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ELECTROENCEPHALOGRAM OSCILLATIONS DIFFERENTIATE SEMANTIC AND PROSODIC PROCESSES DURING SENTENCE READING

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Abstract—How prosodic information is processed at the neural level during silent sentence reading is an unsolved issue. In this study, we investigate whether and how the processing of prosodic constraints can be distinguished from the processing of semantic constraints by measuring changes in event-related electroencephalogram (EEG) power. We visually presented Chinese sentences containing verb–noun combinations that were semantically congruent or incongruent and that had normal or abnormal rhythmic patterns and asked participants to judge whether the sentences were semantically and rhythmically acceptable. In Chinese, the rhythmic pattern refers to the combination of words with different syllable lengths. While the [1+1] pattern is normal for a verb–noun combination, the [2+1] pattern is abnormal. With the critical nouns, we found that the violation of semantic constraints was associated with the low beta (16–20 Hz) decrease in the early window (0–200 ms post onset) and the alpha (10–15 Hz) and low beta decrease in the later window (400–657 ms) while the processing of the abnormal rhythmic pattern was associated with the theta (4–6 Hz) and the alpha increase in the early window and the alpha and upper beta (20–24 Hz) decrease in the later window. These findings suggest that although the processing of semantic constraints and the processing of rhythmic pattern may partially share neuro-cognitive processes, as reflected by the similar decreases in alpha band power, they can nevertheless be differentiated in EEG responses during sentence reading. **© 2010 IBRO. Published by Elsevier Ltd. All rights reserved.**

Key words: semantic congruency, rhythmic pattern, prosody, sentence processing, time-frequency analysis.

Prosody is well known to convey affective and linguistic information in spoken language via variations of phonological properties (Besson et al., 2002; Böcker et al., 1999; Christophe et al., 2003; Cutler and Otake, 1999; Mitchell et al., 2003; Pell, 2006; Wildgruber et al., 2005). In written sentence processing, although prosodic information is not accompanied by explicit acoustic signals, the mental representation of prosodic features may nevertheless play an important role in sentence comprehension, affecting syntactic parsing (Fodor, 2002; Hwang and Schafer, 2009) and indexing information structure (Zhou, 2006). But how the brain responds to prosodic information during silent reading is still an open question.

Prosodic processes during listening to aurally presented sentences have been explored in studies with the event-related potential (ERP) technique. These studies indicate the immediate use of prosodic cues in spoken language comprehension. For instance, the prosodic boundary cue (including pitch variation in the preceding and subsequent words) is immediately used in sentence parsing (Steinhauer et al., 1999; Kerkhofs et al., 2007) and it elicits a positive-going waveform (Closure-Positivity Shift, CPS) (Pannekamp et al., 2005; Steinhauer et al., 1999; Steinhauer and Friederici, 2001) in ERP responses. Different patterns of ERP responses are also evoked by intonational violation (Astésano et al., 2004; Eckstein and Friederici, 2005, 2006) and inappropriate syllabic lengthening (Magne et al., 2007), which differ from, but interact with, the ERP responses to syntactic or semantic violation.

The ERP technique has also been used to investigate prosodic processing during silent sentence reading. As in spoken language, the CPS is observed for prosodic boundary, which is cued by commas in sentences or primed by melodies of intonational contour presented before sentences (Steinhauer, 2003; Steinhauer and Friederici, 2001). A N400 effect is observed on the German subject noun in the second clause when stress is put, through information structure, on the subject noun rather than on the object noun, inconsistent with the implicit, default stress on the object noun in the preceding clause (Stolterfoht et al., 2007). These few studies suggest that prosodic information is actively used in sentence reading, with the neural correlates being similar to those in spoken language comprehension.

In a recent ERP study, we explored how prosodic constraints affect the neural activity in processing Chinese written sentences (Luo and Zhou, 2010). In Chinese, combining words into compounds and phrases is constrained not only by the syntactic and semantic structures of these combinations, but also by their rhythmic pattern, which refers to the composition of words with different number of syllables. Most words in Modern Chinese are monomorphemic, monosyllabic or disyllabic. 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. Linguistically, it is known that

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Abbreviations: CPS, closure-positivity shift; EEG, electroencephalogram; ERD, event-related desynchronization; ERP, event-related potential; ERS, event-related synchronization; RHY, rhythmic pattern; SEM, semantic congruency; TF, time-frequency.

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native speakers prefer some particular compositions but feel odd with others (Lü, 1963). For the verb–noun combination, the [2+1] pattern (numbers in brackets stand for the number of syllables of the verb and of the noun, respectively) is generally not acceptable, but the [1+1] or the [2+2] pattern is allowed. These prosodic constraints can be accounted for by the relationship between rhythmic pattern and information focus, which is in turn determined by the syntactic structure of the combination (Zhou, 2006). In the case of verb–noun combination, for example, the object noun, being the most deeply embedded constituent in the syntactic structure, is assigned as the default focus according to the rule of focus marking (Cinque, 1993; Zhou, 2006). However, a monosyllabic noun in the [2+1] pattern cannot carry the focus due to its less prominence than the disyllabic verb in terms of word length (Duanmu, 2007; Lu and Duanmu, 2002). 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).

This interesting phenomenon demonstrates the prosodic impact upon grammatical rules governing the combination of words in both spoken and written sentences, and provides us with the opportunities to investigate (1) whether this type of prosodic information is activated in silent reading which, on surface, needs no prosodic information for comprehension, and (2) whether neural marks of prosodic processing in silent reading are similar to those in spoken language processing. Our previous ERP study (Luo and Zhou, 2010) showed that, compared with the normal [1+1] verb–noun combination, the abnormal [2+1] pattern elicited a delayed N400 effect followed by a late positivity when the verb–object combination is semantically congruent. By contrast, an earlier posterior positivity developed in the 300–600 ms time window when the verb–object combination is semantically incongruent. This surprising positivity effect was interpreted as the overlap between the P300, which responds to the detection of anomalous prosodic features, and the N400, which reflects the difficulty of semantic integration caused by the abnormal rhythmic pattern. On the other hand, the semantic mismatch between the verb and the noun engendered the typical N400 effect. Thus prosodic processing and semantic processing may have both common and differential neural bases and they may interact in silent sentence reading, at least in Chinese.

The purpose of this study is to investigate further the neural activity associated with prosodic and semantic processes in sentence reading. To this end we utilized the time-frequency analysis to explore the synchronization and desynchronization of oscillatory dynamics related to these processes. The traditional ERP methodology reveals the phase-locked neural activities evoked by a particular cognitive process. The time-frequency (TF) analysis, on the other hand, can reveal the non-phase-locked neural activity that is hidden in the standard ERP analysis. Although the functions of synchronous oscillations in language processing have been stressed in recent years (Weiss and Mueller, 2003), previous studies concentrate merely on lexical processing (Bastiaansen et al., 2005, 2008; Khader and Rösler, 2004) and semantic (Hagoort et al., 2004; Hald et al., 2006; Röhm et al., 2001; Willems et al., 2008) or syntactic processes (Bastiaansen et al., 2002; Davidson and Indefrey, 2007

Table 1. Conditions and exemplar sentences with approximate literal translations. 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 separately as two segments. Sentences are segmented by "/"

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

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Design and materials

We manipulated the normality of the rhythmic pattern and the semantic congruency between the verb and the noun. The experiment had four conditions, each containing 72 sentences (see Table 1): 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 comprised a main subject noun (S), a verb (V1), an object noun (N2), a second verb (V2), and its object noun (N2). These constituents were structured as "S+(V1+N1)+(V2+N2)," with the subject followed by two verb 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 object of the main verb (i.e., N1).

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 stringent such that each pair of verbs was synonyms, expressing the same or similar meanings and having the same syntactic properties. These verbs initially appeared with the monosyllabic form in history but were given a disyllabic form in Modern Chinese via the combination of the morphemes with other morphemes of similar or related meanings. This expansion was to avoid the phonological ambiguity of monomorphemic words and thus the increased processing load given that the Mandarin Chinese uses only about 1400 syllables and there are a large number of homophonic morphemes in the language. Although the disyllabic verbs and the corresponding monomorphemic counterparts may differ in some way, such as nominalization (i.e., the disyllabic ones can be used as nouns in some context while the monosyllabic ones cannot), they are of similar meanings and usages when they act as verbs, as in the present study. Hence the verbs were combined with a monosyllabic noun which fit the selectional restrictions of the verbs (e.g., 蒜, suan, garlic), forming the SEM+RHY+ and the SEM+RHY− conditions. The same monosyllabic noun was recombined with another pair of verbs, which were semantically incongruent with the noun, to form the SEM−RHY+ and the SEM-RHY− conditions.

The stimuli were split 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 appeared twice in a list, but with different verbs of different lengths. One hundred and eight filler sentences of various syntactic structures were added to 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 naturalness of expression measures the native speaker's general intuition towards various aspects of the sentence, including semantic, syntactic, pragmatic and prosodic structures. In this study, both the semantic congruency and the rhythmic pattern for the verb-noun combination would contribute to the judgment of naturalness of the experimental sentences, as indicated by the pretest below. The 72 pairs of sentences from the SEM+RHY+ and SEM+RHY− conditions were split into two versions in a counterbalanced manner. Ten participants, who were 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 10 participant were asked to do the opposite for the two lists. A 5-point scale was used for each rating, with "1" indicating that the sentence was semantically anomalous or the expression was unnatural, and "5" indicating 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 patterns (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 that 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, sentences with abnormal rhythmic patterns (mean=2.60, SD=0.44) were rated far less natural than sentences in the SEM+RHY+ condition (mean=4.26, SD=0.51), $t(71)=24.25$, $P<0.001$.

Procedure

Sentences in each test list were pseudo-randomized, such that at least 50 sentences intervened 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 a 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. A question mark was then presented after the full stop. Participants 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 it was expressed in a natural way in the same task. They were explicitly told that "no" responses should be given to both nonsense sentences and unnatural sentences. The assignment of the "yes" or "no" response to the left or right button was counter-balanced between participants. The critical verb and the noun were presented as two separate segments, with the EEG recording time-locked to the noun.

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. Participants accepted a practice block of 15 sentences before they were tested in the formal experiment. The entire session, including electrode application and removal, lasted about 2 h.

EEG recording

The electroencephalogram was continuously recorded from 62 scalp electrodes mounted on an elastic cap according to the extended 10–20 system, with the addition of two mastoid electrodes. Signals from these electrodes were referenced online to the left mastoid and were re-referenced offline to the mean of the left and right mastoids. Eye blinks and vertical eye movement were monitored with electrodes located above and below the left eye. The horizontal electro-oculogram was recorded from electrodes placed 1.5 cm lateral to the left and right external canthi. The electrode impedance was less than 5 kΩ. The EEG was amplified (bandpass 0.01–70 Hz) and digitized at 500 Hz.

Time-frequency analysis

The TF wavelet decomposition of the EEG activity was used to quantify changes in oscillatory activity. The EEG was convoluted with complex Morlet's wavelet w(t, f_0) (Kronland-Martinet et al., 1987) that has a Gaussian shape both in the time domain (SD σt) and in the frequency domain (SD σf) around its central frequency f_0:

$$w(t, f_0)=A\ \mathrm{exp}(-t\text{\^{}}2/2\sigma t\text{\^{}}2)\ \mathrm{exp}(2i\pi f0t)$$

with $\sigma f=1/2\pi\sigma t$. Wavelets were normalized so that their total energy was 1. The normalization factor A was determined with $A=1/\mathrm{sqrt}(\sigma t\times \mathrm{sqrt}(\pi))$.

The unique characteristics of the time-frequency wavelet decomposition are revealed by the time and frequency resolution of the transform at a specific scale C_0, which decides σf ($\sigma f=f_0/C_0$) for each specific f_0. The time resolution and the frequency resolution cannot approach optimum simultaneously since the product of σf and σt always equals $1/2\pi$. In other words, the improvement in time resolution is accompanied by a weakened frequency resolution. C_0 was then selected to ensure that the time resolution and the frequency resolution varied in a tolerable range. Traditionally, C_0 is usually fixed at a specific value in analyzing all frequencies of interest, which lead to a suitable time resolution and a suitable frequency resolution for only a specific frequency band but low time resolution or low frequency resolution for other frequencies. For example, C_0 is usually set as 5 in studies concerning alpha oscillations (Fell et al., 2006; Mu et al., 2008). However, the frequency bands below the alpha band had poor time resolution and the frequency bands above the alpha band had poor frequency resolution. To solve this problem, we used a variable C_0 for analyzing different frequencies in this study.

The frequencies were analyzed in 0.5 Hz increments, ranging from 4 to 30 Hz. We used wavelets with C_0 ranging from 2.4 to 10, which corresponded respectively to the lowest frequency (4 Hz) and the highest frequency (30 Hz), with linear interpolation between these values for intermediate frequencies.

We chose three frequencies 4, 13 and 30 Hz, representing the theta, alpha, and beta bands, to assess the differences in convolution results between using a fixed wavelet family and using variable wavelet families. Convolution results were characterized by time resolution and frequency resolution which were represented by wavelet duration (2σt) and spectral bandwidth (2σf). The fixed wavelet family were characterized by C_0 which equaled 5 (Davidson and Indefrey, 2007; Mu et al., 2008) while variable wavelet families were characterized by a changing C_0 as suggested above.

As shown in Table 2, the time resolution and the frequency resolution for the three frequencies stayed in a comparatively reliable range when our method was used, while they showed large variations across the frequencies when the fixed value of C_0 waswas lyamplified J0-1he

Table 3. The number and percentage of correct responses in each experimental condition

	SEM+RHY+	SEM+RHY−	SEM−RHY+	SEM−RHY−
Mean (SD)	33.5 trials (2.63)	32.9 trials (2.80)	35.7 trials (0.62)	35.4 trials (0.89)
Accuracy rate	93.1%	91.3%	99.0%	98.3%

terior (Pz, POz). For the lateral analysis, the additional factors were Hemisphere (left and right) and Region (anterior, central, and posterior). Thus lateral electrodes were organized into six regions of interest (ROIs), each having five or six representative electrodes: left anterior (F1, F3, F5, FC1, FC3, FC5), left central (C1, C3, C5, CP1, CP3, CP5), left posterior (P1, P3, P5, PO3, O1), right anterior (F2, F4, F6, FC2, FC4, FC6), right central (C2, C4, C6, CP2, CP4, CP6), right posterior (P2, P4, P6, PO4, O2). Averaged ERS/ERD over electrodes in each ROI was used for statistical purposes. In cases in which the sentence type interacted with topographic factors, separate analyses were computed for midline electrodes, hemispheres, or regions. All *P*-values in statistical analyses were adjusted with the Greenhouse–Geisser correction for nonsphericity when necessary.

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 from 91.3% to 99.0% for the four conditions (Table 3), suggesting that they properly accomplished the task according to the instruction. ANOVA with semantic congruency and rhythmic pattern as two within-participant factors revealed a significant main effect of semantic congruency, $F(1,15)=48.23$, $P<0.001$, but no main effect of rhythmic pattern nor the interaction between the two factors, $Fs<1$. These results indicate that participants made more errors in responding to semantically congruent sentences than to incongruent sentences.

Time-frequency data

We calculated the percentage of TF power changes in each TF window relative to the TF power of baseline (from −150 to 0 ms pre-onset of the stimulus). Based on both visual inspection and analyses of power changes in consecutive 50-ms time windows, we clustered the adjacent small windows that showed similar patterns of effects, resulting in two big windows: an early window (0–200 ms) and a late window (400–657 ms). Four frequency bands in the two windows were defined. These were theta: 4–6 Hz (Schiirmann and Basar, 1994; Fell et al., 2006), alpha: 10–15 Hz (Kolev et al., 2002; Digiacomo et al., 2008), low beta: 16–20 Hz, and upper beta: 20–24 Hz (Schiirmann and Basar, 1994; Fell et al., 2006). Thus eight time-frequency windows in total were chosen for statistical analyses. Significant results are summarized in Tables 4 and 5, and the topographies of the effects are illustrated in Fig. 1.

In the early theta TF window, ERS was found in response to the four conditions for most regions of the scalp distributions (Fig. 1). Repeated-measures ANOVA showed that there was no significant main effect of either SEM or RHY over the midline and the lateral electrodes. But the SEM×Region interaction was marginally significant, $F(2,30)=3.56$, $P=0.064$, and RHY×Hemisphere interaction was significant in the lateral analyses (see Table 4). Further analysis revealed no significant effect of SEM. However, the abnormal rhythmic pattern induced a larger ERS than the normal rhythmic pattern on the left, but not on the right hemisphere ($F<1$).

In the early alpha window, ERS was induced in the SEM+RHY+ and SEM+RHY− conditions in anterior regions, and in the SEM-RHY− condition in all regions, while ERD was mainly found in the SEM+RHY+, SEM+RHY−, and SEM−RHY+ conditions (Fig. 1). ANOVAs showed that there was no main effect of SEM ($Fs<1$), but the abnormal rhythmic pattern induced a significantly larger alpha power increase (or less alpha decrease) than the normal rhythmic pattern in both the midline and the lateral analysis (Table 4). No other significant effect was found.

Table 4. TF analysis in the early time window. Only significant results are shown. SEM, RHY and Region are the three factors in the midline analysis, while SEM, RHY, Region and Hemisphere are the four factors in the lateral analysis. Separate analyses were conducted only when significant interaction was found

Frequency	Factor	Early (0–200 ms)		
		F	*df*	*P*
Theta (4–6 Hz)	Lateral analysis			
	RHY×Hemisphere	11.31	1, 15	0.004
	Separate analysis for lateral			
	At left hemisphere			
	RHY	5.17	1, 15	0.038
Alpha (10–15 Hz)	Midline analysis			
	RHY	4.75	1, 15	0.046
	Lateral analysis			
	RHY	8.24	1, 15	0.012
Lower beta (16–20 Hz)	Midline analysis			
	SEM×Region	4.60	2, 30	0.022
	Lateral analysis			
	SEM×Region	6.38	2, 30	0.009
	Separate analysis for midline			
	At anterior			
	SEM	4.73	1, 15	0.046
Upper beta (20–24 Hz)	Midline analysis			
	SEM×Region	4.37	2, 30	0.033
	Lateral analysis			
	SEM×Region	4.73	2, 30	0.016
	Separate analysis for midline			
	At center			
	SEM×RHY	5.74	1, 15	0.03

Table 5. TF analysis in the late time window. Only significant results are shown. SEM, RHY and Region are the three factors in the midline analysis, while SEM, RHY, Region and Hemisphere are the four factors in the lateral analysis. Separate analyses were conducted only when significant interaction was found

Frequency	Factor	Later (400–657 ms)		
		F	*df*	*P*
Theta (4–6 Hz)	Lateral analysis			
	SEM×Hemisphere	8.86	1, 15	0.009
	RHY×Hemisphere	4.77	1, 15	0.045
Alpha (10–15 Hz)	Midline analysis			
	SEM	5.85	1, 15	0.029
	SEM×RHY	18.59	1, 15	0.001
	Lateral analysis			
	RHY	5.90	1, 15	0.028
	SEM×RHY	8.04	1, 15	0.013
	Separate analysis for midline			
	When RHY+			
	SEM	14.06	1, 15	0.002
	When SEM+			
	RHY	10.87	1, 15	0.005
	Separate analysis for lateral			
	When RHY+			
	SEM	9.06	1, 15	0.009
	When SEM+			
	RHY	12.03	1, 15	0.003
Lower beta (16–20 Hz)	Midline analysis			
	SEM	14.13	1, 15	0.002
	Lateral analysis			
	SEM	10.45	1, 15	0.006
Upper beta (20–24 Hz)	Lateral analysis			
	RHY	5.22	1, 15	0.037

In the early low beta window, normal sentences were associated with both ERD over posterior regions and ERS over the others. ERD was distributed over the central and posterior regions in the SEM+RHY-condition, in the central and posterior regions in the SEM−RHY+ condition, and in most regions of the left hemisphere in the SEM−RHY− condition. There was no significant main effect of SEM or RHY. But SEM×Region interaction was significant both in the midline and the lateral analysis (Table 4). Further analysis showed that the semantically incongruent sentences induced a larger ERD in the anterior region for the midline, and a marginal effect in the anterior region for the lateral, $F(1,15)=3.84$, $P=0.069$, compared to the semantically congruent sentences. This effect was not found in the central or posterior regions ($P\text{s}>0.1$).

In the early upper beta window, the distribution of ERD/ERS was similar to that in the early low beta window. ANOVAs showed that the main effect of neither SEM nor RHY reached significance. The SEM×Region interaction was significant in both midline and lateral analysis (Table 4). However, further analysis revealed no significant effect of SEM in either region ($P\text{s}>0.1$).

In the late theta window, global ERS was induced in all four conditions (Fig. 1). ANOVAs revealed no significant differences between conditions in midline analysis. In lateral analysis, there was no significant main effect of SEM or RHY, but there were significant SEM×Hemisphere interaction and RHY×Hemisphere interaction (Table 5). However, further analysis showed no differences between conditions in left or right hemisphere.

In the late alpha window, all four conditions induced ERD (Fig. 1). ANOVAs revealed a significant main effect of SEM in the midline analysis, with larger power decreases for semantically incongruent than for congruent sentences. This effect was also marginally significant in lateral analysis, $F(1,15)=3.98$, $P=0.064$. A significant main effect of RHY was also found in lateral analysis (Table 5), suggesting that the abnormal rhythmic pattern induced larger ERD than the normal rhythmic pattern. The SEM×RHY interaction was significant for both the midline and the lateral. Further analysis showed that when sentences were semantically congruent, the abnormal rhythmic pattern in the SEM+RHY− condition induced a larger power decrease relative to the SEM+RHY+ condition for both the midline and the lateral. In contrast, when sentences were semantically incongruent, no difference was found between SEM−RHY+ and SEM−RHY− conditions ($P>0.1$). On the other hand, when sentences had normal rhythmic pattern, the semantic in congruency in the SEM−RHY+ condition induced a larger power decrease relative to SEM+RHY+, for both the midline and the lateral. In contrast, when sentences had abnormal rhythmic patterns, no difference was found between SEM+RHY− and SEM−RHY− ($F<1$).

In the late low beta window, ERD was again found in all four conditions. ANOVAs revealed a significant main effect of SEM for both the midline and the lateral (Table 5). This showed that the semantically mismatching noun elicited larger power decreases in this window than the semantically congruent noun. No other main effect or interaction was found.

In the late upper beta window, consistent with the low beta window, all four conditions induced ERD. ANOVAs revealed a significant main effect of RHY in lateral analysis (Table 5), suggesting that sentences with the abnormal rhythmic pattern induced larger ERD than those with normal rhythmic pattern. No other main effect or interaction was significant.

DISCUSSION

The processing of semantic constraints and of rhythmic pattern can be partially distinguished in brain oscillation

For the first time we showed that the processing of semantic constraints and of rhythmic pattern can be distinguished in both early and late stages of brain oscillation. In the early time window from 0 to 200 ms, power in the low beta band was associated with semantic congruency, as critical words in semantically incongruent sentences inducing a greater decrease than the same words in congruent sentences in anterior regions. Conversely, an early change in the theta band power in the same time window was associated with the processing of rhythmic pattern, as sentences with abnormal rhythmic pattern inducing larger ERS

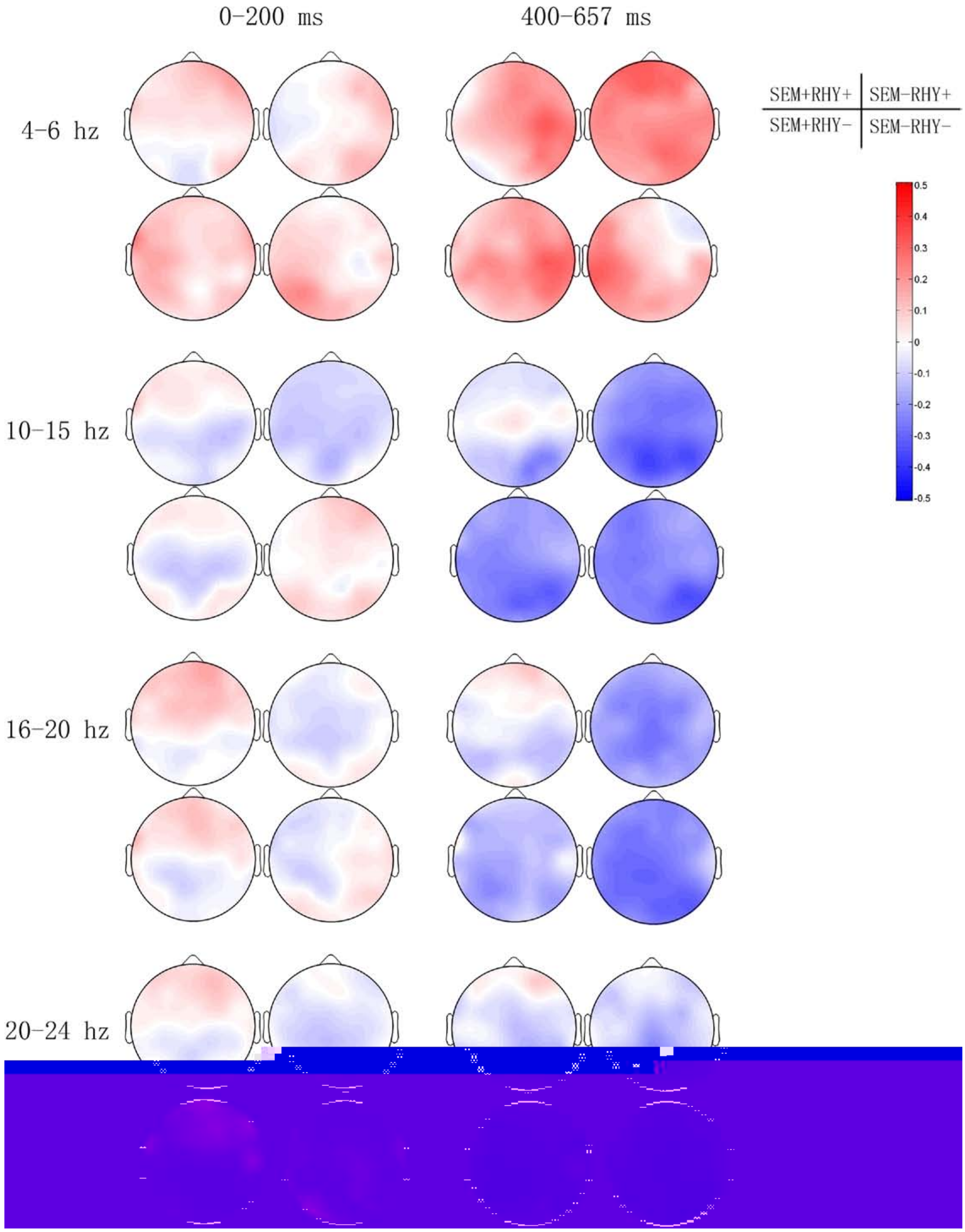

Fig. 1. Topographies of theta (4–6 Hz), alpha (10–15 Hz), low beta (16–20 Hz), and upper beta (20–24 Hz) band activity induced by the four types of sentences in two time windows. SEM+ RHY+, semantically congruent with the normal [1+1] rhythmic pattern; SEM+ RHY−, semantically congruent with the abnormal [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.

in left sites than sentences with normal pattern. Moreover, an early change in alpha band power was also associated with rhythmic pattern, with a weaker ERD in sentences with abnormal rhythmic pattern than those with normal pattern.

These early effects on power change for semantic congruency and rhythmic pattern suggest the immediate use of these types of information in sentence reading; but the semantic and prosodic processes may nevertheless function differently, as indicated by the different brain oscillatory activities and scalp distributions. Contrary to previous ERP findings suggesting an earlier appearance in time course for the processing of semantic constraints than for the processing of rhythmic pattern (Luo and Zhou, 2010), with TF analysis we found that the effect of rhythmic pattern was as early as the effect of semantic congruency. The simultaneous processing of semantic and of rhythmic pattern information in Chinese sentence reading, as suggested by the EEG oscillatory activity, is in agreement with a behavioral study suggesting that the semantic and phonological information of the Chinese word is activated with no significant temporal difference (Zhou and Marslen-Wilson, 2000). But given that the timing of EEG data presented in the time-frequency domain is not as precise as that presented in the time domain (Pfurtscheller and Lopes da Silva, 1999), i.e., the time resolution for time-frequency analysis is lower than that for traditional ERP analysis, and given that the signal conversion to time-frequency representation using a moving time window smears over time (Willems et al., 2008), further evidence is needed to derive firm conclusions concerning the subtle differences in time tailed descriptions of this structure and its functions in sentence comprehension) and we examined the theta oscillation associated with the verb. No statistically significant difference was found in the theta power change between the semantically matching and mismatching verbs, consistent with the present null effect on the noun. There could be two possible explanations for the inconsistency between the previous work and our results. One assumes that the theta power increase is related to task demand. In the previous work, participants were required to attend to the stimuli with no need to give a response (Bastiaansen et al., 2002; Davidson and Indefrey, 2007; Hagoort et al., 2004; Hald et al., 2006). In this study, however, participants had to complete an acceptability judgment task after each sentence. The alternative explanation is that the presence of theta power increase for semantic violation depends on the language structure, as Dutch and Chinese differ in a number of dimensions, including the writing system. More evidence is needed to demonstrate the functional significance of the theta power increase in language comprehension.

Power changes in the alpha band for semantic violation and abnormal rhythmic pattern were found in either the early or the later time window. The alpha band activity has been associated with general levels of attention or vigilance (Harmony et al., 1996; Klimesch et al., 1999; Shahin et al., 2009), with power reduction indicating active processing that consumes attentional resources and power increase indicating cortical idling and/or inhibitory processes (Pfurtscheller and Lopes da Silva, 1999). On the other hand, the alpha band has also been implicated in semantic processing in language tasks, with larger power decrease for active semantic processing than for simple sentence reading (Röhm et al., 2001). Willems et al. (2008) reported decrease of alpha power in a study on semantic congruency. The semantic mismatch between the aurally presented verb and noun induced power decrease in 8–12 Hz in the 0–300 ms window. But this effect was not found in the semantic mismatch between spoken sentence context and the visually presented picture. They thereby interpreted the power decrease in the alpha band as an early detection of mismatch in the linguistic stimuli based upon the context of preceding sentence. The above attentional and semantic accounts are feasible in explaining the decrease in alpha that we found in this experiment.

In the later time window, both sentences with semantic violation and those with abnormal rhythmic pattern caused difficulty for the semantic integration process. One may assume that the decrease in alpha in the 400–657 ms time window simply reflects the semantic integration process itself. However, the interaction between semantic congruency and rhythmic pattern was also found in this time window, as the power decrease did not differ between double violation and the single violation of semantic congruency or rhythmic pattern. This interaction may suggest that the alpha decrease is sensitive not only to processes underlying semantic integration, but also to processes underlying the processing of rhythmic pattern. It is possible that all these processes are linked to the consumption of attentional resources.

We also found an effect of alpha power *increase* for the abnormal rhythmic pattern in the early 0–200 ms time window. This effect cannot be explained in terms of the link between alpha power and attentional resources. Interestingly, Klimesch et al. (1999) reported that ERS in the alpha band increased with the increase of items to be remembered in the memory retaining state. Alpha increase with working memory load has also been found in other studies (Jensen and Tesche, 2002; Scheeringa et al., 2009). Thus we may attribute the alpha increase for the abnormal rhythmic pattern in our study to the increased working memory load, as the monosyllabic noun perceived might activate the corresponding, more appropriate disyllabic word based on the prosodic expectation derived from the preceding verb. That is to say, it is possible that both the monosyllabic noun and the disyllabic noun sharing the same meaning are activated and retained when the critical monosyllabic noun occurs in the sentence with an abnormal [2+1] rhythmic pattern. This speculation, however, needs to be further tested.

The differentiation between the processing of semantic constraints and that of rhythmic pattern also occurred in beta bands, as the larger power decrease in 16–20 Hz was specifically related to semantic violation while the larger power decrease in 20–24 Hz was specifically related to abnormal rhythmic pattern. Oscillatory activity in the beta band (15–25 Hz) has been primarily assumed to reflect active inhibition of ongoing processes involved in motor tasks (Pfurtscheller, 1992; Pfurtscheller and Lopes da Silva, 1999; Salmelin and Hari, 1994). The neural basis and functional significance of the activity of beta-band rhythms in linguistic paradigms is unclear due to the lack of convergent evidence (Bastiaansen et al., 2005). One reason might be that previous studies focused on different frequency ranges in the beta band, leading to diversified interpretations of the beta power. For instance, Weiss and Rappelsberger (1996) found differences in 13–18 Hz between concrete and abstract nouns; Bastiaansen et al. (2005) reported a power decrease in 16–21 Hz for both open class and closed class words and they interpreted the power decrease as reflecting sensory processing of the visual input; Davidson and Indefrey (2007) reported a reduction in 13–30 Hz for phrase structure violation and they interpreted the finding as suggesting an increase of the involvement of cortical areas in grammatical processing after violation is encountered. Given the findings in the present study, we believe that the beta band activity is unlikely to simply reflect sensory processing. It is more likely to be associated with linguistic functions in language processing. Moreover, given that different frequency bands were specifically associated with the processing of semantic constraints or rhythmic pattern, it is possible that different frequency ranges in the beta band may have different functional roles. The power decrease in the early and later time windows in the 16–20 Hz frequency band for semantic violation may reflect a continuous process related to lexico-semantic integration and reanalysis. The power decrease in the later time window in the 20–24 Hz frequency band for abnormal rhythmic pattern may reflect a reanalysis/repair process of prosodic structure after encountering the abnormality of rhythmic pattern. Collaborative work is needed to distinguish the various functions of beta power.

CONCLUSION

By applying the TF analysis to the EEG data collected by Luo and Zhou (2010), the present study shows distinct power changes for the processing of semantic constraints and the processing of rhythmic pattern in both the early and the later time windows during Chinese sentence reading, although similar decreases in alpha band power were also observed for semantic and rhythmic processing. The low beta decrease in the early window, the alpha and low beta decrease in the later window were associated with the violation of semantic constraints, while the theta and alpha increase in the early window, the alpha and upper beta decrease in the later window were associated with the abnormal rhythmic pattern. These findings suggest that differential neuro-cognitive processes are involved in the processing of the two kinds of linguistic information in Chinese sentence reading.

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