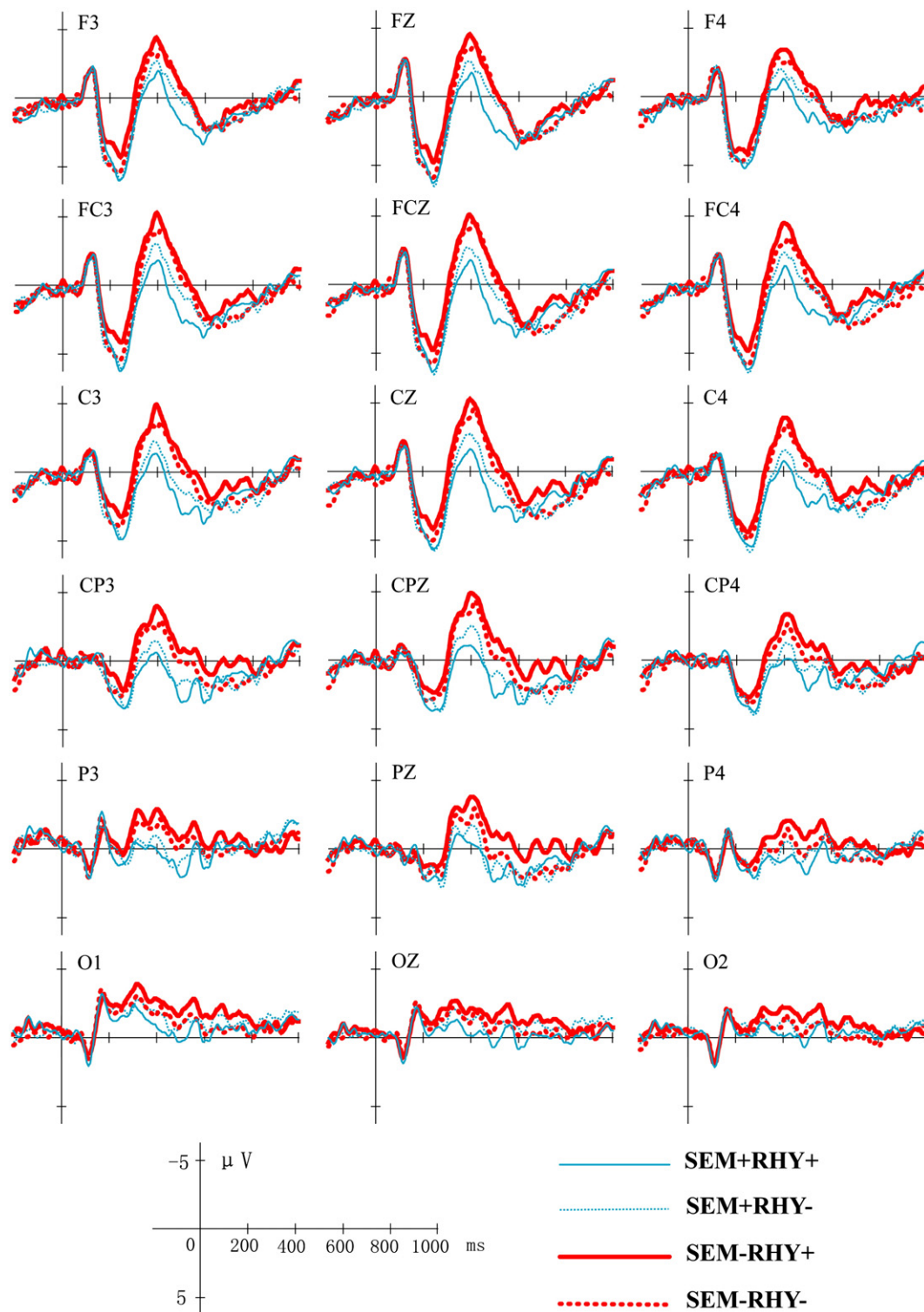


Fig. 1. Grand average ERP waveforms on 18 exemplar electrodes in [Experiment 1](#), epoched from -200 to 1000 ms after the onset of the critical verb–noun combination and baseline corrected by using the EEG activity in the 100 ms interval post-onset of the combination. SEM+ RHY+, semantically congruent with the normal $[1 + 1]$ rhythmic pattern; SEM+ RHY-, semantically congruent with the abnormal $[2 + 1]$ rhythmic pattern; SEM-RHY+, semantically incongruent with the normal $[1 + 1]$ rhythmic pattern; SEM-RHY-: semantically incongruent with the abnormal $[2 + 1]$ rhythmic pattern.

central (FC1, FC3, FC5), left central (C1, C3, C5), left centro-parietal (CP1, CP3, CP5), left parietal (P1, P3, P5), left occipital (PO3, O1), right frontal (F2, F4, F6), right fronto-central (FC2, FC4, FC6), right central (C2, C4, C6), right centro-parietal (CP2, CP4, CP6), right parietal (P2, P4, P6) and right occipital (O2, PO4). Averaged ERPs over electrodes in each ROI were used for the statistical purpose. In cases in which the

sentences type interacted with topographical factors, separate analyses were computed for midline electrodes, hemispheres or regions, respectively. All p values in statistical analyses were adjusted with the Greenhouse–Geisser correction for nonsphericity when necessary or with Bonferroni correction for multiple comparisons when appropriate.

Results

Behavioral data

The “yes” responses to sentences in the SEM+RHY+ condition and “no” responses to sentences in the other three conditions (SEM+RHY−, SEM−RHY+, SEM−RHY−) were counted as accurate responses. Participants showed on average an accuracy rate of 93.1% for the SEM+RHY+ condition (mean trials=33.5, SD=2.63), 91.3% for the SEM+RHY− condition (mean trials=32.9, SD=2.80), 99.0% for the SEM−RHY+ condition (mean trials=35.7, SD=0.62) and 98.3% for the SEM−RHY− condition (mean trials=35.4, SD=0.89). ANOVA with semantic congruency and rhythmic pattern as two within-participant factors revealed a significant main effect of congruency, $F(1,15)=29.06$, $p<0.001$, but no main effect of rhythmic pattern nor the interaction between rhythmic pattern and semantic congruency, $F_s<1$. This indicates that participants made more errors in responding to semantically congruent sentences than to incongruent sentences. Overall, the participants responded correctly (over 90%) to trials of the 4 conditions, suggesting that the participants understood the task and could conduct the semantic and the naturalness judgment tasks at the same time, ruling out the possibility that the participants attended only to the semantic congruency or rhythmic pattern.

ERP data

ERPs time-locked to the critical verb–noun combination onset are provided in Fig. 1. It is clear that conditions differed in a wide range of time windows, starting at 200 ms and lasting until 850 ms post-onset.

In the 200- to 300-ms time window, a significant main effect of semantic congruency was found in the midline analysis ($0.86 \mu\text{V}$), $F(1,15)=5.91$, $p<0.05$, and in the lateral analysis ($0.81 \mu\text{V}$), $F(1,15)=6.25$, $p<0.05$, with the critical segments in semantically incongruent sentences elicited less positive-going responses than the critical segments in semantically congruent sentences. The interaction between semantic congruency and Electrode was significant in the midline analysis, $F(5,75)=3.71$, $p<0.05$, so was the interaction between Semantic Congruency and Region in the lateral analysis, $F(5,75)=4.05$, $p<0.05$. Further comparisons showed that the semantic congruency effect was significant on Fz, FCz, Cz and CPz in the midline and in the frontal, fronto-central, central, centro-parietal regions,

$ps<0.05$, with the largest effect appeared on Cz ($-1.12 \mu\text{V}$) and in the central regions ($-1.04 \mu\text{V}$).

It is clear from visual inspection that the four conditions differed in the N400 time window, but with differences appearing mostly in a later stage. Therefore, we carried out the analysis of the N400 effects separately, in two smaller windows (i.e. 300–400 and 400–600 ms). In the 300- to 400-ms time window, semantically incongruent sentences was found to elicit larger negativities than semantically congruent sentences in the midline analysis ($-1.64 \mu\text{V}$), $F(1,15)=18.00$, $p<0.01$, and in the lateral analysis ($-1.51 \mu\text{V}$), $F(1,15)=17.80$, $p<0.01$. This effect interacted significantly with Electrode, $F(5,75)=6.27$, $p<0.01$, and marginally with Region, $F(5,75)=3.80$, $p=0.056$. Importantly, this effect interacted with rhythmic pattern in both the midline and lateral analysis, $F(1,15)=5.20$, $p<0.05$, and $F(1,15)=5.29$, $p<0.05$, respectively, although the main effect of rhythmic pattern was not significant, $F(1,15)<1$. The semantic congruency effect was larger when sentences had the normal rhythmic pattern ($-2.33 \mu\text{V}$ for the midline and $-2.13 \mu\text{V}$ for the lateral) than when sentences had the abnormal rhythmic pattern ($-0.94 \mu\text{V}$ for the midline and $-0.89 \mu\text{V}$ for the lateral). Detailed analysis showed that the semantic congruency effect for sentences with the normal rhythmic pattern appeared over the whole scalp (all $ps<0.05$), with its maximum on Cz and in the central regions. However, the semantic congruency effect for sentences with abnormal rhythmic patterns was restricted mainly to FCz, Cz, CPz and Pz in the midline and to the frontal–central, central, central–parietal and parietal regions ($ps<0.05$). On the other hand, ERP responses to the abnormal rhythmic pattern were *more positive* (by $0.75 \mu\text{V}$) in the lateral analysis than to the normal rhythmic pattern when sentences were semantically incongruent, $F(1,15)=4.36$, $p=0.054$. When sentences were semantically congruent, however, there was no differences between ERP responses to the abnormal and those to the normal rhythmic patterns in either the midline analysis, $F(1,15)=1.42$, $p>0.1$, or the lateral analysis, $F(1,15)=1.18$, $p>0.1$ (see left, upper panels of Fig. 2).

In the 400- to 600-ms time window, the main effect of semantic congruency was highly significant in the midline analysis ($-1.85 \mu\text{V}$), $F(1,15)=28.50$, $p<0.001$, and in the lateral analysis ($-1.62 \mu\text{V}$), $F(1,15)=27.44$, $p<0.001$, with more negative ERP responses to semantically incongruent sentences than to semantically congruent sentences. This negativity effect was broadly distributed over the scalp

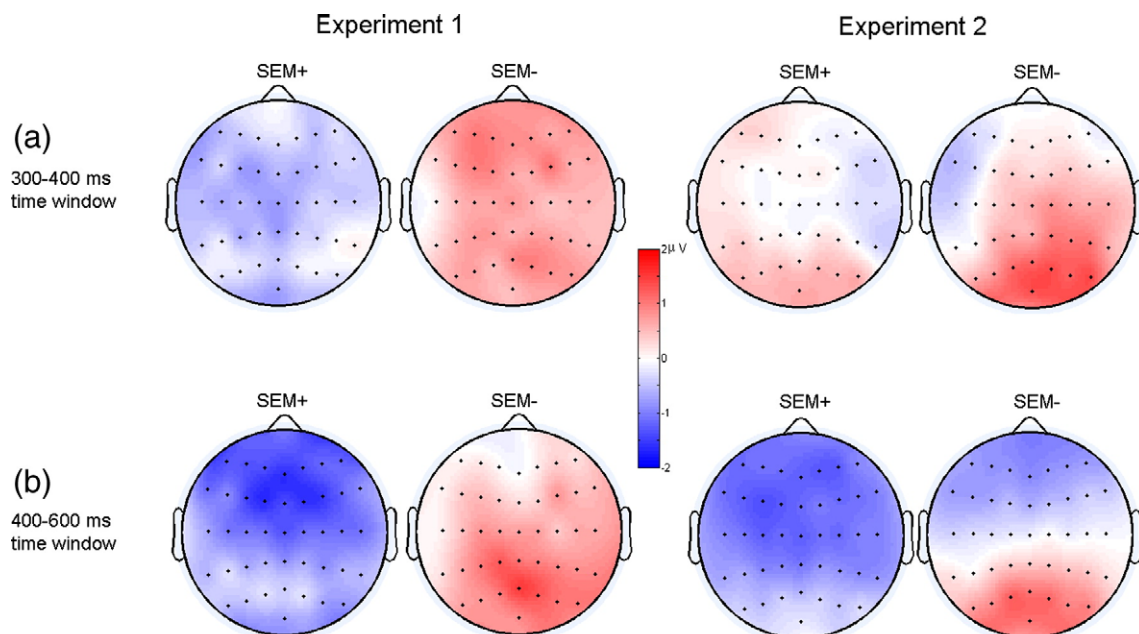


Fig. 2. Topographic distributions of the mean differences between sentences with the abnormal rhythmic and sentences with normal pattern as a function of semantic congruency between the verb and the noun in Experiments 1 and 2, respectively: (a) effects in the 300- to 400-ms time window and (b) effects in the 400- to 600-ms time window.

and reached maximum on Cz ($-2.28 \mu\text{V}$) and in the central region ($-2.10 \mu\text{V}$), as it interacted with Electrode in the midline, $F(5,75) = 6.66$, $p < 0.01$, and with Region in the lateral, $F(5,75) = 4.45$, $p < 0.05$. On the other hand, the rhythmic pattern showed no main effect in either the midline or the lateral analysis, $F_s < 1$, although the interaction between rhythmic pattern and Electrode was significant, $F(5,75) = 5.30$, $p < 0.01$, so the interaction between rhythmic pattern and Region, $F(5,75) = 3.91$, $p < 0.05$.

Importantly, the interaction between rhythmic pattern and semantic congruency was significant, $F(1,15) = 9.90$, $p < 0.01$ for the midline, and $F(1,15) = 9.83$, $p < 0.01$ for the lateral, although the three-way interaction between rhythmic pattern, semantic congruency and Electrode/Region was not, $F_s < 1$. It is clear, however, from the left, lower panels of Fig. 2 that the effect of rhythmic pattern had different manifestations over scalp locations in semantically congruent and incongruent sentences. Further analyses showed that, in semantically congruent sentences, the abnormal rhythmic pattern elicited larger negativities than the normal pattern on Fz ($-1.62 \mu\text{V}$), FCz ($-1.37 \mu\text{V}$) and Cz ($-1.33 \mu\text{V}$) and in the frontal ($-1.26 \mu\text{V}$), frontal-central ($-1.38 \mu\text{V}$) and central ($-1.09 \mu\text{V}$) regions, $p_s < 0.05$. In semantically incongruent sentences, however, the abnormal rhythmic pattern elicited *more positive* responses than the normal pattern on Pz ($1.48 \mu\text{V}$) and Oz ($0.68 \mu\text{V}$) for the midline and in the central-parietal ($0.97 \mu\text{V}$), parietal ($0.97 \mu\text{V}$) and occipital ($0.90 \mu\text{V}$) regions, $p_s < 0.05$. This effect was the continuation of an earlier positivity effect in the 300- to 400-ms time window.

On the other hand, the semantic congruency effect was significant both when sentences had the normal rhythmic pattern ($-2.72 \mu\text{V}$ for the midline and $-2.43 \mu\text{V}$ for the lateral), $F(1,15) = 27.40$, $p < 0.001$ for the midline and $F(1,15) = 24.70$, $p < 0.001$ for the lateral, and when sentences had the abnormal rhythmic pattern ($-0.98 \mu\text{V}$ for the midline and $-0.82 \mu\text{V}$ for the lateral), $F(1,15) = 7.88$, $p < 0.05$ for the midline and $F(1,15) = 7.79$, $p < 0.05$, with the effect in sentences with normal rhythmic pattern being larger than that in sentences with abnormal rhythmic pattern as suggested by the interaction between semantic congruency and the rhythmic pattern.

No significant effects were observed in the 600- to 700-ms time window. However, in the 700- to 850-ms time window, there was a significant main effect of rhythmic pattern in the midline analysis ($0.81 \mu\text{V}$), $F(1,15) = 4.60$, $p < 0.05$, and a marginally significant main effect in the lateral analysis ($0.63 \mu\text{V}$), $F(1,15) = 3.68$, $p = 0.07$. The abnormal rhythmic pattern elicited more positive ERP responses than the normal pattern, showing a late positivity effect. No other effects or interactions were found in this time window.

Discussion

Not surprisingly, semantic incongruence between the critical verb and noun elicited a negativity (N400) effect in the 200- to 600-ms time window with its maximum at the central regions. Importantly, compared with the normal rhythmic pattern (i.e., the [1 + 1] pattern), the abnormal pattern (i.e., the [2 + 1] pattern) elicited a frontal-to-centrally distributed negativity in the 400- to 600-ms time window, but only when the verb–noun combinations were semantically congruent. When the verb–noun combinations were semantically incongruent, however, the ERP responses to the abnormal pattern were *more positive* than the responses to the normal pattern in posterior areas in the 300- to 600-ms time window. In addition, for both semantically congruent and incongruent verb–noun combinations, the abnormal rhythmic pattern elicited a larger positivity effect in the 700- to 850-ms time window. These findings suggest that information concerning rhythmic pattern is activated in silent sentence reading and this activation interacts with the semantic integration process for the verb and its object noun.

Our finding of an N400 effect occurring between 200 and 600 ms post-onset for semantic incongruence between the verb and the noun in Chinese sentence comprehension is consistent with previous

studies (e.g., Jiang et al., 2009; Li et al., 2006; Ye et al., 2007). In the present experiment, the violation of selectional restrictions between the verb and the noun elicited an even earlier effect in the 200- to 300-ms time window (i.e., on the P2 component). This effect appeared independently of the rhythmic pattern, suggesting that the selection-based semantic process may occur earlier than the prosody-based process in silent reading.

The more interesting finding in this experiment was that the violation of rhythmic constraints between the verb and the noun elicited a frontal-to-centrally distributed N400-like effect in the 400- to 600-ms window, although this effect appeared only when sentences were semantically acceptable (see Fig. 2). A similar N400-like effect was reported for prosodic violations in spoken sentences involving intonation mistakenly signaling the constituent position of the critical word in a sentence (Eckstein and Friederici, 2005, 2006) or involving incorrect syllabic lengthening of the critical word (Magne et al., 2007). It has been suggested that the N400-like effect was due to the mismatch between acoustic input and the underlying phonological representation. This mismatch impaired semantic access of the word and/or its integration with the prior context (Eckstein and Friederici, 2006; Magne et al., 2007).

Although there was no acoustic input in the present sentence reading task, phonological information of the visually present words could nevertheless be activated automatically (Zhou and Marslen-Wilson, 1999, 2000) and the rhythmic pattern computed on the basis of phonological activation of individual words could be consistent or inconsistent with the stored knowledge concerning canonical rhythmic pattern of the verb–noun combination. A mismatch with the knowledge would immediately increase the difficulty in accessing semantic representation of the current word and/or in semantically integrating the verb and the noun, resulting in the N400-like effect in ERPs and the slightly lower semantic acceptability rating for the SEM+RHY– sentences as compared with the SEM+RHY+ sentences.

This prosody-based N400-like effect was absent for the SEM–RHY– sentences as compared with the SEM–RHY+ sentences. Instead, the combination of an abnormal rhythmic pattern with semantic incongruence produced a *more positive* ERP response in the posterior regions in the 300- to 600-ms time window (see Fig. 2). These findings suggest a relatively early interaction between the semantic integration process based on selectional restrictions and the processing of rhythmic information in sentence reading. There could be two possible accounts for the positivity effect for the abnormal rhythmic pattern found. One account assumes that when sentences are semantically incongruent, the abnormal rhythmic pattern may consume more processing resources and weaken the semantic integration process between the verb and the noun, leading to reduced N400 responses in the 300- to 600-ms time window. The positivity effect is thus due to *less negative* responses to the semantically incongruent sentences with the abnormal rhythmic pattern. The alternative account suggests that the abnormal rhythmic pattern elicits two different effects in the 300- to 600-ms time window. The first effect is the fronto-to-centrally distributed negativity and the second effect is the parieto-to-occipitally distributed positivity. The negativity effect elicited by the abnormal rhythmic pattern is more evident in semantically congruent sentences while the positivity effect elicited by the abnormal rhythmic pattern is more evident in semantically incongruent sentences. When sentences are semantically congruent, an abnormal rhythmic pattern would hinder the semantic integration process as suggested above, resulting in the N400-like effect. When sentences are semantically incongruent, it may be easier for the reader to perform the judgment task, as demonstrated by the higher accuracy as compared with semantically congruent sentences. More attentional resources could be spent on the anomalous rhythmic pattern of the verb and the noun, resulting in more positive-going ERP responses (such as P300; cf. Kok, 2001).

The appearance of a late positivity effect in the 700- to 850-ms time window, for the abnormal rhythmic pattern in sentences with or without semantic incongruence, demonstrates that a late process may take place after the detection of the violation of rhythmic constraints and its impact upon semantic integration. The late positivity effect, referred to as either P800 or P600, has been observed in a number of studies for prosodic information processing in spoken sentence comprehension. For instance, a left-lateralized P800 was found for the violation of intonation pattern of interrogative and declarative sentences (Astésano et al., 2004); a broadly distributed P600 was found for sentence-final words intoned as continuation (Eckstein and Friederici, 2005); a broadly distributed P800 was found for French trisyllabic words lengthened mistakenly on the second syllables (Magne et al., 2007). This late positivity effect may reflect a prosodic reanalysis/repair process in which the difficulty arising from the violation of prosodic constraints is to be resolved.

Experiment 2

Experiment 1 presented the critical verb and noun as one segment and measured ERP responses to the segment. The segment with the abnormal [2 + 1] rhythmic pattern was longer in terms of the number of syllables involved than the corresponding [1 + 1] pattern. Although we did not believe that this difference in word length could account for the ERP effects we observed in Experiment 1, it was nevertheless important to examine whether the same pattern of effects would be observed when the verb and the noun were presented separately.

Method

Participants

Eighteen right-handed students from Peking University participated in the experiment. They were native speakers of Mandarin Chinese and were not tested for Experiment 1. Two male participants were excluded due to excessive artifacts, leaving us with 16 participants (8 females). Their mean age was 22 (with a range of 19 to 26) years. They had normal or corrected-to-normal vision and had no history of neurological, psychiatric or cognitive disorders.

Material, procedures and EEG analysis

The same sentences and procedures employed in Experiment 1 were used here, except that the verb and the noun of the critical verb–noun combinations were presented separately as two segments. Two epochs were extracted from each sentence for ERP data analysis. The first epoch ranged from 200 ms before to 800 ms after the onset of the critical verb. Trials from the SEM+RHY+ and the SEM–RHY+ conditions were combined to form ERP responses to the monosyllabic verbs and trials from the SEM+RHY– and the SEM–RHY– conditions were combined to form ERP responses to the disyllabic verbs. A comparison between them would allow us to see whether word length played a role in modulating ERP responses to verbs and to the one-segment presentations in Experiment 1. The second epoch ranged from 200 ms before to 1000 ms after the onset of the critical noun. For the first epoch, the EEG activity in the –200- to 0-ms post-onset of the verb was selected for baseline correction. For the second epoch, the EEG activity in the 0- to 100-ms post-onset of the noun was used for baseline correction, given that the same set of nouns was preceded by different verbs in different conditions. For EEG averaging, only trials with correct responses and without artifacts were included. On average, 30 trials in the SEM+RHY+, 30 trials in the SEM+RHY–, 32 trials in the SEM–RHY+ and 33 trials in the SEM–RHY– conditions were included, with at least 24 trials in each condition for each participant.

Results

Behavioral data

Participants showed on average an accuracy rate of 91.1% for the SEM+RHY+ condition (mean trials = 32.8, SD = 1.47), 90.1% for the SEM+RHY– condition (mean trials = 32.4, SD = 2.80), 99.0% for the SEM–RHY+ condition (mean trials = 35.6, SD = 0.72) and 98.6% for the SEM–RHY– condition (mean trials = 35.5, SD = 0.97). ANOVA with semantic congruency and rhythmic pattern as two within-participant factors revealed a significant main effect of semantic congruency, $F(1,15) = 48.23$, $p < 0.001$. No other effects reached significance. Thus, the same pattern of behavioral responses as that in Experiment 1 was obtained here.

ERP data

ERPs time-locked to the critical nouns are given in Fig. 3.

In the 200- to 300-ms time window, ANOVA with semantic congruency, rhythmic pattern and topographic factors found a significant main effect of semantic congruency in the midline analysis ($-0.61 \mu\text{V}$), $F(1,15) = 5.54$, $p < 0.05$ and in the lateral analysis ($-0.60 \mu\text{V}$), $F(1,15) = 7.46$, $p < 0.05$. ERP responses to nouns were more negative in the incongruent conditions than in the congruent conditions. No other significant effects were observed.

In the 300- to 400-ms time window, there was a main effect of semantic incongruence in the midline analysis ($-2.48 \mu\text{V}$), $F(1,15) = 23.78$, $p < 0.001$, and in the lateral analysis ($-2.13 \mu\text{V}$), $F(1,15) = 24.04$, $p < 0.001$. ERPs in the semantic incongruent conditions were more negative than in the congruent conditions. The interaction between semantic congruency and Electrode reached significance in the midline analysis, $F(5,75) = 12.18$, $p < 0.001$, so did the interaction between semantic congruency and Region in the lateral analysis, $F(5,75) = 6.31$, $p < 0.01$. Further tests showed a broadly distributed negativity effect for semantic congruency over electrodes and regions (all $ps < 0.05$) with its maximum on Cz ($-3.40 \mu\text{V}$) and in the central–parietal region ($-2.68 \mu\text{V}$). Neither the main effect of rhythmic pattern nor the interaction between rhythmic pattern and semantic congruency reached significance, $p > 0.1$. However, the interaction between rhythmic pattern and Region was significant in the lateral analysis, $F(1,15) = 4.42$, $p < 0.05$. The violation of rhythmic constraints elicited, as in Experiment 1, more positive-going responses in the parietal ($0.82 \mu\text{V}$), $F(1,15) = 6.34$, $p < 0.05$, and the occipital regions ($0.78 \mu\text{V}$), $F(1,15) = 11.15$, $p < 0.01$. This effect appeared to be larger in semantically incongruent sentences ($1.07 \mu\text{V}$ in the parietal and $0.97 \mu\text{V}$ in the occipital regions) than in semantically congruent sentences ($0.36 \mu\text{V}$ in the parietal and $0.38 \mu\text{V}$ in the occipital regions; see the right, upper panels of Fig. 2), although the interaction between rhythmic pattern and semantic congruency did not reach significance, $ps > 0.1$.

In the 400- to 600-ms time window, there was an N400 effect for semantic incongruent sentences both in the midline analysis ($-1.08 \mu\text{V}$), $F(1,15) = 7.77$, $p < 0.05$, and in the lateral analysis ($-1.05 \mu\text{V}$), $F(1,15) = 12.14$, $p < 0.01$. Although there was no main effect of rhythmic pattern, the interaction between rhythmic pattern and Electrode reached significance in the midline analysis, $F(5,75) = 13.94$, $p < 0.001$, so the interaction between rhythmic pattern and Region in the lateral analysis, $F(5,75) = 32.18$, $p < 0.001$. Moreover, the interaction between semantic congruency and rhythmic pattern was significant in the lateral analysis, $F(1,15) = 4.73$, $p < 0.05$, and marginally significant in the midline analysis, $F(1,15) = 3.19$, $p = 0.095$. Detailed analyses showed that, in semantically congruent sentences, the abnormal rhythmic pattern elicited more negative responses than the normal rhythmic pattern on Fz, FCz, Cz and CPz and in the frontal, frontal–central, central and central–parietal regions, $ps < 0.05$. Thus, the N400 effect for the rhythmic pattern was mainly distributed over frontal-to-central scalp areas (see the right, lower panels of Fig. 2). In semantically incongruent sentences,

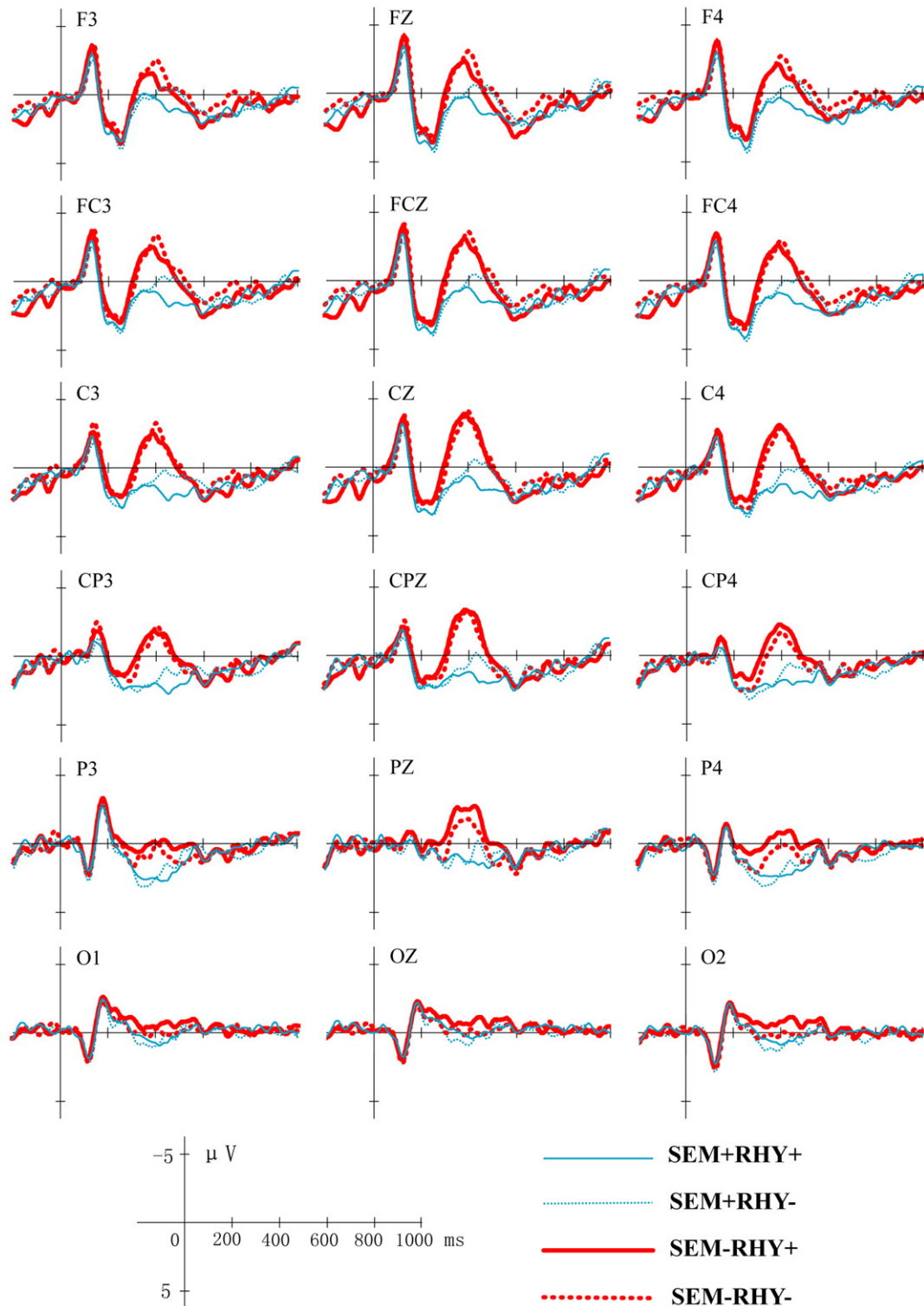


Fig. 3. Grand average ERP waveforms for the critical nouns on 18 exemplar electrodes in Experiment 2, epoched from -200 to 1000 ms after the onset of the nouns and baseline corrected by using the EEG activity in the 100 ms interval post-onset of the nouns. SEM+ RHY+, semantically congruent with the normal $[1 + 1]$ rhythmic pattern; SEM+ RHY-, semantically congruent with the abnormal $[2 + 1]$ rhythmic pattern; SEM-RHY+, semantically incongruent with the normal $[1 + 1]$ rhythmic pattern; SEM-RHY-: semantically incongruent with the abnormal $[2 + 1]$ rhythmic pattern.

however, the abnormal rhythmic pattern elicited *more positive* responses than the normal pattern on Pz ($1.02 \mu\text{V}$) and Oz ($0.65 \mu\text{V}$) for the midline and in the parietal ($0.94 \mu\text{V}$) and occipital ($0.87 \mu\text{V}$) regions, $p < 0.05$. This was consistent with the finding in the earlier 300- to 400-ms time window. On the other hand, the N400 effect for

semantic congruency ($-1.54 \mu\text{V}$ for the midline and $-1.52 \mu\text{V}$ for the lateral) was significant when sentences had the normal rhythmic pattern, $F(1,15) = 10.37$, $p < 0.01$ for the midline and $F(1,15) = 15.55$, $p = 0.01$ for the lateral, with its maximum on CPz ($-2.26 \mu\text{V}$) and the central-parietal region ($-1.91 \mu\text{V}$). When sentences had the

abnormal rhythmic pattern, however, the semantic congruency effect ($-0.61 \mu\text{V}$ for the midline and $-0.59 \mu\text{V}$ for the lateral) did not reach significance, $ps > 0.1$.

In the 600- to 700-ms time window, the main effect of neither semantic congruency nor rhythmic pattern was significant, nor the interaction between them, $F_s < 1$. However, the interactions between rhythmic pattern and Electrode and between rhythmic pattern and Region were significant, $F(5,75) = 4.56$, $p < 0.05$ for the midline, and

$F(5,75) = 9.35$, $p = 0.001$ for the lateral. Further analyses showed that the abnormal rhythmic pattern elicited more negative responses than the normal rhythmic pattern in the frontal ($-0.50 \mu\text{V}$) and fronto-central ($-0.55 \mu\text{V}$) regions ($ps < 0.05$) and on Fz ($-0.57 \mu\text{V}$; $p = 0.053$).

In the 700- to 850-ms time window, there was no significant main effect of either semantic congruency or rhythmic pattern. However, the interaction between semantic congruency and rhythmic

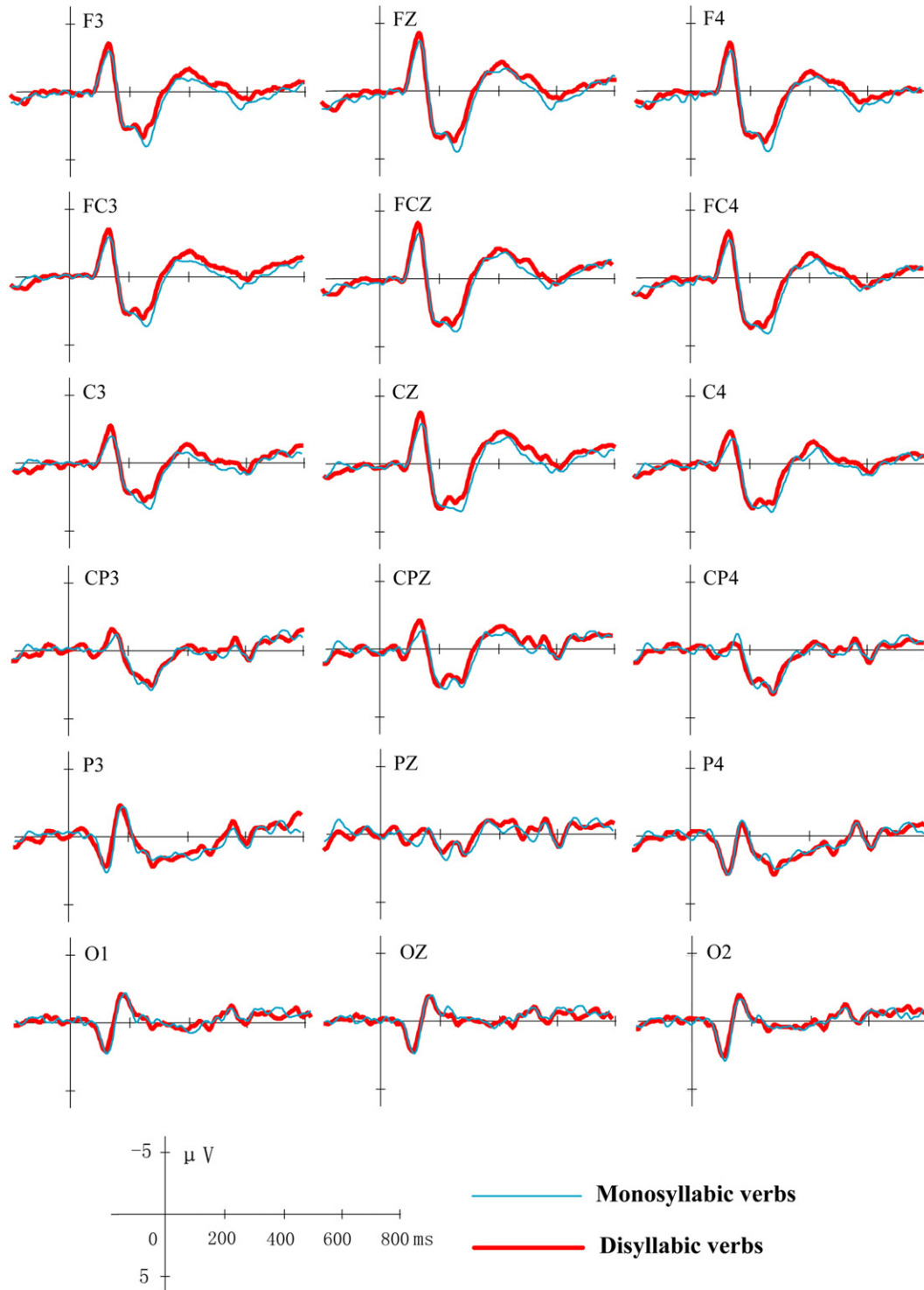


Fig. 4. Grand average ERP waveforms for the critical verbs on 18 exemplar electrodes in Experiment 2, epoched from -200 to 800 ms after the onset of the verbs and baseline corrected by using the EEG activity in the 200 ms interval pre-onset of the verbs. The same set of monosyllabic verbs in the SEM+RHY+ and the SEM-RHY+ conditions were combined, so the same set of disyllabic verbs in the SEM+RHY- and the SEM-RHY- conditions.

pattern reached significance, $F(1,15) = 5.05$, $p < 0.05$ for the midline and $F(1,15) = 6.16$, $p < 0.05$ for the lateral. Further analyses showed that when sentences were semantically congruent, the abnormal rhythmic pattern in the SEM+RHY– condition elicited a larger positivity as compared with the SEM+RHY+ condition on the midline electrodes ($0.51 \mu\text{V}$), $F(1,15) = 4.42$, $p = 0.05$, and on the lateral electrodes ($0.54 \mu\text{V}$), $F(1,15) = 6.99$, $p < 0.05$. In contrast, when sentences were semantically incongruent, no significant difference was found between the SEM–RHY– and the SEM–RHY+ conditions, $p > 0.1$.

ERPs time-locked to the critical verbs are displayed in Fig. 4. It is clear that there was no remarkable difference between the monosyllabic and disyllabic verbs, indicating that word length had no apparent effect on ERP responses to verbs. Statistical analyses confirmed this observation, with no significant difference between the two types of verbs over different time windows, either small (consecutive 100 ms time windows) or large (the 300–600, 350–600, 400–600 or 700–850 ms time window; all $ps > 0.1$).

Omnibus analysis across Experiments 1 and 2

To compare directly the results between Experiments 1 and 2, we conducted an omnibus ANOVA across the two experiments, with semantic congruency, rhythmic pattern and topographical factors as within-participant factors and with Experiment as a between-participant factor. As can be seen in Table 3, over different time windows, Experiment as a factor did not, in general, interact with other factors, suggesting that the presentation mode has no impact upon the ERP responses to experimental manipulations. In the following paragraphs, we report the main findings from the omnibus analyses concerning the processing of rhythmic patterns.

In the 200- to 300-ms time window, there was no significant effect of rhythmic pattern but a main effect of semantic congruency, $F(1,30) = 11.23$, $p < 0.01$ for the midline and $F(1,30) = 13.00$, $p = 0.001$ for the lateral, indicating that the processing system is more sensitive to semantic congruency than to rhythmic pattern in the early phase. In the 300- to 400-ms time window, although there was no main effect of rhythmic pattern, $ps > 0.1$, it nevertheless interacted with semantic congruency, $F(5,150) = 4.62$, $p < 0.05$ for the midline and $F(5,150) = 4.84$, $p < 0.05$ for the lateral. Further analyses showed that the ERP responses elicited by the abnormal rhythmic pattern were more positive as compared with the responses elicited by the normal rhythmic pattern in semantically incongruent sentences, $F(1,30) = 4.53$, $p < 0.05$ for the midline and $F(1,30) = 5.95$, $p < 0.05$ for the lateral, but not in

semantically congruent sentences, $F_s < 1$. In the 400- to 600-ms time window, although the main effect of rhythmic pattern continued to be non-significant, $ps > 0.1$, it interacted with semantic congruency, $F(5,150) = 12.36$, $p < 0.001$ for the midline and $F(5,150) = 14.45$, $p < 0.001$ for the lateral, and with Electrode/Region, $F(5,150) = 15.37$, $p < 0.001$ for the midline and $F(5,150) = 19.90$, $p < 0.001$ for the lateral. Further analyses showed when sentences were semantically congruent, the abnormal rhythmic pattern elicited a *negativity effect* in the frontal and fronto-central regions, $ps < 0.01$; when sentences were semantically incongruent, the abnormal rhythmic pattern elicited instead a *positivity effect* in parieto-occipital regions, $ps < 0.01$.

In the 600- to 700-ms time window, an interaction between rhythmic pattern and Electrode/Region was found, $F(5,150) = 3.35$, $p < 0.05$ for the midline and $F(5,150) = 3.90$, $p < 0.05$ for the lateral. However, unlike the interaction found in Experiment 2, here the interaction indicated a centro-parietally distributed positivity effect elicited by the abnormal rhythmic pattern, $ps < 0.05$. This effect was very likely to be the precursor of the late positivity effect found in the 700- to 850-ms time window, in which a marginally significant main effect of rhythmic pattern was observed, $F(1,30) = 4.11$, $p = 0.052$ for the midline and $F(1,30) = 4.06$, $p = 0.053$ for the lateral. Thus, across the experiments, the abnormal rhythmic pattern elicited a late positivity effect, possibly starting from 600 ms post-onset, although this effect was more reliable for semantically congruent than for incongruent sentences (see Table 3).

Discussion

Findings in this experiment were very similar to those in Experiment 1. The semantic incongruence between the verb and the noun elicited the typical semantic N400 effect, which started very early and lasted a relatively long time, in the 200- to 600-ms time window. Importantly, the abnormal rhythmic pattern elicited a positivity effect in the posterior regions in the 300- to 400-ms time window, a fronto-centrally distributed N400-like effect in the 400- to 700-ms time window and a late positivity effect on the noun in semantically congruent sentences. In contrast, for semantically incongruent sentences, this abnormal rhythmic pattern elicited more positive-going ERP responses in the posterior regions in the 300- to 600-ms time window and more negative responses in the frontal regions in the 600- to 700-ms time window. Furthermore, the omnibus analysis across the two experiments revealed that the presentation mode in general had no significant impact upon the patterns of ERP

Table 3
Statistical results (p values) of the Experiment 1, Experiment 2 and of the omnibus analysis across the two experiments.

Factor	<i>df</i>	200–300 ms		300–400 ms		400–600 ms		600–700 ms		700–850 ms		
		Midline	Lateral	Midline	Lateral	Midline	Lateral	Midline	Lateral	Midline	Lateral	
SEM	Experiment 1	1,15	<0.05	<0.05	<0.001	<0.001	<0.001	<0.001				
	Experiment 2	1,15	<0.05	<0.05	<0.001	<0.001	<0.05	<0.01				
	Global	1,30	<0.01	<0.001	<0.001	<0.001	<0.001	<0.001				
RHY	Experiment 1	1,15									<0.05	
	Experiment 2	1,15										
	Global	1,30									0.052	0.053
SEM * RHY	Experiment 1	1,15		<0.05	<0.05	<0.01	<0.01					
	Experiment 2	1,15					<0.05				<0.05	<0.05
	Global	1,30			<0.05	<0.05	<0.001	<0.001				
SEM * ELEC/REG	Experiment 1	5,75	<0.05	<0.05	<0.01	0.056	<0.01	<0.05				
	Experiment 2	5,75					0.053					
	Global	5,150	<0.05		<0.001	<0.001	<0.001	<0.01				
RHY * ELEC/REG	Experiment 1	5,75					<0.01	<0.05				
	Experiment 2	5,75				<0.05	<0.001	<0.001	<0.05	<0.001		
	Global	5,150					<0.001	<0.001	<0.05	<0.05		
RHY * ELEC/REG * EXP	Global	5,150	0.053	<0.05								

Note: *df*, degrees of freedom; SEM, semantic congruency; RHY, rhythmic pattern; ELEC, electrode; REG, region; EXP, experiment.

responses. Below we focus on the effects of abnormal rhythmic pattern on ERP responses.

The finding of an early posterior positivity effect in the 300- to 400-ms time window for the abnormal rhythmic pattern in semantically congruent sentences helps us to rule out one of the two possible accounts for the positivity effect discussed in [Experiment 1](#). This account assumes that the abnormal rhythmic pattern weakens the semantic integration process between the mismatching verb and noun, leading to the reduction of the N400 responses (i.e., the more positive-going responses) to the noun in the semantically incongruent sentences with the abnormal rhythmic pattern. If this assumption stands, we would expect to see *no* reduction of the negative responses in the corresponding time window to semantically congruent sentences with the abnormal rhythmic pattern. However, unlike [Experiment 1](#), we did observe the positivity effect for semantically congruent sentences, although this effect was relatively weak. On the other hand, the alternative account assumes that the abnormal rhythmic pattern would attract attentional resources and initiate an anomaly detection process, which would engender positive ERP responses. This detection process may take place for both semantically congruent and incongruent sentences, resulting in the positivity effect we observed, although this effect could be stronger for the incongruent sentences. We will return this point in [General discussion](#).

Unlike [Experiment 1](#), we observed a frontal negativity effect for semantically incongruent sentences with the abnormal rhythmic pattern in the 600- to 700-ms time window as compared with the semantically incongruent sentences with normal rhythmic pattern. We suggest that this negativity effect is functionally the same as the fronto-central N400-like effect in the 400- to 700-ms time window for semantically congruent sentences, reflecting the difficulty in the semantic integration process caused by the abnormal rhythmic pattern.

ERP responses to the monosyllabic and disyllabic verbs were statistically indistinguishable in this experiment. This finding allows us to rule out any alternative accounts based on word length for the ERP effects in [Experiment 1](#). Given that the monosyllabic and disyllabic verbs were synonyms and given that there was no processing difference between them, the differential ERP responses to the abnormal [2 + 1] verb–noun combination and to the canonical [1 + 1] combination must have come from the phrase level phonological (rhythmic) linkage between the verb and the noun.

General discussion

Two ERP experiments obtained convergent evidence for the online processing of rhythmic pattern during silent reading of Chinese sentences. Both the separate analyses for each experiment and the omnibus analyses across the two experiments found a negativity (N400) effect for semantic incongruent sentences, as compared with congruent sentences, in the 200- to 600-ms time window. More importantly, the analyses unfolded several effects for the abnormal rhythmic pattern: (1) a fronto-central negativity in the 400- to 600-ms time window, which was more pronounced for semantically congruent sentences than for semantically incongruent sentences; (2) a parieto-occipital positivity effect in the 300- to 600-ms time window, which was larger in semantically incongruent sentences than in congruent sentences; and (3) a late positivity effect in the 700- to 850-ms time window, which tended to be larger in semantically congruent sentences than in semantically incongruent sentences.

These three important findings highlight the impact of rhythmic pattern upon cognitive processes during Chinese sentence reading, with rhythmic information being initially analyzed at the phrasal level and being used to constrain semantic integration. Firstly, an unexpected, abnormal rhythmic pattern would impair the semantic process, resulting in an N400-like effect with a fronto-central

distribution. This effect was different from the semantic N400 in terms of scalp distribution, as the semantic N400 was found to have a wide distribution, with a maximum at the central area. The influence of prosodic information upon semantic processing has been shown in previous studies on spoken language processing ([Eckstein and Friederici, 2005, 2006](#); [Magne et al., 2007](#); [Mietz et al., 2008](#)). According to a model of auditory sentence processing ([Friederici, 2002](#)), the mismatch between the incoming information about prosodic structure and the stored knowledge about the prosodic properties of lexical candidates would affect the identification of the current word and increase integration costs. Similarly, when information concerning the prosodic structure of a phrase is obtained through another modality (e.g., visual modality in this study), the mismatch between the input and the stored knowledge would also cause difficulty in semantic access/integration. However, the extent to which the rhythmic constraint has on semantic process may depend on whether a normal semantic process is ongoing. For semantically congruent sentences, an abnormal rhythmic pattern would act upon the semantic integration process between the verb and the noun, leading to an increased negativity. This rhythmic constraint may function in a slower time course than the time course needed for the initiation of the meaning integration process. In contrast, in the case of the semantically incongruent sentences, since the semantic integration process has already encountered difficulty, the rhythmic constraint could not affect the semantic integration as much as it does in the case of the semantically congruent sentences, presumably because the system may simply assign the priority to the process of resolving the semantic mismatch between the verb and the noun. The semantic N400 effect has reached its maximum amplitude (i.e., a ceiling effect) and can hardly increase further in the presence of abnormal rhythmic pattern. However, when the semantic congruency effect dies down over time, the N400-like effect of the abnormal rhythmic pattern may manifest in a later time window (i.e., the 600- to 700-ms time window). However, it is not clear yet why we consistently observed the effect of rhythmic processing as modulated by semantic congruency during Chinese sentence reading while in the previous work the prosodic effect on the N400 component, elicited by incorrect syllabic lengthening, was not modulated by either semantic congruency or a change of experiment task during French spoken sentence comprehension ([Magne et al., 2007](#)).

Secondly, an early, posterior positivity effect for the abnormal rhythmic pattern may reflect the functioning of the P300 which responds to the detection of anomalous prosodic features. The positivity effect in the 300- to 600-ms time window is commonly recognized as P300, occurring in processing infrequent stimuli or novelty as a function of attentional demand ([Polich, 2007](#)). A study in spoken language manipulating the congruency of pitch contour in sentences also observed a similar positivity effect ([Schön et al., 2004](#)). This study artificially increased the F0 of the last word and the participants were asked to judge whether the pitch of the last word was congruent or incongruent with the context. An increased positivity between 200 and 850 ms, with a parieto-temporal scalp distribution, was found for incongruent pitch contour. This positivity effect was interpreted as reflecting the detection of pitch violations. In the present study, the early positivity (P300) effect and the N400-like effect elicited by the abnormal rhythmic pattern overlapped in time and possibly in scalp distribution. For semantically congruent sentences, the abnormal rhythmic pattern engendered a weak posterior positivity effect in the 300- to 400-ms time window (in [Experiment 2](#)). But this effect could have been overshadowed by the N400-like effect in the 400- to 600-ms time window (see [Fig. 2](#)). For semantically incongruent sentences, the abnormal rhythmic pattern engendered a positivity effect in both the 300–400 ms and the 400–600 ms time windows. It seems that the manifestation of the posterior positivity effect depends (partly) on the appearance of the N400-like effect for the abnormal rhythmic pattern.

Thirdly, the abnormal rhythmic pattern elicited also a late positivity, which can be taken as reflecting the reprocess/repair process after the processing system encounters difficulty in semantic access/integration. The reprocess/repair process could be overshadowed by other processes more related to semantic interpretation, as in the case of semantically incongruent sentences and the separate presentation of the verb and the noun (Experiment 2), although a proper task demand on prosodic processing could enhance the effect of the prosodic reprocess/repair process. This interpretation of the late positivity effect for prosodic violation (Astésano et al., 2004; Eckstein and Friederici, 2005) is along the same line as the interpretation of the syntactic P600 which is widely observed in sentences involving morphosyntactic violation (Hagoort et al., 1993; Osterhout & Holcomb, 1992). An alternative interpretation of the late positivity effect for prosodic processing would be that the rhythmic pattern is used to constrain an integrative process in which different types of information, syntactic, semantic and prosodic, are integrated to construct a coherent sentential representation (Eckstein and Friederici, 2005; Magne et al., 2007). Although the two accounts are generally undistinguished in many previous discussions, they nevertheless have different implications. For example, while the latter account assumes a general process that is conducted at a late stage of sentence processing, the former assumes a process that arises only when violation of a prosodic constraint is detected. Since the late positivity for the violation of prosodic constraints has been observed on critical words that are at the sentence-final position (Astésano et al., 2004; Eckstein and Friederici, 2005, Magne et al., 2007) but not at a sentence-medial position (Eckstein and Friederici, 2005; 2006) and is more likely to be elicited when prosodic information is relevant to the current task (Astésano et al., 2004; Magne et al., 2007), we may conclude that the late positivity we observed for the abnormal rhythmic pattern is likely to reflect a conditionally initiated prosodic reanalysis/repair process.

Although sentences in this study were presented visually, segment-by-segment and prosodic (rhythmic) information was not accompanied by acoustic input or punctuation, the ERP effects for rhythmic information processing are similar to those obtained for prosodic processing in the spoken domain, for example, on the N400 component (Eckstein and Friederici, 2005, 2006; Magne et al., 2007; Miez et al., 2008) and on the late positivity (Astésano et al., 2004; Eckstein and Friederici, 2005, Magne et al., 2007). This observation is not only consistent with previous studies suggesting that prosodic information is available during silent reading (Steinhauer and Friederici, 2001; Stolterfoht et al., 2007) but also consistent with the argument that there are general mechanisms for prosodic information processing regardless of the modality of language input.

Before accepting the arguments above, we may need to rule out an alternative account for the increased negativity (i.e. the N400-like effect) for sentences with the abnormal rhythmic pattern. This account assumes that this increased negativity is simply caused by the (mis)use of the disyllabic verb and the monosyllabic noun. It is the lack of co-occurrence between them, rather than the abnormal rhythmic pattern *per se*, that is responsible for the negativity effect we observed. However, since the N400-like effect for the abnormal rhythmic pattern differed, in terms of time course, scalp distribution and magnitude, from the semantic N400 effect associated with the lack of co-occurrence between the verb and the noun, it is unlikely that the former effect can be simply attributed to this lack of co-occurrence.

To conclude, by manipulating the rhythmic pattern as well as the semantic congruency between the verb and the object noun and by visually presenting sentences segment by segment, we found that an abnormal rhythmic pattern would elicit an early, posterior positivity effect in the 300- to 600-ms time window, a fronto-central N400-like effect and a late positivity effect in the 700- to 850-ms window in silent reading of Chinese sentences. These findings suggest that

information concerning rhythmic pattern is activated and used rapidly and interactively to constrain semantic integration during Chinese sentence reading.

Acknowledgments

This study was supported by grants from the Natural Science Foundation of China (30770712, 30970889), from the Ministry of Science and Technology of China (2010CB8339004), and from the Beijing Key Laboratory of Learning and Cognition, Capital Normal University. We thank Dr. Ren Zhou, Dr. Yiya Chen and Dr. Bei Wang for their help in the preparation of this study and we thank the anonymous reviewers for their constructive comments and suggestions. Electronic mail concerning this study should be addressed to Dr. Xiaolin Zhou, xz104@pku.edu.cn.

References

- Astésano, C., Besson, M., Alter, K., 2004. Brain potentials during semantic and prosodic processing in French. *Cogn. Brain Res.* 18, 172–184.
- Besson, M., Magne, C., Schön, D., 2002. Emotional prosody: sex differences in sensitivity to speech melody. *Trends Cogn. Sci.* 6, 405–407.
- Birch, S., Clifton, C., 1995. Focus, accent, and argument structure: effects on language comprehension. *Lang. Speech* 38 (4), 365–391.
- Bock, J.K., Mazzella, J.R., 1983. Intonational marking of given and new information: some consequences for comprehension. *Mem. Cogn.* 11, 64–76.
- Böcker, K.B.E., Bastiaansen, M.C.M., Vroomen, J., Brunia, C.H.M., De Gelder, B., 1999. An ERP correlate of metrical stress in spoken word recognition. *Psychophysiology* 36, 706–720.
- Christophe, A., Gout, A., Peperkamp, S., Morgan, J., 2003. Discovering words in continuous speech stream: the role of prosody. *J. Phon.* 31, 581–598.
- Cinque, G., 1993. A null theory of phrase and compound stress. *Linguist. Inq.* 18, 239–297.
- Cutler, A., Otake, T., 1999. Pitch accent in spoken-word recognition in Japanese. *J. Acoust. Soc. Am.* 105, 1877–1888.
- Dahan, D., Tanenhaus, M.K., Chambers, C.G., 2002. Accent and reference resolution in spoken-language comprehension. *J. Mem. Lang.* 47, 292–314.
- Duanmu, S., 2007. *The Phonology of Standard Chinese*. Oxford University Press, Oxford, New York.
- Eckstein, K., Friederici, A.D., 2005. Late interaction of syntactic and prosodic processes in sentence comprehension as revealed by ERPs. *Cogn. Brain Res.* 25, 130–143.
- Eckstein, K., Friederici, A.D., 2006. It's early: event-related potential evidence for initial interaction of syntax and prosody in speech comprehension. *J. Cogn. Neurosci.* 18, 1696–1711.
- Friederici, A.D., 2002. Towards a neural basis of auditory sentence processing. *Trends Cogn. Sci.* 6, 78–84.
- Feng, S., 2000. *Hanyu Yunlv Jufaxue [Prosodic syntax of Chinese]*. Shanghai Educational Press, Shanghai.
- Fodor, J.D., 2002. Prosodic disambiguation in silent reading. In: Hirotani, M. (Ed.), *Proceedings of the 32nd Annual Meeting of the North East Linguistic Society (NELS)*, 32, NY, pp. 113–132.
- Frazier, L., Carlson, K., Clifton, C., 2006. Prosodic phrasing is central to language comprehension. *Trends Cogn. Sci.* 10, 244–249.
- Hagoort, P., Brown, C.M., Groothusen, J., 1993. The syntactic positive shift (SPS) as an ERP measure of syntactic processing. *Lang. Cogn. Processes* 8, 439–483.
- Jiang, X., Tan, Y., Zhou, X., 2009. Processing the universal quantifier during sentence comprehension: ERP evidence. *Neuropsychologia* 47, 1799–1815.
- Jun, S., 2003. Prosodic phrasing and attachment preferences. *J. Psycholinguist. Res.* 32, 219–249.
- Kerkhofs, R., Vonk, W., Schriefers, H., Chwilla, D.J., 2007. Discourse, syntax, and prosody: the brain reveals an immediate interaction. *J. Cogn. Neurosci.* 19, 1421–1434.
- Kok, A., 2001. On the utility of P3 amplitude as a measure of processing capacity. *Psychophysiology* 38, 557–577.
- Kutas, M., Federmeier, K.D., 2000. Electrophysiology reveals semantic memory use in language comprehension. *Trends Cogn. Sci.* 4, 463–470.
- Li, X., 1983. Zhongguoren de zuoyou lishou fenbu [The distribution of handedness of Chinese]. *Xinli Xuebao [Acta Psychologica Sinica]* 3, 268–275.
- Li, X., Yang, Y., Hagoort, P., 2008a. Pitch accent and lexical tone processing in Chinese discourse comprehension: an ERP study. *Brain Res.* 222, 192–200.
- Li, X., Hagoort, P., Yang, Y., 2008b. Event-related potential evidence on the influence of accentuation in spoken discourse comprehension in Chinese. *J. Cogn. Neurosci.* 20, 906–915.
- Li, X., Shu, H., Liu, Y., Li, P., 2006. Mental representation of verb meaning: behavioral and electrophysiological evidence. *J. Cogn. Neurosci.* 18, 1774–1787.
- Lu, B., Duanmu, S., 2002. Rhythm and syntax in Chinese: a case study. *J. Chinese Lang. Teachers Assoc.* 37 (2), 123–136.
- Lü, S., 1963. Xiandai hanyu danshuang yinjie wenti chutan [Preliminary discussion about mono-/disyllabic issues in modern Chinese]. *Zhongguo Yuwen [Chinese Language]* 1, 10–22.
- Magne, C., Astésano, C., Aramaki, M., Ystad, S., Kronland-Martinet, R., Besson, M., 2007. Influence of syllabic lengthening on semantic processing in spoken French: behavioral and electrophysiological evidence. *Cereb. Cortex* 17, 2659–2668.

- Magne, C., Astésano, C., Lacheret-Dujour, A., Morel, M., Besson, M., 2005. Online processing of “pop-out” words in spoken French dialogues. *J. Cogn. Neurosci.* 17, 740–756.
- Mietz, A., Toepel, U., Ischebeck, A., Alter, K., 2008. Inadequate and infrequent are not alike: ERPs to deviant prosodic patterns in spoken sentence comprehension. *Brain Lang.* 104, 159–169.
- Mitchell, R.L.C., Elliott, R., Barry, M., Cruttenden, A., Woodruff, P.W.R., 2003. The neural response to emotional prosody, as revealed by functional magnetic resonance imaging. *Neuropsychologia* 41, 1410–1421.
- Osterhout, L., Holcomb, P.J., 1992. Event-related brain potentials elicited by syntactic anomaly. *J. Mem. Lang.* (31-6), 785–806.
- Pannekamp, A., Toepel, U., Alter, K., Hahne, A., Friederici, A.D., 2005. Prosody-driven sentence processing: an ERP study. *J. Cogn. Neurosci.* 17, 407–421.
- Pell, M.D., 2006. Cerebral mechanisms for understanding emotional prosody in speech. *Brain Lang.* 96, 221–234.
- Polich, J., 2007. Updating P300: an integrative theory of P3a and P3b. *Clin. Neurophysiol.* 118, 2128–2148.
- Schön, D., Magne, C., Besson, M., 2004. The music of speech: electrophysiological study of pitch perception in language and music. *Psychophysiology* 41, 341–349.
- Steinhauer, K., 2003. Electrophysiological correlates of prosody and punctuation. *Brain Lang.* 86, 142–164.
- Steinhauer, K., Friederici, A.D., 2001. Prosodic boundaries, comma rules, and brain responses: the closure positive shift in ERPs as a universal marker for prosodic phrasing in listeners and readers. *J. Psycholinguist. Res.* 30, 267–295.
- Steinhauer, K., Alter, K., Friederici, A.D., 1999. Brain potentials indicate immediate use of prosodic cues in natural speech processing. *Nat. Neurosci.* 2, 191–196.
- Strelnikov, K.N., Vorobyev, V.A., Chernigovskaya, T.V., Medvedev, S.V., 2006. Prosodic clues to syntactic processing—a PET and ERP study. *NeuroImage* 29, 1127–1134.
- Stolterfoht, B., Friederici, A.D., Alter, K., Steube, A., 2007. Processing focus structure and implicit prosody during reading: differential ERP effects. *Cogn.* 104, 565–590.
- Wang, H., 2002. Putonghuazhong jielv bianjie yu jielv moshi, yufa, yuyong de guanlian [The association between prosodic boundary and rhythmic pattern, grammar and pragmatics in Mandarin Chinese]. *Yuyanxue Luncong [Linguistics Analects]* 26, 279–300.
- Wildgruber, D., Riecker, A., Hertrich, L., Erb, M., Grodd, W., Ethofer, T., Ackermann, H., 2005. Identification of emotional intonation evaluated by fMRI. *NeuroImage* 24, 1233–1241.
- Ye, Z., Luo, Y., Friederici, A.D., Zhou, X., 2006. Semantic and syntactic processing in Chinese sentence comprehension: evidence from event-related potentials. *Brain Res.* 1071, 186–196.
- Ye, Z., Zhan, W.D., Zhou, X., 2007. The semantic processing of syntactic structure in sentence comprehension: an ERP study. *Brain Res.* 1142, 135–145.
- Zhou, R., 2006. Hanyu xinxi jiaodian jigou de yunlv jieshi [The prosodic explanation of information focus structure in Chinese]. *Yuyan Kexue [Linguistic Science]* 22, 24–38.
- Zhou, X., Marslen-Wilson, W., 1999. Phonology, orthography, and lexical semantic activation in reading Chinese. *J. Mem. Lang.* 41, 579–606.
- Zhou, X., Marslen-Wilson, W., 2000. The relative time course of semantic and phonological activation in reading Chinese. *J. Exp. Psychol. Learn. Mem. Cogn.* 26, 1245–1265.
- Zhou, X., Marslen-Wilson, W., Taft, M., Shu, H., 1999. Morphology, orthography, and phonology in reading Chinese. *Lang. Cogn. Processes* 14, 525–565.