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Processing different levels of syntactic hierarchy: An ERP study on Chinese

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ABSTRACT

The event-related potential (ERP) technique was used to investigate the neural dynamics in processing different levels of the hierarchical syntactic structure during comprehension of Chinese sentences with the *ba* construction. In these sentences, the structural auxiliaries, which mark either the adjective (*-de*) or the adverb (*-di*) category, were embedded in a hierarchical structure at the lower level, i.e., *BA – adjective* (*-de*)*–noun–verb*, or at the higher level, i.e., *BA – noun–adverb* (*-di*)*–verb*. Violations of the lower- and the higher-level structural constraints were constructed by misapplication of these structural auxiliaries. Participants were required to read all the sentences for comprehension and to complete a sentence recognition test at the end of the experiment. Violation of the lower-level constraints elicited a left-lateralized, anteriorly maximized negativity, whereas violation of the higher-level constraints elicited a right anterior negativity (RAN) and a right centro-parietal negativity (N400) from 300 to 500 ms post-onset of the auxiliary phrase. Neither type of violation led to a late positivity effect on the critical auxiliary phrases. These findings suggest that processing different levels of syntactic hierarchy during natural language comprehension may involve different neural mechanisms.

1. Introduction

Human language is represented in the brain with respect to grammatical rules (Chomsky, 1957, 1965). The syntactic hierarchy is created by embedding local sequences within other sequences in either linear or hierarchical way, leading to different levels of syntactic complexity. It has been suggested that processing the higher-level constraints in syntactic hierarchy, characterized by the licensing of complex hierarchical structures and long-distance dependencies, is an ability uniquely endowed to human beings whereas processing the lower-level constraints in syntactic hierarchy, crucially parametered by the local phrase structure, is common to both human and non-human primates (Fitch & Hauser, 2004; Hauser, Chomsky, & Fitch, 2002). It is therefore of great interest to investigate whether such differentiation between the lower- and the higher-level syntactic structures is supported by differential neural mechanisms in language comprehension (Bahlmann, Gunter, & Friederici, 2006; Friederici, 2004; Friederici, Bahlmann, Heim, Schubotz, & Anwander, 2006; Opitz & Friederici, 2007).

Friederici (2004) hypothesized that processing different levels of syntactic hierarchy involves brain structures differing in their phylogenetic age, with the more fundamental rules of lower-level constraints, e.g., the local phrase structure, supported by the phylogenetically older structure and with the more advanced and extricate rules of higher-level constraints, e.g., the recursive, hierarchical phrase structure, supported by the phylogenetically younger structure. Recent neuroimaging studies showed that rule-based processing of artificial grammar for local phrase structural dependencies and long-distance dependencies have different neural correlates on both spatial (Friederici, Bahlmann, et al., 2006; Opitz & Friederici, 2007) and temporal (Bahlmann et al., 2006) scales. In the fMRI study by Opitz and Friederici (2007), participants were trained and tested on a set of artificial grammar (i.e., the modified BROCANTO). Two types of structural dependencies (local vs. long-distance) were contrasted. The local dependency was built by two neighboring syntactic elements which must be of different syntactic categories. The long-distance dependency was built by embedding a sequence (e.g., a complementizer structure) within a local syntactic combination, making the structure more complex and hierarchical. For violation of the local phrase structure, two elements of the same category were successively presented. For violation of long-distance dependencies, the sequence (e.g., determiner–noun–verb) was not preceded by a clause complementizer but by a never-allowed verb-modifier. When brain activities associated with these violations were compared to their respective baselines, the left ventral premotor cortex was activated for the processing of local dependencies whereas the opercular part of the inferior frontal gyrus (Broca's area, BA 44) showed activation for the processing of long distance dependencies.

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Imaging studies using natural languages also implicate differential neural activations for processing violations of hierarchical syntactic structure at different levels. Typically, the lower-level structure processing is investigated by using sentences in which an upcoming syntactic category cannot be integrated into the preceding local syntactic structure (e.g., the preposition structure in the German sentence *Das Eis wurde im gegessen*/*The ice-cream was in the eaten*). The higher-level structure processing is investigated by comparing sentences involving or not involving syntactic transformation and constituent reordering. It was found that the lower-level structural violation elicits activity in the left frontal operculum (for German, Friederici, Rüschemeyer, Hahne, & Fiebach, 2003) whereas processing higher-level, long-distance dependencies activates the Broca's area (for English, Ben-Shachar, Hendler, Kahn, Ben-Bashat, & Grodzinsky, 2003; for German, Bornkessel, Zysset, Friederici, von Cramon, & Schlesewsky, 2005; Röder, Stock, Neville, Bien, & Rösler, 2002; also see Caplan, 2001 for a review). Friederici, Fiebach, Schlesesky, Bornkessel, & von Cramon (2006) parametrically varied the syntactic complexity of hierarchically organized German syntactic constituents from the most canonical (e.g., S–IO–DO–V, in which S = subject, IO = indirect object, DO = direct object, and V = verb) to the less (e.g., IO–S–DO–V) and to the least (e.g., IO–DO–SO–V). The sentence grammaticality was also manipulated. They found that violation of syntactic structures built upon hierarchically ordered constituents engendered activation in deep posterior frontal operculum whereas processing normal sentences with different levels of syntactic complexity was parametrically related to activity in the inferior portion of pars opercularis (BA 44).

In the electrophysiological domain, most studies on syntactic processing focus on the lower-level constraints in syntactic hierarchy, in which the local phrase structure constraints were violated on the main syntactic categories, mostly verbs (for German, Hahne & Friederici, 1999, 2002; for Dutch, Hagoort, Wassenaar, & Brown, 2003; and for Chinese, Ye, Luo, Friederici, & Zhou, 2006) and occasionally on other categories, such as preposition (for English, Neville, Nicol, Barss, Forster, & Garrett, 1991). These local, phrase structure violations typically elicit two ERP components. One is the early left anterior negativity (ELAN, starting at about 150 ms post-onset), reflecting initial phrase structure building processes. The onset of this early negativity could be postponed when the syntactic category information is signaled by the suffix (Friederici, Hahne, & Mecklinger, 1996; Friederici & Meyer, 2004; Hagoort et al., 2003) rather than by the prefix (Gunter, Friederici, & Hahne, 1999; Hahne & Friederici, 1999, 2002). In a study on Chinese, Ye et al. (2006) observed an early starting negativity which merged into a sustained anterior negativity during the P600 time window when a critical sentence-final verb violated the syntactic category constraints of the preposition *ba* during Chinese sentence comprehension. The ELAN is usually accompanied by a late centro-parietal positivity (P600), which starts at about 500 ms after the onset of syntactic violation and lasts for a few hundreds of milliseconds. Syntactic processing may also lead to a task-relevant P600 effect. When the participants are encouraged to judge whether a sentence is grammatical or not, the P600 is observed (Coulson, King, & Kutas, 1998; Gunter, Stowe, & Mulder, 1997; Roehm, Bornkessel-Schlesewsky, Rösler, & Schlesewsky, 2007; van Herten, Kolk, & Chwilla, 2005). The P600 is usually assumed to reflect syntactic reanalysis or repair process (Friederici, Pferfer, & Hahne, 1993; Friederici, Steinhauer, & Pfeifer, 2002; Hahne & Friederici, 1999, 2002; Hahne & Jescheniak, 2001) or effort taken to establish unification links of sufficient strength between syntactic constituents (Hagoort, Wassenaar, & Brown, 2003).

Comparatively, less work has been carried out to investigate the temporal dynamics of processing higher-level, more complex constraints in the hierarchical structure. Several studies examined the long-distance dependencies by comparing grammatical sentences with non-canonical versus canonical word orders (Fiebach, Schlesewsky, & Friederici, 2001; Fiebach et al., 2002; King & Kutas, 1995; Kluender & Kutas, 1993; Phillips, Kazanina, & Abada, 2005; Rösler, Pechmann, Streb, Röder, & Hennighausen, 1998) or by manipulating the easiness of syntactic integration between two separated sentential constituents (Kaan, Harris, Gibson, & Holcomb, 2000). Critical words in the non-canonical sentences typically elicit a frontal negativity whereas the syntactic integration difficulty is associated with a larger amplitude of P600. For example, Phillips et al. (2005) compared English sentences with (e.g., ...*the lieutenant knew which accomplice the shrewd witness would recognize*...) and those without a wh-dependency (e.g., ...*the lieutenant knew the shrewd witness would recognize the accomplice*...). The wh-phrase which marks the initiation of wh-dependency engendered a larger frontal negativity, which sustained for several words. Moreover, the verb (e.g., *recognize*) which marks the completion of wh-dependency engendered a larger positivity. Similar patterns of effects were also observed in studies comparing object- vs. subject-extracted clauses (Fiebach et al., 2001, 2002; King & Kutas, 1995) or comparing sentences with wh-questions vs. yes/no questions (Kluender & Kutas, 1993). The positivity was suggested to reflect the syntactic integration difficulty in processing the complex structure. The frontal negativity was suggested to reflect additional load imposed upon working memory capacity during the processing of long-distance dependencies (Fiebach et al., 2001; Kluender & Kutas, 1993; Rösler et al., 1998).

With one exception, no ERP studies have been conducted to investigate explicitly whether processing different levels of hierarchical syntactic structure may have different neural dynamics. The exception was carried out on the artificial language, in which two types of artificial grammar consisting of sequences of meaningless syllables were learned and tested (Bahlmann et al., 2006). One type of structure was based on local transitions (e.g., ABAB) while another type was based on long-distance dependencies with center-embedded structures (e.g., A[AB]B). It was found that, for violation of local transitions, a 300–400 ms early posterior negativity plus a 400–750 ms late positivity were observed; moreover, these effects did not differ in amplitude or scalp distribution for violation in the early vs. late position of the stimulus sequence. In contrast, for violation of more complex, hierarchical dependencies, only a late positivity was observed and this positivity was larger in terms of amplitude in later vs. early position of violation. Thus, it seems that there exists dissociation in temporal dynamics between the parsing of different levels of syntactic hierarchy, consistent with the fMRI studies.

The main purpose of this study was to collect more evidence from natural language comprehension for the neural dissociation between processing lower- vs. higher-level syntactic structures. To achieve this aim, we manipulated the structural auxiliaries to realize structural violations in Chinese sentences with the *ba* construction.

As an important type of function words in Mandarin Chinese, the structural auxiliaries have been extensively examined in linguistics (e.g., Chao, 1968; Zhu, 1961, 1966). Like a bound morpheme in Western languages, a Chinese structural auxiliary (e.g., 的 , -*de*; 地 , -*di*) adheres to the end of a content lexical item, e.g., noun, adjective, adverb and classifier, such as in 一杯杯的 (yibeibei-*de*, *cups of*) or 一杯杯地 (yibeibei-*di*, *one cup by another*). A structural auxiliary serves to reassign or specify a syntactic category to a given lexical item with which it is connected (Gan, 1986). Generally, a *de-phrase* is marked as an adjective by the auxiliary -*de*, while a *di-phrase* is marked as an adverb by the auxiliary -*di*. These phrases predict the syntactic category of the following words they modify: a noun phrase (NP) or a verb phrase (VP; Chao, 1968; Xu, 2006).

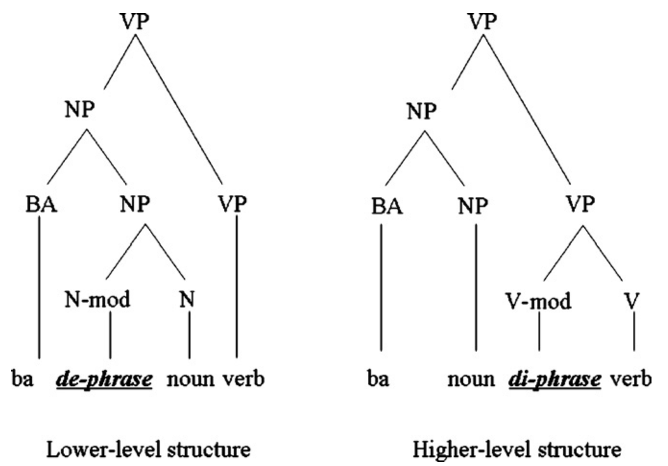

Fig. 1. The syntactic hierarchy of the lower-level and the higher-level structures in the *ba* constructions employed in this study. The critical manipulation was carried out on the auxiliary phrases underlined. P = preposition; NP = noun phrase; N-mod = noun-modifier; VP = verb phrase; V-mod = verb-modifier.

As described in Ye et al. (2006) and Ye, Zhan, and Zhou (2007), the *ba* construction transforms Chinese sentences with the canonical S–V–O order into sentences with a less common format, S–*BA*–O–V. That is, a *ba* sentence has a subject, a function word *BA*, an object NP (which may consist of a noun and its preceding modifiers), and finally a VP (which may consist of a verb and its preceding modifiers). In the *ba* construction, the BA, the following auxiliary phrase (i.e., the adjective) and the modified noun would constitute a local *ba* phrase with a relatively lower-level syntactic structure, whereas the auxiliary phrase (i.e., the adverb), the modified verb, and other preceding constituents would form a more complex syntactic structure (i.e., having more levels of syntactic nodes; see Fig. 1).

From the perspective of online processing, the function word *BA* directly predicts and governs the following NP and indirectly constrains the noun-modifier. In reading comprehension, the parser expects a noun or a combination of adjective (with *-de*) and noun after *BA*. The appearance of a adjective, licensed by the function word *BA*, would initiate a local phrase structure building process linking the modifier with the preceding *BA* and with the predicted (and yet not presented) noun. An auxiliary violation (i.e., an adverb with *-di*) would cause local difficulty in this process and would elicit a violation effect on the phrase. In processing the verb-modifying auxiliary phrase (e.g., the adverb with *-di*), however, the parser needs not only to syntactically link the modifier with the predicted (and yet no presented) verb, but also to link the predicted VP with the preceding *ba* construction (i.e., *BA* + NP), including linking the VP with the NP. Thus syntactic processing of the verb-modifying auxiliary phrase would be at a more complex, higher-level than processing of the noun-modifying auxiliary phrase. A previous study (Ye, Zhan, & Zhou, 2007) has shown that the mismatch between the abstract meaning of *ba* construction and properties of the following verb is sufficient to elicit abnormal ERP responses on the N400 component, even though the link between VP and the preceding NP is perfectly acceptable by itself.

These properties of the Chinese auxiliaries in the *ba* sentences allow us to investigate, in a controlled manner than is possible in Western languages, to what extent the syntactic hierarchy or syntactic complexity, affects the neural dynamics of syntactic processing in natural language comprehension and whether there is a neural dissociation between different levels of syntactic hierarchy, consistent with the hypothesis proposed by Friederici (2004). We manipulated two variables in the experiment: type of structure (lower-level vs. higher-level) and grammaticality (syntactic category violation vs. normal control). Violation of the lower-level structure was created by replacing *-de* with *-di* in the *BA* – *adjective*(*-de*)–*noun*–*verb* structure; violation of the higher-level structure was created by replacing *-di* with *-de* in the *BA* – *noun*–*adverb*(*-di*)–*verb* structure (see Table 1). It should be noted that the adjective or adverb modifiers are optional constituents in the Chinese *ba* sentences and are mostly not expected by the reader (see Section 2).

Based on previous studies on word category processing in sentence comprehension (e.g., Friederici et al., 1993; Hahne & Friederici, 1999, 2002; Hahne & Jescheniak, 2001; Hagoort, 2003; Ye et al., 2006), we predicted that the lower-level structural violation may cause an ELAN effect on the violating words. However, given that the auxiliary *de*/*di* is embedded as the last character of the four-character auxiliary phrase, the latency for processing the syntactic category of the auxiliary phrase might be postponed (i.e., a LAN effect rather than an ELAN effect). For the higher-level structural violation, given the ERP study on the artificial language (Bahlmann et al., 2006) and given the studies on long-distance dependencies (e.g., Fiebach et al., 2001, 2002; King & Kutas, 1995; Kluender & Kutas, 1993; Phillips et al., 2005; Rösler et al., 1998), we also predicted a frontal negativity on the violating words. In addition, if the incorrect use of *de-phrase* in a higher-level violation sentence caused a mismatch between the abstract meaning of *ba* construction and properties of the pre-verbal auxiliary phrase, we may predict a centro-parietal N400 effect in the violation conditions as compared with the control sentence (Ye et al., 2007). The P600 effect may not appear in sentences with either the lower- or the higher-level structural violation because the participants were given no extra task but to read sentences for comprehension. If we indeed obtain differential ERP effects for different structural violations, we may argue that structural processing in natural language comprehension is subserved by different neural mechanisms, depending on the level of syntactic hierarchy (Bahlmann et al., 2006; Friederici, 2004; Friederici, Bahlmann, et al., 2006; Friederici, Fiebach, et al., 2006; Opitz & Friederici, 2007).

A secondary purpose of this study was to examine whether additional syntactic constraint or syntactic expectancy would elicit differential ERP responses on the critical words. To achieve this aim, the auxiliary phrases that were used to modify the nouns or verbs in the two types of control sentences (Table 1) were removed, creating sentences with bare nouns and vebs (Condition 5 in Table 1). One previous ERP study (Hinojosa, Moreno, Casado, Muñoz, & Pozo, 2005) manipulated the strength of syntactic expectancy towards the category of target words and found that, compared with words in the category with higher expectancy, words in the category with lower expectancy elicited a larger negativity with a central distribution in the time window of 300–500 ms post-onset. This enhancement of the N400 magnitude for the unexpected word category was assumed to reflect the temporary difficulty in assigning thematic roles to the current words. In this study, by comparing ERP responses to words modified or not modified by the auxiliary phrases, we could examine whether the processing of current words is affected by an additional syntactic constraint and whether the potential effect can be attributed to the syntactic expectancy towards the category these words belong to.

2. Method

2.1. Participants

Twenty-seven right-handed undergraduate students (15 Females, age ranging from 18 to 26 years, mean = 20.8 years) at Peking University were paid to participate in the experiment. All of them were monolingual native Chinese speakers and had normal or corrected-to-normal vision. Informed consent was obtained from each participant before the experiment. ERP data from two participants (one female) were excluded due to excessive artifacts. This study was approved by the Academic Committee of the Department of Psychology, Peking University.

Table 1
Experimental conditions and exemplar sentences with approximate literal translations. The meaning of these sentences is provided at the bottom of the table. Characters underlined are the critical auxiliary phrases.

Conditions	Examples									
(1)	吴彬	出差	回来，	把	一盒盒的	月饼	分发	到	办公室	。
Lower-level control	BinWu	chuchai	huilai,	ba	yihehede	yuebing	fenfa	dao	bangongshi	
(2)	吴彬	出差	回来，	把	一盒盒地	月饼	分发	到	办公室	。
Lower-level violation	BinWu	chuchai	huilai,	ba	yihehedi	yuebing	fenfa	dao	bangongshi	
	BinWu	business travel	went back,	BA	boxes of	mooncakes	distributed	to	the office.	
(3)	吴彬	出差	回来，	把	月饼	一盒盒地	分发	到	办公室	。
Higher-level control	BinWu	chuchai	huilai,	ba	yuebing	yihehedi	fenfa	dao	bangongshi	
(4)	吴彬	出差	回来，	把	月饼	一盒盒的	分发	到	办公室	。
Higher-level violation	BinWu	chuchai	huilai,	ba	yuebing	yihehede	fenfa	dao	bangongshi	
	BinWu	business travel	went back,	BA	mooncakes	boxes of	distributed	to	the office.	
(5)	吴彬	出差	回来，	把	月饼	分发	到	办公室	。	
With bare noun and verb	BinWu	chuchai	huilai,	ba	yuebing	fenfa	dao	bangongshi		
	BinWu	business travel	went back,	BA	mooncakes	distributed	to	the office.		
	When Bin Wu went back from his business travel, he distributed (boxes of) mooncakes to anyone in the office.									

2.2. Design and materials

All the critical sentences were of the Chinese *ba* construction. Each *ba* sentence has a subject, a subject-modifying clause, a function word BA, an object noun, a main verb, an auxiliary phrase modifying the noun or the main verb, and a sentence-final locative phrase (see Table 1). The auxiliary phrase had four morphemes (four characters) and was always composed of a numeral, two repetitive classifiers and a structural auxiliary *-de* or *-di*. The auxiliary phrase was either an adjective with auxiliary *-de* (e.g., 一盒盒的, *yihehe-de*, *boxes of*) or an adverb with auxiliary *-di* (e.g., 一盒盒地, *yihehe-di*, *one box by another*). The two groups of auxiliary phrases differed only in the phrase-ending auxiliaries. The lower-level structural violation was created by replacing the auxiliary *-de* with *-di* in the *de*-phrase serving as a modifier of the object noun. The higher-level structural violation was created by replacing the auxiliary *-di* with *-de* in the *di*-phrase serving as a modifier of the verb. In Condition 5, the auxiliary phrases in sentences used in other conditions were simply omitted, resulting in correct sentences with a *BA – noun–verb* structure.

A pretest was conducted to examine the expectancy towards the auxiliary phrases. Thirty-two participants who did not participate in the ERP experiment were asked to complete sentence fragments with most appropriate words for the lower-level (*subject + subject-modifying clause + ba*) and the higher-level (*subject + subject-modifying clause + BA + object noun*) conditions. In both cases, the participants did not produce any auxiliary phrases exactly used in the experiment to modify the object nouns or the main verbs. But they did produce other adjective continuations after *BA* for the lower-level condition (23%) and adverb continuations after the *BA + object noun* for the higher-level condition (21%). In other words, in most cases, they produced a noun continuation immediately after BA (77%) or a verb continuation immediately after the object noun (79%). Moreover, no participant produced any adjectives or adverbs in a way similar to the violation conditions in Table 1. These findings ensured that there were no differences in the syntactic category expectancy towards the target auxiliary phrases between the lower-level and the higher-level comparisons.

Another group of 32 participants who also did not participate in the ERP experiment was asked to complete sentence fragments both with and without the auxiliary phrases (i.e., at the noun or the verb position, respectively). For the words produced, we computed percentages of the mostly used words and percentages of the target words that were actually used in sentences. For the mostly used words, the percentages were 30% in sentence fragments with the *de-phrase* (Condition 1), 28% in sentence fragments without the *de-phrase* (Condition 5), 36% in sentence fragments with the *di-phrase* (Condition 3), and 33% in sentence fragments without the *di-phrase* (Condition 5), There were no significant differences between these conditions. For the target words, the percentages were 23%, 22%, 25%, and 29%, respectively for the conditions. Again, there were no significant differences between conditions. These analyses ensured that the target nouns or verbs were equally semantically constrained across conditions. In contrast, the syntactic expectancy towards the category of target words was higher for Conditions 1 and 3 with the auxiliary phrases than for Condition 5 without auxiliary phrases: with no exception, all the participants produced a noun continuation after the sentence fragments in Condition 1 at the noun position or a verb continuation after the sentence fragments in Condition 3 at the verb position, whereas the noun continuation directly after the proposition *BA* was 72% and the verb continuation after the *AB – noun* structure was 73%.

Altogether there were 200 sets of critical stimuli, each describing a different event. Five lists of experimental stimuli were created using a Latin-square design. Each list contained 200 critical stimuli with forty in each condition. Another 148 non-*ba*-sentences with a variety of sentential structures were used as fillers in each list. Sentences in each list were pseudo-randomized with the condition that no more than two consecutive sentences were of the same condition and no more than four consecutive sentences were with or without syntactic violation.

2.3. Procedures

Participants were seated in a comfortable chair in a sound-attenuating and electrically shielded chamber. They were instructed to move their head and body as little as possible and to keep their eyes fixated on a sign at the center of the computer screen before the onset of each sentence. The fixation sign was at the eye-level and was approximately 1 m away. Sentences were presented segment-by-segment in serial visual presentation mode at the center of the screen, with each sentence consisting of a series of 8–11 frames. The auxiliary-phrase was always presented as one segment. Segments were presented in white against black background, with 0.2–1° of visual angle horizontally and 0.2° vertically. Each segment was presented for 400 ms followed by a blank screen lasting 400 ms. This presentation rate was natural and comfortable for Chinese readers (Ye et al., 2007). Sentences were separated by a 2500 ms interval.

Participants were randomly assigned to one of the five experimental lists using a Latin square design. They were required to read all sentences for comprehension and were told that there would be a sentence recognition test after the ERP experiment (see also Federmeier, Wlotko, Ochoa-Dewald, & Kutas, 2007). In addition, participants had to respond to the reference ambiguity in some of the filler sentences by pressing a response key at the end of the sentence. [This design was for the purpose of another study not reported here.] Before the formal test, each participant received 27 practice sentences, including 15 sentences that had the same composition as the critical stimuli. For the recognition test, 40 sentences were selected such that, for each participant, 20 were from the stimuli seen in the list with 4 in each critical condition, and 20 were new. Participants were given three breaks of about 5 min each during the ERP test. On average, the experiment took about 1 h and 45 min, including the time for electrode preparation.

2.4. EEG recording

EEGs were recorded from 62 electrodes in a secured elastic cap (Electrocap International), which were positioned over the midline (i.e., FPZ, FZ, FCZ, CZ, CPZ, PZ, POZ and OZ), over the left hemisphere (i.e., AF7, AF3, FP1, F7, F5, F3, F1, FT7, FC5, FC3, FC1,

T7, C5, C3, C1, TP7, CP5, CP3, CP1, P7, P5, P3, P1, PZ, PO7, PO5, PO3, and O1) and over the corresponding locations in the right hemisphere. The vertical electro-oculogram (VEOG) was recorded from electrodes placed above and below the left eye. The horizontal EOG (HEOG) was recorded from electrodes placed at the outer cantus of each eye. The EEGs on these electrodes were referenced online to the left mastoid and were re-referenced offline to the average of two mastoids. Electrode impedance was kept below 5 kΩ. The biosignals were amplified with a band pass from DC to 100 Hz and digitized on-line with a sampling frequency of 500 Hz.

2.5. Data analysis

Trials contaminated by excessive movement artifacts (mean voltage exceeding ±50 μV) were excluded before averging. For eye-blink rejection, the maximum voltage difference was set at ±150 μV on the vertical EOG channel. Shifts with 300 μV/s were corrected with linear regression. ERPs were computed separately for each participant and for each experimental condition, epoching from −200 to 800 ms after the onset of the auxiliary phrase. In analyzing the potential effects on auxiliary phrases, baseline correction was performed using the average EEG activity in the 200 ms preceding the onset of the target auxiliary phrase. Additional procedures of baseline correction were performed with respect to the first 100 ms ERPs post-onset of the auxiliary phrase. Because the two ways of baseline correction did not change the ERP patterns for the critical comparisons, only the statistical analyses based on the pre-onset baseline were reported here. In analyzing the effect of additional syntactic constraints upon the NP or VP processing, however, only the second way of baseline correction was used since the critical words were preceded by different words in different conditions. Trials with potential amplitude greater than 70 μV were rejected, resulting in 87.4% artifact-free trials overall. On average, each condition had 34 or 35 (out of 40) trials accepted for data analysis. The number of rejected trials did not differ between the conditions, $F < 1$.

The first four experimental conditions (Table 1) formed a 2 (grammaticality: syntactic violation vs. control) × 2 (structure type: lower- vs. higher-level) factorial design. Repeated measures analyses of variance (ANOVAs) were conducted on the average ERP amplitudes in three time windows, 170–230 ms for an early positive component, 300–500 for a negative component, and 600–800 ms for the late positive deflection, locked on either the auxiliary phrases or on the words immediately following the phrases. Two topographical factors were also entered the ANOVAs. The first topographical factor was hemisphere, which had three levels: left, medial and right sites. The second topographical factor was region, which had five levels: frontal, fronto-central, central, centro-parietal and parietal. Thus there were 15 regions of interests (ROI), each had 3 or 2 representative electrodes: left frontal (F3, F5, F7), left fronto-central (FC3, FC5, FT7), left central (C3, C5), left centro-parietal (CP3, CP5, TP7), left parietal (P3, P5, P7), medial frontal (F1, FZ, F2), medial fronto-central (FC1, FCZ, FC2), medial central (C1, CZ, C2), medial centro-parietal (CP1, CPZ, CP2), medial parietal (P1, PZ, P2), right frontal (F4, F6, F8), right fronto-central (FC4, FC6, FT8), right central (C4, C6), right centro-parietal (CP4, CP6, TP8), and right parietal (P4, P6, P8). Averaged ERPs over electrodes in each ROI regions were used for the statistical purpose. When there were significant interactions between grammaticality, type of structure and topographic variables, planned comparisons between the syntactic category violation and its control condition were performed separately on the two types of structure manipulations within each level of topographic variables. To detect the effect of additional syntactic constraint upon the NP or VP processing, additional ANOVAs comparing Condition 1 with Condition 5 on the noun and Condition 3 with Condition 5 on the verb were conducted, with constraint strength and target type as two within-participant factors. The Greenhouse–Geisser correction was applied when appropriate (Geisser & Greenhouse, 1959).

3. Results

3.1. Behavior

In the sentence recognition test, participants correctly recognized on average 17 out of the 20 experimental sentences (84.7%) and made false responses to on average 2 of the 20 new sentences (9.1%). Repeated-measures ANOVA revealed neither the main effect of grammaticality or type of structure, nor the interaction between the two, Fs < 1. This suggests that participants paid attention equally well to stimuli of the lower- and the higher-level structures.

3.2. ERPs

Figs. 2–4 depict the ERP observations on the auxiliary phrases in different conditions. Visual inspection of the waveforms revealed more negative deflections on the auxiliary phrases in sentences with syntactic violations as compared with the control sentences on some of the electrodes. Sentences with structural violations appeared to be deviated from the controls on the early positive component (170–230 ms), the second negative component (300–500 ms) and the late positive deflection (600–800 ms). Moreover, the negativity effects for the lower-level structural violation had a clear left lateralization and appeared to be stronger in the anterior regions (Fig. 2). In contrast, the negativity effects for the higher-level structural violation was right lateralized and appeared to be composed of two components: a frontal negativity and a centro-parietal negativity (Figs. 3 and 4). These descriptive findings were examined by the statistical analyses over the above three windows.

3.3. Effects of syntactic violation

ANOVA with grammaticality, structure type, hemisphere and region as four within-participant factors did not reveal a significant effect of grammaticality in the 170–230 ms (i.e., P200) window, $F(1, 24) = 1.26$, $p > 0.1$. The main effect of structure type was not significant either, $F(1, 24) = 1.71$, $p > 0.1$. The main effect of hemisphere was significant, $F(2, 48) = 30.07$, $p < 0.001$, with ERP responses on the medial electrodes the most positive (3.10 μV), less so on the right hemisphere (2.33 μV) and the least so on the left hemisphere (1.18 μV). The main effect of region was also significant, $F(4, 96) = 8.25$, $p < 0.01$, with ERP responses in the anterior regions more positive than in the posterior regions. Similarly, in the 600–800 ms time window, the main effect of grammaticality was not significant, $F(1, 24) = 2.84$, $0.05 < p < 0.1$, neither the main effect of structure type, $F < 1$. Only the three-way interaction between grammaticality, structure type and hemisphere was significant, $F(2, 48) = 3.53$, $p < 0.05$. It appears on Figs. 2 and 3 that sentences with lower-level syntactic violation elicited a negativity effect mainly in the left hemisphere in this time window whereas sentences with higher-level syntactic violation elicited a negativity effect mainly in the right hemisphere. These effects, however, did not reach significance in further analyses.

Importantly, ANOVA with grammaticality, structure type, hemisphere and region as four within-participant factors found a significant main effect of grammaticality in the 300–500 ms time window, $F(1, 24) = 7.28$, $p < 0.05$, demonstrating that the syntactic violations in general elicited more negative-going activity as compared with the controls. The main effect of structure type was significant (see later), so the main effect of hemisphere, $F(2, 48) = 15.50$, $p < 0.001$. ERP responses on the left hemisphere electrodes were the most negative (−1.00 μV), less so on the medial (−0.66 μV) and positive on the right hemisphere (0.36 μV). The main effect of region was significant, $F(4, 96) = 31.90$, $p < 0.001$, with ERP responses more negative on the anterior electrodes than on the posterior electrodes. Moreover, ANOVA for this time window revealed a significant three-way interaction between grammaticality, structure type, and hemisphere, $F(2, 48) = 13.01$, $p < 0.001$, suggesting that the violation effects for the two types of syntactic structures were distinct in scalp distribution (see Fig. 4). This interaction was resolved by further, separate analyses for each type of violation and each hemisphere site.

For the lower-level conditions, ANOVA with grammaticality and region as two within-participant factors revealed a significant main effect of grammaticality (−1.67 μV for the violation and −0.75 μV for the control) on the left hemisphere, $F(1, 24) = 9.55$, $p < 0.001$, but not on the medial, $F(1, 24) = 2.25$, $p > 0.1$, or the right sites, $F < 1$. Although the interaction between grammaticality and region was not significant for the left hemisphere, $F < 1$, it seems that the negativity effect was stronger in the anterior regions than in the posterior regions (−1.27 μV, −0.97 μV, −0.78 μV, −0.86 μV, and −0.80 μV, respectively over the left frontal, left frontal-central, left central, left central-parietal, and left parietal regions; see Fig. 4). A broadly distributed negativity with anterior maximum was also

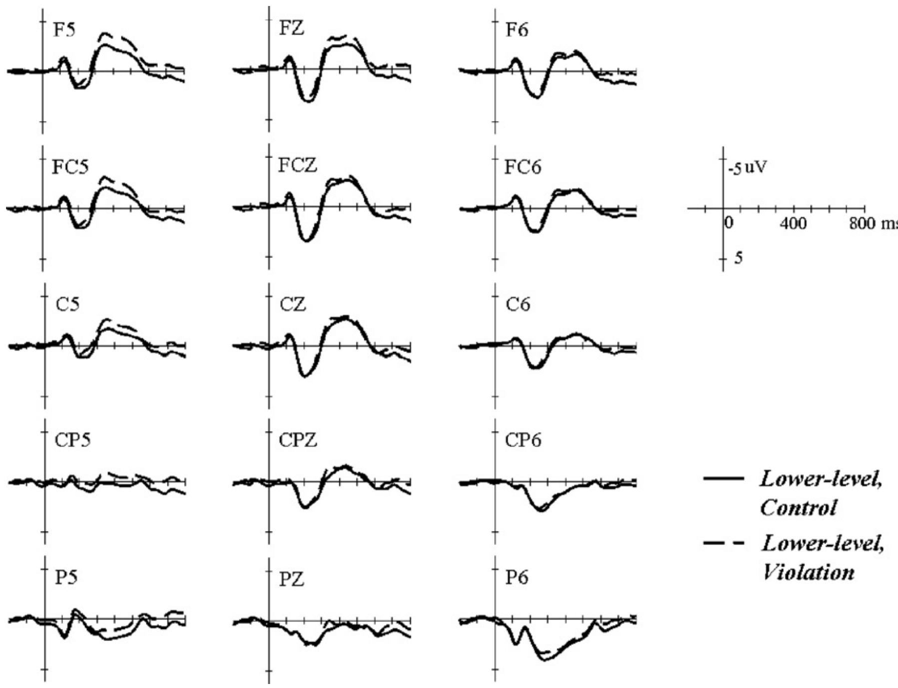

Fig. 2. Grand average ERP waveforms, at 15 exemplar electrodes, for auxiliary phrases satisfying or violating the lower-level syntactic constraints. The solid line represents the grammatical sentences and the broken line represents the ungrammatical sentences.

observed for spoken Chinese sentences with local structural violation (Ye et al., 2006).

For the higher-level conditions, ANOVA with grammaticality and region as two within-participant factors revealed a significant main effect of grammaticality on the right site electrodes, $F(1, 24) = 5.69$, $p < 0.05$, but not on the medial, $F(1, 24) = 3.18$, $0.05 < p < 0.1$, or the left site electrodes, $F < 1$. Moreover, although the interaction between grammaticality and region in the right hemisphere did not reach significance in the overall ERP analysis covering the whole time window, $F(4, 96) = 2.12$, $p > 0.1$, a further ANOVA dividing the time window into smaller ones (300–350 ms, 350–400 ms, 400–450 ms, 450–500 ms; see Fig. 4) and with the time series as an additional factor did reveal a significant two-way interaction effect between grammaticality and region, $F(4, 96) = 4.33$, $p < 0.05$. The higher-level structural violation elicited a significant negativity effect in the right frontal ($-0.97\ \mu V$), $F(1, 24) = 5.59$, $p < 0.05$, the right central ($-0.95\ \mu V$), $F(1, 24) = 5.88$, $p < 0.05$, and the right centro-parietal ($-0.69\ \mu V$), $F(1, 24) = 4.75$, $p < 0.05$, but not in the right fronto-

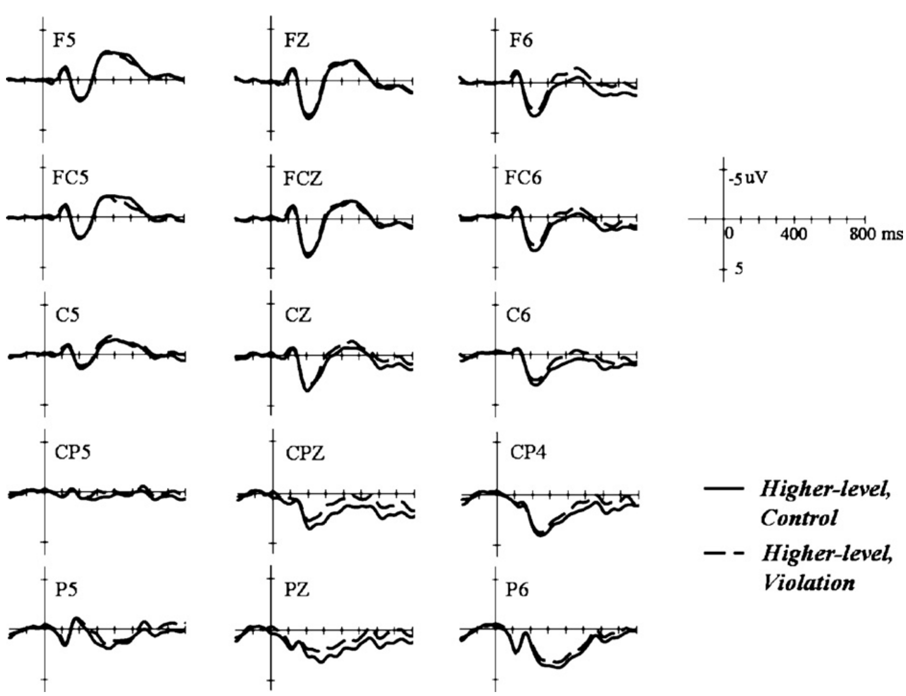

Fig. 3. Grand average ERP waveforms, at 15 exemplar electrodes, for auxiliary phrases satisfying or violating the higher-level syntactic constraints. The solid line represents the grammatical sentences and the broken line represents the ungrammatical sentences.

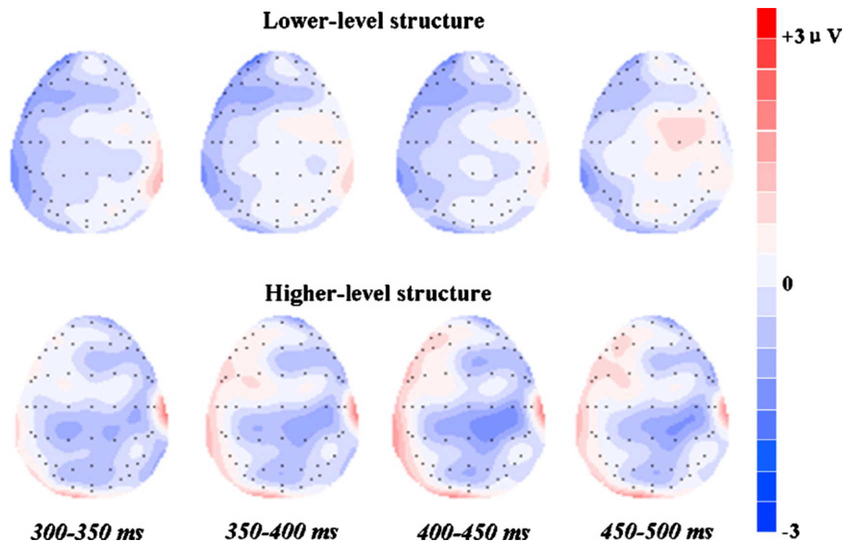

Fig. 4. Topographic distributions of the mean differences between the lower-level violation sentences and the controls (top panel) and between the higher-level violation sentences and the controls (bottom panel) in the consecutive time windows. The differentiation of the RAN and the N400 for the higher-level structural violation can be seen over the time course.

central (−0.47 μV), $F(1, 24) = 3.42$, $p > 0.1$, and the right parietal region (−0.45 μV), $F(1, 24) = 1.95$, $p > 0.1$, suggesting that the negativity on the right hemisphere in this time window was composed of two independent ERP effects (i.e., a frontal negativity and a centro-parietal negativity; see Fig. 4), consistent with the hypotheses laid out in Section 1. Indeed, although the frontal negativity was only obtained on the right hemisphere, the centro-parietal negativity was extended to the medial site: for the medial central (−0.93 μV), $F(1, 24) = 5.35$, $p < 0.05$; for the medial centro-parietal (−0.99 μV), $F(1, 24) = 7.92$, $p < 0.05$ (see also Fig. 4). This centro-parietal negativity was very likely to be the N400 effect.

3.4. The main effect of structure type

For the 170–230 ms time window, ANOVA with grammaticality, structure type, hemisphere and region as four within-participant factors, did not reveal a main effect of structure type, $F(1, 24) = 1.71$, $p > 0.1$, nor its interaction with grammaticality, $F(1, 24) = 1.81$, $p > 0.1$. Although it appeared in Fig. 5 that auxiliary phrases in grammatical sentences of the higher-level structure did elicit more positive P200 than auxiliary phrases in grammatical sentences of the lower-level structure on the medial and right sites, separate analysis on the grammatical sentences showed an at most marginally significant effect, $F(1, 24) = 3.65$, $p = 0.068$. For the 300–500 ms window, the main effect of structure type was significant, $F(1, 24) = 6.63$, $p < 0.05$, with sentences of the lower-level structure (−0.89 μV) more negative than sentences of the higher-level structure (0.03 μV). Moreover, this effect interacted significantly with grammaticality and hemisphere, $F(2, 48) = 13.01$, $p < 0.001$. This three-way interaction was resolved by further, separate analyses for the grammatical and ungrammatical sentences.

For the grammatical sentences (Fig. 5), ANOVA with structure type, hemisphere and region as three within-participant factors revealed a significant main effect of structural type, $F(1, 24) = 5.17$, $p < 0.05$, with sentences of the lower-level structure (−0.62 μV) more negative than sentences of the higher-level structure (0.26 μV). Moreover, structure type interacted with hemisphere, $F(2, 48) = 14.02$, $p < 0.001$, with significant effects on the medial sites, $F(1, 24) = 7.45$, $p < 0.05$, and on the right hemisphere, $F(1, 24) = 11.04$, $p < 0.005$, but not on the left hemisphere, $F < 1$.

For the ungrammatical sentences, ANOVA with structural type, hemisphere and region as three within-participant factors revealed a significant main effect of structure type, $F(1, 24) = 5.09$, $p < 0.05$, with sentences of lower-level structure (−1.16 μV) more negative than sentences of higher-level structure (−0.20 μV). No interactions were found between structure type and hemisphere or region, suggesting that this negativity was broadly distributed. Hence the only difference between the grammatical and ungrammatical sentences for the effect of structure type was in the hemispheric distribution.

3.5. Effects of structural violation on ERP responses to the following nouns or verbs

Although we did not observe a P600 effect in the 600–800 ms time window in ERP responses to the critical auxiliary phrases with structural violations, further analyses did reveal late positivity effects on the nouns or the verbs following these phrases, as shown in the main effect of grammaticality, $F(1, 24) = 6.32$, $p < 0.05$. While the effect on the nouns in sentences of lower-level structure was anteriorly distributed, the effect on the verbs in sentences of higher-level structure was posteriorly distributed, as reflected by a significant three-way interaction between grammaticality, structure type and region, $F(8, 192) = 7.27$, $p < 0.01$. Thus, the nouns following structural violation produced a late positivity effect in the frontal [$F(1, 24) = 5.92$, $p < 0.05$] and fronto-central [$F(1, 24) = 5.32$, $p < 0.05$] regions, and the verbs following structure violation produced a late positivity effect in the parietal region [$F(1, 24) = 6.11$, $p < 0.05$]. However, given that the nouns and the verbs differed in a number of dimensions, such distributional differences may not be related to the level of structural violation.

3.6. ERP responses to nouns and verbs additionally constrained by auxiliary phrases

It appeared in Fig. 6 that nouns and verbs modified by auxiliary phrases elicited more positive ERP responses than bare nouns and verbs in posterior regions (left centroparietal, left parietal, medial centroparietal, medial parietal, right centroparietal, and right parietal). ANOVA with constraint strength, target word type, hemisphere and region as four within-participant factors was

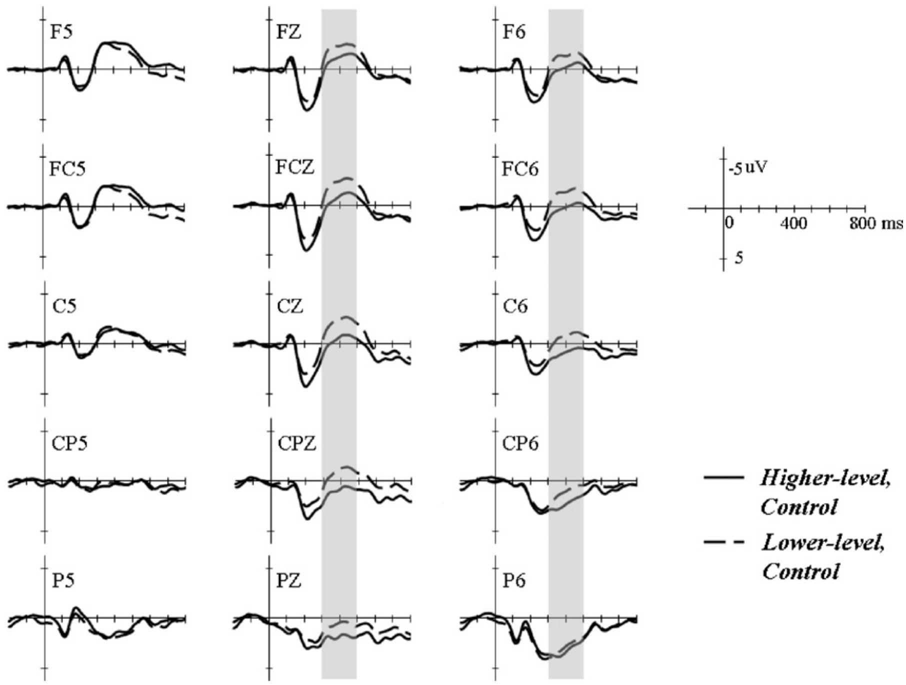

Fig. 5. Grand average ERP waveforms, at 15 exemplar electrodes, for auxiliary phrases in the grammatical (control) sentences with the lower- and the higher-level constraints. Mean amplitudes are computed for ERPs (N400) in the shadowed time windows for the purpose of statistical analyses.

conducted on the posterior ERP responses in the time window of 300–700 ms. The main effect of constraint strength was significant, $F(1, 24) = 3.27$, $p < 0.05$. This effect (0.98 μV) did not interact with target type, $F < 1$, but with hemisphere, $F(2, 48) = 3.11$, $p < 0.05$, indicating that this effect was larger on the left than on the right sides. Thus, the additional syntactic constraint provided by auxiliary phrases would elicit a sustained positivity on the processing of the critical words being modified.

4. Discussion

The main purpose of this study was to investigate the differential neural dynamics in processing different levels of hierarchical syntactic structure during Chinese sentence comprehension. Two factors were crossed: whether the auxiliary phrase was embedded in a lower-level or a higher-level syntactic structure, and whether the auxiliary phrase satisfied or

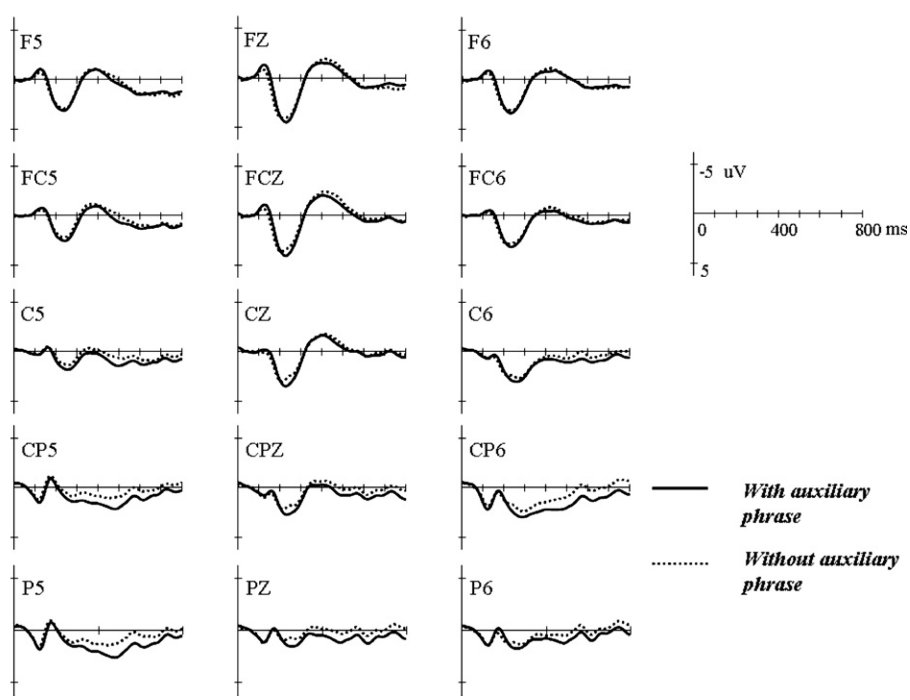

Fig. 6. Grand average ERP waveforms, at 15 exemplar electrodes, for nouns and verbs modified by auxiliary phrases (Conditions 1 and 3) and for bare nouns and verbs (Condition 5). ERP waveforms are collapsed over the two types of critical words.

violated the syntactic category constraints of its preceding syntactic context. In the 300–500 ms time window, ERP responses to the auxiliary phrases violating the lower-level structural constraints showed a left-lateralized, anteriorly maximized negativity. In contrast, ERP responses to the auxiliary phrases violating the higher-level structural constraints showed a right-lateralized negativity, which was very likely composed of two components: a right anterior negativity and a centro-parietal negativity (N400) maximizing in the right hemisphere and extended to the medial sites. Neither type of structural violation elicited a P600 effect on the critical auxiliary phrases. Moreover, auxiliary phrases embedded in the lower-level or the higher-level structures elicited differential ERP responses in general, with the ones in the higher-level demonstrating a smaller negativity (i.e., N400) than ones in the lower-level. Furthermore, ERP responses to nouns and verbs modified by auxiliary phrases were more positive, at posterior regions and in the 300–700 ms time window, than ERP responses to bare nouns and verbs. These findings were not entirely consistent with our predictions laid out in Section 1. In the following discussion, we focus on three issues: (1) lower-level constraints in a hierarchical structure and left-lateralized, anteriorly maximized negativity; (2) processing high-level constraints in a hierarchical structure; and (3) neural differentiation in processing different levels of syntactic hierarchy.

4.1. Lower-level constraints in a hierarchical structure and left-lateralized negativity

In this experiment, violation of lower-level constraints in a hierarchical syntactic structure elicited a left-lateralized, anteriorly maximized negativity between 300 and 500 ms post-onset of the critical stimuli. This finding is not, on the surface, entirely consistent with earlier studies showing that violation of local phrase structure constraints is typically associated with an early left anterior negativity (ELAN). This ELAN for word category violation has been observed across a variety of languages, including German (Friederici et al., 1993; Hahne & Friederici, 1999, 2002; Münte, Heinze, & Mangun, 1993), English (Neville et al., 1991), French (Isel, Hahne, Maess, & Friederici, 2007), as well as Chinese (Ye et al., 2006). However, as pointed out in Section 1, the onset of this early negativity is postponed when the syntactic category information is signaled by the suffix rather than by the prefix, resulting in LAN (left anterior negativity). Although LAN is typically associated with the processing of local violation of morpho-syntactic (inflectional) constraints, such as the subject–verb number disagreement (Kutas & Hillyard, 1983; Osterhout & Mobley, 1995), the verb tense/participle inflection violation (Friederici et al., 1993; Kutas & Hillyard, 1983), and the gender/number disagreement (Barber & Carreiras, 2005; Gunter, Friederici, & Schriefers, 2000), some studies demonstrated that LAN can be observed for both local phrase structure violation and verb inflection violation (Newman, Ullman, Pancheva, Waligura, & Neville, 2007), suggesting that there may exist shared neurocognitive substrates for processing the rule-governed local phrase structure and morpho-syntax (Ullman, 2001, 2004).

In this experiment, the structural violation was realized by the word-ending auxiliary *-de*/*-di* in the four-character auxiliary phrase. A possible interpretation for the observation of an anteriorly maximized left negativity rather than ELAN in Chinese is that a morpho-syntactic process is involved in the current violation, in accordance with the three-stage parsing model (Friederici, 2002). In Mandarin Chinese, the structural auxiliary functions to reassign or specify a particular syntactic category to the given lexical item with which it is connected (Gan, 1986). The observation of a left-lateralized, anteriorly maximized negativity, rather than the typical LAN, is consistent with Ye et al. (2006), which showed that the local structural violation in Chinese engendered an early starting, broadly distributed negativity, also anteriorly maximized.

LAN has also been observed in sentences that made a heavy demand on working memory (King & Kutas, 1995; Kluender & Kutas, 1993). For instance, King and Kutas (1995) observed LAN in response to verbs in object-relative sentences as compared with subject-relative sentences in English. The object-relative structures tax more on working memory than subject-relative structures, because the antecedent words are more distant from the sites of their probable reactivation. In this experiment, however, the auxiliary in the lower-level structure was close to either the preceding *BA* or to the noun it modified. Moreover, sentences with the structural violation did not differ from their control sentences in terms of sentence constituents omitted or added, as was the case in those working memory studies. Therefore, the LAN-like effect observed here could not be attributed to a high working memory load in the ungrammatical as compared with the grammatical sentences (cf. Vos, Gunter, Kolk, & Mulder, 2001).

Interestingly, violations in the auxiliary phrases, which were optional sentential constituents, did not elicit a P600 effect which usually accompanies ELAN for phrase structure violation on mandatory sentential constituents (Friederici et al., 1993, 2002; Hahne & Friederici, 1999, 2002; Hahne & Jescheniak, 2001). It is plausible that the occurrence of the P600 effect for phrase structure violation relies upon the necessity of the constituent in the structure. Alternatively, the absence of the P600 effect on the critical auxiliary phrases could be due to the absence of an explicit task demand on each sentence or due to the unexpectedness of these phrases as continuation within the lower-level or the higher-level structures, as demonstrated by the pretests. Gunter et al. (2000) observed that the magnitude of syntactic P600 effect was reduced on words with low cloze probability as compared with words with high cloze probability. To the extent these alternatives stand, they are consistent with the claim that the P600 is related to strategic control in syntactic processing (Gunter & Friederici, 1999; Hahne & Friederici, 1999).

4.2. Processing the higher-level syntactic structure

In contrast to the LAN-like effect observed for the lower-level structural violation, violation of higher-level structural constraints elicited, between 300 and 500 ms and on auxiliary phrases, a right-lateralized negativity which was likely composed of an anterior negativity (RAN) and a right centro-parietal negativity. One might argue that the distinction between the left and the right negativities reflects simply a fundamental difference between violations in the nominal domain vs. violations in the verbal domain. However, it should be noted that it was the violation effect we obtained on the noun-modifiers, rather than on the verb-modifiers, that was similar to the effect for local phrase structure violation on verbs in previous studies (e.g., Hagoort, 2003; Hahne & Friederici, 1999, 2002; Ye et al., 2006).

Consistent with our hypothesis in the Introduction, a centro-parietal negativity was engendered by the higher-level structural violation. We would like to interpret this negativity as a construction based N400 effect (Ye et al., 2007). As discussed in Ye et al. (2007), the *ba* construction in Chinese has abstract meanings such as “causation” or “disposal” and it permits only verbs encoding such meanings to appear in the construction (Chao, 1968; Cui, 1995; Lü, 1984; Wang, 1943). For example, although it is perfectly acceptable to say “shimin xinshang minghua [the citizens viewed the famous paintings]”, it is not acceptable to say “*shimin ba minghua xinshang* [The citizens BA the famous painting *viewed*], because the “view” action cannot result in state change and it does not fit with the "disposal" or "causation" meaning of the *ba* construction. But by forcefully transforming such S–V–O sentences into *ba* sentences, a semantic mismatch between the *ba* construction and the verb is created. It was found that this mismatch elicits a N400 effect, although this effect is weaker than the N400 effect for lexical-semantic mismatch (Ye et al., 2007).

Similarly, with the *ba* construction of *BA – noun*, the following verb should have the abstract meaning of "causation" or "disposal"; moreover, the verb-modifier preceding the verb should also be semantically compatible with the meaning conveyed by the *ba* construction. Specifically, this verb-modifier should encode the meaning of "in which manner", which would be compatible with the abstract meanings embodied in the *ba* construction and the verb, i.e., the modifier expressing "in which manner" can describe an action of "causation". The adverb phrase with the auxiliary *-di* does encode the meaning of "in which manner", but the adjective phrase with the auxiliary *-de* encodes only the meaning of "what kind of" or "how many". Consequently, violation of the higher-level structural constraints leads to a semantic mismatch between the auxiliary phrase and the *ba* construction of *BA – noun*, eliciting the centro-parietal negativity we observed in this study. Note, the absence of this negativity for the lower-level structural violation does not contradict the argument here, but rather strengthens this argument. As pointed out by Ye et al. (2007), it is not the mismatch between the function word *BA* itself and the following verb (or the verb-modifier) that elicits the N400 effect; it is the mismatch between the *ba* construction, which requires the combination of *BA* and the following noun, and the verb (or the verb-modifier) that elicits the N400 effect. For sentences with the lower-level constraints, the *ba* construction has not been established by the time the auxiliary phrase appears.

A striking finding for the violation of the higher-level structural constraints in this study was the observation of right negativity (RAN), rather than LAN, on the auxiliary phrases. It was as if the neural dominance underlying the anterior negativity has been shifted from the left to the right hemisphere for processing more complex, higher-level constraints in the hierarchical syntactic structure. Yamada and Neville (2007) reported a similar anterior negativity with a right maximum in response to the pronoun which cannot be integrated into a complex verb argument structure. In their experiment, English sentences like *Mommy can cut the meat with her *that knife* were visually presented word-by-word while the participant was asked to judge whether a sentence was grammatically acceptable. The presence of an extra demonstrative pronoun (*that*) after an already complete verb argument structure elicited a right frontal negativity (between 180 and 250 ms post-onset) as compared with the control sentence. However, when the pronoun only violated the local syntactic constraints derived from a preceding verb, this anterior negativity was larger in the left hemisphere (see also Coulson et al., 1998). The right negativity, with a relative late onset (300 or 400 ms post-onset of the critical words), was also observed for morpho-syntactic processing when the verb violated the constraints of a tense-structure (i.e., *The cat won't eating the food that Mary leaves them*; Osterhout & Nicol, 1999) or doubly violated the constraints of both person and number on a nominal feature hierarchy (i.e., *You*[2nd *person plural] jump* [1st *person single]in the backyard*; Silva-Pereyra & Carreiras, 2007). The right distribution might be a consequence of processing the hierarchical organization of the agreement features (e.g., tense, person and number, etc.), although these studies did not provide an explicit account for the effect. It is intriguing that the hemispheric dissociation between processing the lower-level and the higher-level hierarchical structures should be observed in this study. We discuss this neural differentiation in more detail in the next paragraphs.

4.3. Neural differentiation in processing different levels of syntactic hierarchy

Violation of the lower-level and the higher-level constraints in the hierarchical syntactic structure elicited the left-lateralized and the right-lateralized negativity, respectively on the critical auxiliary phrases. Moreover, auxiliary phrases embedded in the lower-level structure elicited in general a more negative N400 than auxiliary phrases embedded in the higher-level structure, irrespective of whether the sentences were grammatical or not. These contrasting effects demonstrated that processing different levels of syntactic hierarchy in natural language comprehension may involve different neural mechanisms, consistent with the hypothesis by Friederici (2004) and echoing findings in processing artificial grammar (Bahlmann et al., 2006; Friederici, Bahlmann, et al., 2006; Opitz & Friederici, 2007).

As the initial piece of evidence for natural language processing, we observed a clear shift of topographical lateralization of the negativity effect associated with processing the lower- vs. the higher-level syntactic structure. This was somewhat different from Bahlmann et al. (2006) on artificial language processing, which obtained a posteriorly distributed early negativity and a late positivity for the lower-level structural violation and only a late positivity for the higher-level structural violation.

Bahlmann et al. (2006) accounted for the posteriorly distributed early negativity in terms of violation of expectation towards the incoming constituents (i.e., syllables). Here the negativity effects observed were mostly anteriorly maximized and may not be attributed to violation of expectation, which was minimal anyway for the sentences used (see the pretests in Section 2). It is likely that these anteriorly maximized negativities reflect a structural (for either the lower-level or the higher-level) building process. Indeed, the local structural building process is usually characterized by ELAN, which is typically identified in native speakers but not in non-native speakers (Hahne, 2001; Hahne & Friederici, 2001; Müller, Hahne, Fujii, & Friederici, 2005; Weber-Fox & Neville, 1996). An ERP study found that the early negativity in response to word category violation in Japanese sentences was anteriorly maximized for the native Japanese but was posteriorly maximized for the German participants trained on Japanese (Müller et al., 2005). Processing the artificial grammar is a less skilled process while processing the natural sentences involves the more skillful structural building process. By analogy, the negativity should be more posteriorly distributed for the former and more anteriorly maximized for the latter.

Before we move on to the potential functions of RAN for the higher-level structural violation, we may rule out some possible accounts on the basis of current experimental manipulations and findings. Firstly, the finding of RAN is not necessarily contradictory to the finding of frontal negativity in comparing grammatical sentences with non-canonical vs. canonical word orders (Fiebach et al., 2001, 2002; King & Kutas, 1995; Kluender & Kutas, 1993; Phillips et al., 2005; Rösler et al., 1998) or the P600 effect in the manipulation of the easiness of syntactic integration between two separated sentential constituents (Kaan et al., 2000). Syntactic complexity can be realized in different ways (Chomsky, 1965), such as self-embedding or left branching. Processing such structures does not necessarily involve the same neural mechanisms. Secondly, the differential neural activities for the lower- vs. the higher-level structural violation cannot be simply attributed to differences in structure anticipation, even though the level of expectancy towards a particular word category was found to modulate the anterior negativity elicited by the word category violation (Lau, Stroud, Plesch, & Phillips, 2006). For sentences in the lower-level conditions in this study, the appearance of *BA* preceding the critical auxiliary phrase signaled to the parser that a NP should follow. This NP could be a single noun, a noun-noun combination, or an adjective-noun phrase. The appearance of an adverb with *-di* violated this expectation, leading to the anterior negativity. However, this structural prediction account should predict an equivalent effect for the higher-level structural violation since the critical auxiliary phrases were equally predictable for the lower-level and the higher-level conditions (see the pretests in Section 2). The observed differential ERP responses in the left and the right hemispheres thus cannot be reduced to differences in the anticipation of specific syntactic categories. Thirdly, since the lower-level and the higher-level conditions differed also in whether a function word or a content word preceded the critical auxiliary phrase (see Table 1), one might argue that the neural dissociation between processing the different-level structural violations was somehow related to the semantic integration process between the auxiliary phrase and its preceding word or context. This argument has some merit, as we pointed out above, and it may be the basis for the overall differential ERP responses between the lower-level and the higher-level conditions (see Fig. 5 for an example). However, it is not clear how this semantic process could affect the earlier structure building process and the pattern of the anterior negativity.

On the other hand, RAN may still reflect a syntactic process, as LAN, albeit at a higher level. RAN has been observed for the violation of music syntax when participants listened to harmonically inappropriate/unexpected chords presented within a musical chord sequence as compared with the appropriate ones (Koelsch et al., 2001; Koelsch, Gunter, Wittfoth, & Sammler, 2005; Koelsch & Siebel, 2005). This effect appeared to be larger for musical experts than for novices (Koelsch, Schmidt, & Kansok, 2002). A MEG study further showed that the right negativity was generated in Broca's area and its homologous region in the right hemisphere (Koelsch, Maess, & Friederici, 2000). It is possible that the right or even the bilateral anterior negativity is responsive to the higher-level syntactic violation in language comprehension, in a way similar to the processing of music syntax. Alternatively, RAN in the higher-level syntactic processing may be related to certain inhibitory processes in general. In a stop-signal task, a right frontal negativity associated with the inhibitory process was reduced in children with attention-deficit/hyperactivity disorder, as compared with normal controls (Plizska, Liotti, & Woldorff, 2000). Moreover, the amplitude of such negativity correlated with performance in response inhibition and was larger for successful inhibition than for failed inhibition (Schmajuk, Liotti, Busse, & Woldorff, 2006). In a recent study, Ye and Zhou (2008) found that the individuals' performance in conflict control, as measured by the Stroop task, can predict their ERP patterns in sentence comprehension and that individuals with higher ability in conflict control showed a right-maximal anterior negativity for semantically implausible passive sentences as compared with the plausible ones. The authors related this negativity to an inhibitory process in which implausible semantic representation is being suppressed. Obviously, further studies are needed to explore the exact functional significance of RAN and to localize brain structures involved in processing different levels of syntactic hierarchy in natural language comprehension.

4.4. Effects of additional syntactic constraint upon ERP responses to nouns and verbs

Although it was not the main focus of the current study, we examined the effect of additional syntactic constraint provided by auxiliary phrases upon the processing of nouns and verbs. We observed a sustained (300–700 ms post-onset) positivity upon the critical words modified by the auxiliary phrases, as compared with the same words without this additional constraint. One would be inclined to attribute this effect to the syntactic expectancy towards to the category of the target words since the category of these words was 100% predicted in sentence fragments with auxiliary phrases but was only about 72% predicted in sentence fragments without auxiliary phrases. However, when Hinojosa et al. (2005) manipulated the syntactic expectancy towards the critical words in Spanish, they observed reduced N400 for words in the highly expected category. The difference in findings between this study and Hinojosa et al. (2005) implies that the effect we observed may not be attributed to the difference in syntactic expectancy towards the target word category between experimental conditions. An alternative explanation, consistent with the general arguments of this study, is that the stronger positivity for the critical words modified by auxiliary phrases, as compared with the bare words, may reflect the effect of processing additional syntactic complexity for the former than for the latter words. The nouns or verbs are in a higher syntactic level when they are modified by auxiliary phrases (i.e., forming an additional level of NPs or VPs on the syntactic tree) than when they stand alone. This explanation would be consistent with early findings that additional syntactic complexity in sentence comprehension would elicit the P600 (Fiebach et al., 2001, 2002; Kaan et al., 2000; King & Kutas, 1995), which our finding resembled. Further studies are needed to investigate this issue.

5. Conclusion

By embedding auxiliary phrases at different levels of syntactic hierarchy, this study observed distinct ERP responses to violations of structural constraints, with the processing of lower-level constraints associated with a left, anteriorly maximized negativity and the processing of higher-level constraints associated with a right anterior negativity (RAN) and a right centro-parietal negativity (N400). Neither types of violation led to a late positivity effect on the critical auxiliary phrases. These findings suggest that processing different levels of syntactic hierarchy may involve different neural mechanisms during natural language comprehension. The left-lateralized negativity is possibly related to processes of building a local, lower-level syntactic structure while the right-lateralized anterior negativity may be related to processes of building up a more complex, higher-level syntactic hierarchy.

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