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Sentence integration processes: An ERP study of Chinese sentence comprehension with relative clauses

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ABSTRACT

In an event-related potentials (ERPs) study, we examined the comprehension of different types of Chinese (Mandarin) relative clauses (object vs. subject-extracted) to test the universality and language specificity of sentence comprehension processes. Because Chinese lacks morphosyntactic cues to sentence constituent relations, it allows a test of the possibility that semantic-contextual processes dominate the extraction of clausal relations, in contrast to the structure-dependent processing in English and many other languages. ERP results at the RC embedded verbs showed a P600 effect for the subject-extraction type, reflecting a processing of phrasal reconfiguration, and an N400 effect for the object-extraction type, reflecting a processing of meaning reinterpretation. A central–frontal sustained negativity was produced by the RC head noun of object-extraction, suggesting a combined effect of meaning derivation and referents establishment. LORETA (Low Resolution Electrical Tomography) source localization showed activation of posterior dominance (e.g., BA 22/39/19/41/42) supporting the integration of structure mapping (P600) and meaning derivation (N400) in a developing sentential representation, consistent with the memory unification and control model (Hagoort, 2005). More left-lateralized anterior regions of a frontal–temporal network (e.g., BA 47/38) became active later in the sentence (a sustained central–frontal negativity), when the thematic-role specification for multiple referents may have required additional cognitive and memory resources. Our findings suggest that Chinese sentence reading recruits a neural network that is sensitive to the sequential/hierarchical organization of linguistic inputs in a manner that resembles to the structure-dependent cognitive processes in other languages, reflecting a universal property of language processing. The ERP data shows that early lexical processes are important in the integration process, but also challenges the view that Chinese text reading depends primarily on semantic-contextual processing in the derivation of meaning representation.

1. Introduction

The comprehension of a sentence requires a network of cognitive mechanisms to build a semantically-integrated representation that combines each word with a preceding context. How different sources of information—basic word meaning, syntactic information, and contextually constrained referential mapping—are used in this process is a central question in sentence comprehension.

In general, the processing of sentences is highly incremental, with words being processed immediately before the next word is encountered (for a review, see Pickering, 1999). This incrementality reflects syntactic processes such as attachment (Frazier & Clifton, 1996; MacDonald, Perlmutter, & Seidenberg, 1994) and semantic integration (Boland, Tanenhaus, Garnsey, & Carlson, 1995; Tyler & Marslen-Wilson, 1977). Although theories of parsing differ on whether there are constraints on the ordering of information sources, the final product of integration processes arises from the interaction of semantic, probabilistic lexical information with lexically-derived syntactic information (MacDonald et al., 1994).

Especially interesting, aside from constraints on the ordering of information sources, is the specificity with which semantic and syntactic influences can be detected in on-line measures. Both eye-movements (e.g. Ni, Fodor, Crain, & Shankweiler, 1998) and ERP patterns (Kuperberg et al., 2003) show immediate and differentiated effects when in response to semantic and syntactic anomalies. For example, syntactic anomalies elicited greater regression rate in eye-movements and a P600 effect in ERPs, whereas semantic anomalies led to elevated first-pass reading time in eye-movements and an N400 effect in ERPs. Thus, not only is real-time processing incremental, it may be influenced differentially by different sources of information.

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The universality of incremental accounts and their use of specific information sources is in question, because most studies have used Indo-European languages, especially English. The existence of verb-final East Asian languages, e.g. Japanese and Korean, has led to the argument that these languages are likely to present counter-evidence of incrementality in real-time sentence comprehension (Pritchett, 1992). In contrast to this argument, the research shows evidence of immediate incrementality, consistent with previous findings in English (Aoshima, Philips, & Weinberg, 2004; Kamidie, 2006; Kiaer & Kempson, 2005; Mazuka & Itoh, 1995; Miyamoto & Takahashi, 2001). However, these languages do not depart much from English in some critical ways. Like English, these languages encode thematic-role information in morphemes adjacently attached to referential NPs and their verbal agreement system provides verb–tense information. In contrast, Chinese lacks all these properties that can be used for real-time thematic-role specification, verb–tense retrieval, and phrase grouping.[1] It thus presents a stronger high contrast case for English.

Chinese has an impoverished morphosyntactic system that does not mark subject–verb agreement, case roles (e.g. agent, patient), inflections, and morphological relations. The lack of on-site case-role specification on the referential noun phrases (NP) may discourage a strong commitment to immediate constituent attachment in favor of a more conservative strategy that waits for more information from context in each processed increment. Furthermore, written Chinese has no word boundaries. Because Chinese words can contain a single character or multiple-characters, ambiguities of character grouping can reflect very different sentence meanings (Wu & Yang, 1991)[2]. Thus, Chinese readers have to examine the lexico-semantic relations between neighboring characters to obtain appropriate lexical parsing for word classes, for phrase grouping, for thematic-role specification and to retrieve verb–tense information (Hoosain, 1991). Indeed, some researchers have argued that, compared with English, Chinese text comprehension is driven by a semantically-based contextual process with a reduced role for structure-dependent processes (Chen, 1984; Chu, 1998; Li & Thompson, 1981) . Even if this non-structural claim is incorrect, Chinese does present a moment-to-moment integration task that seems different from English.

The goal of the present study is to use Chinese to examine two integration processing issues that are fundamental to language comprehension. First, *when* do different sources (and levels) of information become available and *how* do they constrain each other at each processing increment? Specifically, are the major sources of linguistic information (e.g., semantic and syntactic) processed distinguishably in Chinese sentence comprehension? The argument that Chinese comprehension is driven by semantics (Chu, 1998; Li & Thompson, 1981) implies a cognitive system that reduces syntactic information to generalized lexico-semantic processing. Some evidence hints that this is not the case. Yang, Gordon, Hendrick, and Hue (2003) found that the sequential and syntactic organization of Chinese affected the coreferential processes of a discourse in a way similar to English. However, because Yang, et al. reported reading times on a whole sentence, their results do not address word-by-word incrementality. The specific question of the present study lies in the temporal immediacy of information availability and recruitment dynamics in each processed increment (i.e., each word) while reading a sentence for comprehension.

The second processing issue concerns cognitive resources that support incremental operations. Because memory constitutes a universal cognitive resource, we expect it to support sentence integration in Chinese as well as in English, where its role in complex sentence processing (e.g., relative clauses) has been well-established across different paradigms (Just, Carpenter, Keller, Eddy, & Thulborn, 1996; King & Just, 1991; King & Kutas, 1995). However, if Chinese and English differ in their moment-to-moment processing, we might observe corresponding differences in memory subsystems (and their neural correlates) that hold different kinds of information that are available in the two languages (Gandour et al., 2003).

To acquire evidence concerning these processing issues and to provide a comparison with a well understood language processing problem studied in other languages, we used an ERP paradigm to focus on the comprehension of relative clause (RC) sentences of native speakers of Chinese (Mandarin). ERPs can provide a fine-grain view of the time-course of the integration processing in Chinese reading, reflecting the spatiotemporal dynamics of cognitive and neural processes that are part of each transient brain event associated with language input. Specifically, to the extent that separable ERP components are sensitive to specific aspects of language processing (e.g., semantics, syntax, and memory operations), they can be used to infer the nature of information recruitment and usage as well as the supporting cognitive mechanisms in each processing increment. We used RC stimuli because studies of RC processing in English have established findings that allow important comparisons concerning the universality and particularity of cognitive mechanisms. Specifically, memory demands have shown to be a primary factor in modulating the RC processing difference (Gibson, 1998; King & Kutas, 1995). Equally important, RC structures in Chinese imply specific contrasts with English in the parsing operations and memory demands, as we explain below.

1.1. The processing contrast of sentences with relative clauses in English and Chinese

In English, object-extracted relative clauses (OR, *The lawyer that the politician attacked stole the ballots*) have been found to be more difficult to comprehend than subject-extracted relative clauses (SR, *The lawyer that attacked the politician stole the ballots.*) (Caplan, Alpert, & Waters, 1998; King & Just, 1991; King & Kutas, 1995). The greater difficulty of OR sentences has been attributed to an increase in memory load (Gibson, 1998) required to keep the semantically unintegrated sentence fragment (*lawyer*) in memory longer. One can see that in the OR example two new discourse entities

[1] Contrary to many Indo-European languages where verbs are marked for tense, aspect, and number, and nouns are marked for definiteness, number, and gender; most of these grammatical markers for nouns and verbs are absent in Chinese, except for the aspect markers. Chinese relies on sequential and structural properties to specify the grammatical/thematic roles of the nominal phrases within a sentence and uses the "marker" system, which relies on cues that are not necessarily located adjacently to the marked phrases to provide morphosyntactic information for verb-tense marking, word-class subcategorization, and phrase grouping (Chu, 1998; Li & Thompson, 1981). Additionally, Chinese has a large number of class-ambiguous words that can play multiple grammatical roles depending on their lexico-semantic relationship with neighboring characters and/or words. These properties conspire to the processing issues of information recruitment and usage addressed in the current study. Relatively few studies have been systematically conducted to examine the universality and particularity of the cognitive/neurocognitive mechanisms in the real-time processing of Chinese sentence integration.

[2] For instance, there can be different parsings in the three-character strings "照顧客..." where the middle character "顧" can be grouped with either the preceding character to become: "照顧｜客..." (*take care the guest*...; "照顧": take care, "客" has a guest-related meaning but itself usually has to be grouped with other following character to provide meaning specification, "|"indicates lexical parsing of legitimate words) or the following character to become "照｜顧客..." (*satisfying the customer*...; "照": according to, "顧客": customer) that results in drastically different meanings. In this linguistic case, the appropriate parsing may be disambiguated from the post-客 information such that, for instance, if the "照顧｜客..." is followed by "人" (*person*) to become "照顧客人...", this will preclude the parsing of "照｜顧客..." as "照顧｜客人..." (*take care the guest*...) results in a coherent interpretation of the phrasal grouping while *"照｜顧客人..." would be anomalous in its local meaning. This lexical parsing is a unique property of the processing of sentences in Chinese. It provides not only an interface to bridge the processing of the basic lexical level (e.g., word identification) with the higher-order processing involved in sentence integration, but also provides a window to examine the dynamic interplay of multiple levels of processing (lexical, semantic, syntactic and contextual) in the incremental reading.

(e.g., *politician* and *attacked*) intervene between the *lawyer* and its unexpressed logical trace, whereas for the SR no new discourse entity intervenes.

Linguistic analysis suggests that the canonical word order in Chinese, as in English, is subject–verb–object, SVO (Sun & Givon, 1985). However, the syntactic parsing in Chinese RC construction is operated on a *head-final* construction. As shown in Table 1, in contrast to the English RC, where the RC comes after the head noun that it modifies (e.g., *lawyer* precedes the clause with *attacked* as the verb), in Chinese the RC comes before the head that it modifies (e.g., in Chinese (2a) and (2b) *lawyer* comes after the RC) and the relativized marker ("DE", 的, as "that" in English) appears immediately *after* the embedded RC noun and verb.

The fact that the head noun follows the RC that modifies it suggests two RC processing differences compared with English. First, multiple referents have to be kept in memory before the integration of a thematic-role representation for multiple referents takes place later in the sentence (e.g., the modified head noun). This predicts that, in Chinese RC, a greater memory load is in effect during the processing of the SR than during the processing of the OR, because the semantic trace of the filler-gap dependency "e.g., e_i—*the lawyer*$_i$" has to be kept in memory longer for the referential integration in the *SR* (with two new, intervening discourse entities, "*attacked* " and "*politician*") than in the OR (no new discourse entity intervened), a pattern of RC processing difficulty opposite to that of English according to the "memory-load" account (Gibson, 1998; Hsiao & Gibson, 2003). Second, numerous studies have indicated that the comprehension of *reduced* RCs in English such as "*The horse raced past the barn fell.*" is difficult because a reinterpretation process of sentence meaning is needed at the end of the sentence when the verb "*fell*" is encountered (Bever, 1970; Frazier & Clifton, 1996). Because Chinese positions the relativized marker after the RC and provides no on-site transparent morphosyntactic markers for thematic-role specification, it may encourage conflicting parsing operations during processing of the embedded verb. One operation attempts to link the embedded verb to the main clause through a canonical SVO string, while a second operation applies to the head-final structure that attempts to attach verb to the RC (Yang & Perfetti, 2006).

To illustrate, Table 2 indicates different types of Chinese RCs that modify the *object* of the main clause. The initial main-clause materials (N + V) induce processing difficulty for the center-embedded RC at the point of the embedded verb. Readers of the OSR sentences tend to initially anticipate a direct object NP argument after the main-clause verb, when it is actually an embedded transitive verb that instantiates a di-transitive verb construction. Thus, the integration of the OSR embedded verbs, needs to recruit syntactic-related information to reinterpret the phrase structure (Hagoort, Brown, & Groothusen, 1993) and memory resources to assign multiple thematic roles (King & Kutas, 1995) for the di-transitive verb construction. Such reinterpretation process would be constrained at the local level of phrasal configuration. For the OOR embedded verb, readers tend to initially anticipate a complementary phrase after interpreting the embedded NP (*politician*, 政客) as the direct object NP predicated by the main-clause verb; later, the linking of the actual OOR embedded verb to the preceding representation requires reinterpretation of the thematic role assignment for the embedded NP and of the message-level proposition associated with its original assignment. This reinterpretation process differs from that in the OSR case because it requires the initial governing and dominance relationships among linguistic constituents be thoroughly destroyed and rebuilt with a high cost to comprehension (Fender, 2001; Osterhout, 1997).

Thus, the fact that the RC precedes the head noun not only induces interactive reanalysis and memory effects, it also creates two possibilities for processing the multiple NPs at the head noun that depend on the structure of the RC. One possibility is that greater memory load is needed for referential bindings at the OSR head noun than the OOR head noun, because the referential dependency of unintegrated multiple thematic roles is held in memory longer for the OSR than for the OOR. The alternative possibility is that a greater integration load occurs for the thematic-role specifications at the OOR head noun than at the OSR head noun, because the OOR embedded verb leads to a reinterpretation of propositional representation due to the multiple thematic-role *reassignments* required at the head noun; in contrast, the OSR embedded verb leads a reinterpretation processing constrained only at the local level of phrasal configuration.

Table 1

Structural contrast of RCs for Chinese and English. The arrows indicate the contrasting integration distance between the modified head noun (律師$_i$ *lawyer*$_i$) and the unexpressed logical NP trace (e_i) for different language systems (ASP: aspect marker; DE: the marker for RCs in Chinese, Li & Thompson, 1981).

2 a). Subject-extracted RC (SR):

Chinese: [[[e_i 攻擊 那個 政客] 的 那個 律師$_i$] 偷 了 選票。]
[[[e_i Attack(ed) the politician] DE the *lawyer*$_i$] stole ASP the ballots.]
ei V N DE N*i* V COMP

English: "The *lawyer*$_i$ that e_i attacked the politician stole the ballots."
N*i* that *ei* V N V COMP

b). Object-extracted RC (OR):

Chinese: [[[那個 政客 攻擊 e_i] 的 那個 律師$_i$] 偷 了 選票。]
[[[The politician attacked e_i] DE the *lawyer*$_i$] stole ASP the ballots.]
N V *ei* DE N*i* V COMP

English: "The *lawyer*$_i$ that the politician attacked e_i stole the ballots."
N*i* that N V *ei* V COMP

Table 2
Sample sentence of the experiment. The RC is either subject- or object-extracted that modifies the *object* NP of the main clause (the *lawyer*, 那個律師, in the main clause: "*The Senator introduced the lawyer to the public.* (那個議員介紹那個律師給公眾認識)".). The first line below each Chinese sentence shows the syntactic profile. Subscripts are used to indicate the syntactic roles of the NPs (1 for subject and 2 for object) and the clausal status of each NP and VP ("m" for main clause and "r" for relative clause). To illustrate, in sentence (a), V_r indicates the verb in the RC and V_m the verb in the main clause. $N_{(r,2)}$ means that this NP functions as a the logical object of the RC. N $_{(m,\ 2;\ r,\ 1)}$ means that this NP functions as the grammatical object of the matrix and the logical subject of the relative clause (DE: marker of RC construction, COMP: complement, OSR: object-modifying subject-extracted RC, OOR: object-modifying object-extracted RC).

Object-modifying RCs

Subject-extracted RC (OSR)

a). 那個 議員 介紹 攻擊 政客 的 那個 律師 給 公眾 認識。

$N_{(m,1)}$ V_m V_r $N_{(r,2)}$ DE $N_{(m,2;\ r,1)}$ $COMP_m$

that Senator introduce(d) *e(i)* attack(ed) politician DE that *lawyer(i)* to public known

"The Senator introduced the lawyer that attacked the politician to the public."

Object-extracted RC (OOR)

b). 那個 議員 介紹 政客 攻擊 的 那個 律師 給 公眾 認識。

$N_{(m,1)}$ V_m $N_{(r,1)}$ V_r DE $N_{(m,2;\ r,2)}$ $COMP_m$

that Senator introduce(d) politician attack(ed) *e(i)* DE that *lawyer(i)* to public known

"The Senator introduced the lawyer that the politician attacked to the public.

1.2. ERPs relevant to the current study

Our ERP analysis focuses on linguistic segments related to the interpretation of the meaning of RCs; these segments include the embedded RC ("the RC Region") and the modified head NP ("the Head Noun Region"; see Fig. 1). We investigated ERP effects that have been well-established to reflect the distinctions among semantic (N400), syntactic (P600) and referential binding (left-anterior negativity, LAN; the referentially induced frontal negativity, Nref) operations in transient brain events. The N400 is a negative deflection between 250 and 500 ms after the stimulus onset with a central–parietal topographic distribution. The less a word fits into the semantically established context the larger its amplitude (Kutas & Hillyard, 1980). Importantly, enhanced negativity of N400 is associated with a more effortful integration process during sentence comprehension (Weckerly & Kutas, 1999). The P600 is a positive deflection, observed between 600 and 800 ms post-stimulus onset with a central–parietal topographic distribution that reflects syntactic-related processing difficulty. It is elicited by antecedent conditions associated with morphosyntactic violations (Hagoort et al., 1993), syntactic ambiguity (Van Berkum, Brown, & Hagoort, 1999) and a reintegration process associated with syntactic complexity (Kaan, Harris, Gibson, & Holcomb, 2000). Two frontal ERP components have been associated with quite distinctive processing in language comprehension. One is a left-lateralized anterior negativity (LAN) from ~250 to 600 ms and is interpreted to reflect binding operations that require referents-tracking in working memory (King & Kutas, 1995; Kluender & Kutas, 1993). The other is a bilateral frontal negativity, which is sustained in the time-course and is interpreted to associate with the processing of reference establishment in the situation model (Van Berkum, Koornneef, Otten, & Nieuwland, 2007).

Based on the notion of incrementality (Pickering, 1999), differential ERP effects at each processed increment reflect variations in the ease of integration as a function of meaning integration and resource constraints. As we explained above, the embedded verbs of different types of RCs (*attack*(*ed*), 攻擊) are mapped into sentence structures of different processing hierarchies, introducing reinterpretation difficulty that varies with the nature of processing levels and with information recruited and utilized. To the extent that the integration of the OSR embedded verb causes reinterpretation of a local non-preferred phrase attachment for a di-transitive verb construction, the OSR embedded verb is predicted to induce an enhanced P600, sensitive to phrase-structure violations (Hagoort et al., 1993), and an enhanced LAN for the assignment of multiple thematic roles (King & Kutas, 1995). On the other hand, since the integration of the OOR embedded verb causes reinterpretation of the thematic role assignment for the OOR embedded NP and in meaning on an essential message-level proposition, the processing of the OOR embedded verb is predicted to elicit an enhanced N400 that reflects integration difficulty in the meaning-derivation processes. ERP patterns like these will provide supporting evidence that the cognitive system exploited in Chinese reading, as in other languages, recruits and utilizes distinct sources of linguistic (semantic/syntactic) information that are subject to contextual constraints of the preceding representation in the meaning and structural mappings.

The ERP effects on the head noun should reflect referent reactivation and meaning integration processes as a function of processing complexity through an interaction of meaning and resource constraints in the integration of a thematic representation for multiple referents. The processing complexity may be mainly associated with referential processing of long-distance binding for the OSR types and with restructuring an appropriate mapping of multiple NPs for the OOR types. To the extent that the LAN indexes memory operations in referential binding (King & Kutas, 1995; Kluender & Kutas, 1993) and the N400 indexes integration effects in comprehending the meaning of a sentence (Kutas & Hillyard, 1980), the OSR head NP is likely to elicit an enhanced LAN and the OOR head NP is likely to elicit negative deflection that resembles the N400 effect.

2. Experiment

To examine the processing issues reviewed in the preceding sections and to allow comparison with English language experiments, the experiment measured ERPs on Chinese subject-extracted (OSR) and object-extracted (OOR) relative clauses (RCs; see Table 2). In both cases, the RC modified the grammatical *object* of the main clauses. One can see in Table 2 that these RCs in Chinese are embedded within the center of a sentence, preceded by a main-clause subject NP and a transitive verb in an N–V-order. This resembles the centered-embedded structure of RCs in English. The crucial contrast, then, is that without a relativized marker to precede the Chinese RC (*cf.* "that" in English RCs) the incremental interpretation of embedded RC materials should be highly constrained by the meaning of the preceding text.

Our use of subject and object-extracted RCs to examine the ERP temporal dynamics of sentence comprehension follows Kutas and her colleagues' ERP studies (King & Kutas, 1995; Muller, King, &

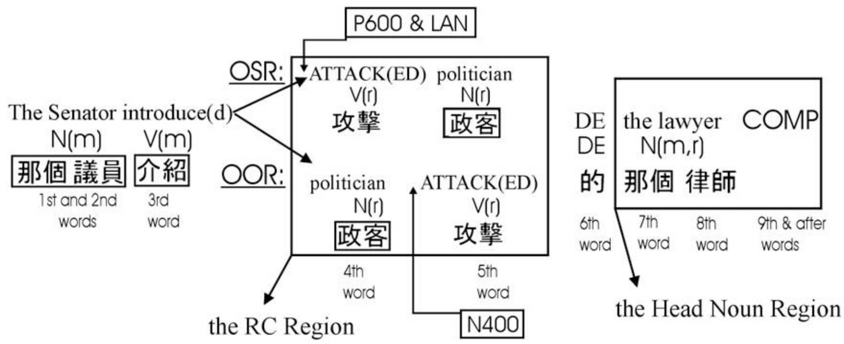

Fig. 1. The two non-overlapping critical regions for the analysis of multiword ERPs. The first region is "the RC Region" that includes the embedded RC words. The second region is "the Head Noun Region" that contains the modified NP and the first word of the complement phrase. Note that the sentence materials preceding the RC Region are identical for both subject- and object-extracted RC sentences (NP + Verb), and thus confer to the anticipation of a canonical word order of N–V–N. The figure also indicates a general prediction of the ERP components elicited by the processing differences of subject-extracted (OSR) and object-extracted (OOR) RCs at the RC Region. The sequential order of word-by-word sentence reading, in a left-to-right reading, is also indexed at the text at the bottom of the figure for each word.

Kutas, 1997) and other studies of English RC comprehension. To the temporal analyses, we add the Low Resolution Electrical Tomography (LORETA) on ERP components to locate cortical sources of the language-sensitive ERP shifts. In this way, the close resemblance of the design, stimulus structure, and paradigm of the current study to previous studies of English RC allows us to draw comparative conclusions concerning the cognitive/neurocognitive mechanisms that support sentence integration.

2.1. Methods

2.1.1. Participants

Twenty-one graduate students at the University of Pittsburgh (14 females) between the ages of 20 and 36 (mean, 26.2; SD, 3.8) participated. They received monetary compensation for their participation. Participants were all native Chinese (Mandarin) speakers with normal or corrected-to-normal visions. They were all right-handed and have used Chinese on a regular basis in the Chinese local community. They all studied at the graduate level and stayed in the USA for between 1 and 5 years (mean, 2.5; SD, 1.4).

2.1.2. Material and tasks

A total of 32 experimental sentences (mean number of words = 11), as shown in Table 2, was constructed. Each experimental sentence is instantiated in two alternative versions by varying the RC-Type factor (subject-/object-extracted).[3] Each sentence also has three definite descriptions relating to human roles (e.g., lawyer, politician, Senator, etc.) to serve the arguments of the verbs in the main and embedded clauses. The construction of RC sentences follows a rigorous word order so that the verb is always adjacent to its NP arguments. Note that the two types of RC sentences have identical linguistic constituents but differ in the word order of the embedded RC words. A set of 90 filler sentences that did not include restrictive relative clauses was used to increase the variation of the sentences read for comprehension.

2.1.3. Norming study

To test out assumptions about the preferences of Chinese speakers for RC sentences, we carried out a written cloze sentence completion task. The written sentence completion test consisted of the 32 experimental sentences in the present study. Thirty-six native Chinese (Mandarin) speakers at the National Taiwan University were instructed to complete sentence fragments on 32 sentences from the present study. The sentences were truncated at the phrasal segments where a left-to-right reading of a canonical continuation would be disrupted by the embedded RC verbs. To illustrate, the sentence fragment required for completion had "那個議員介紹___. (*That Senator introduce(d)_.*)" for the OSR type and "那個議員介紹政客___. (*That Senator introduce(d) politician_.*)" for the OOR type where both object modifying RC sentences were truncated at the embedded verbs "*attack(ed)*, 攻擊" (see Table 2).

The results confirmed that canonical SVO continuations were high for both OSR and OOR types. Crucially, the embedded transitive verb induced effortful integration associated with different levels of information and structural processing as a function of RC-types. For the OSR type that needed to be completed from a S–V-fragment, 98% of the continuations were noun phrases (NP) and 73% were immediate continuation of bare NPs. In contrast, the continuation of a verb phrase (VP) immediately following a SV-fragment was only 1%. For the OOR type that needed to be completed from a S–V–O-fragment, 55% of the continuations were complementary phrases that did not involve VPs and 43% of the continuations were complementary phrases that involved VPs. However, among the continuations that involved VPs, only 3% were immediate continuations of bare transitive verbs.

2.1.4. Design and procedure

For each experimental sentence, one of its two RC-Type versions (Table 2) was assigned to one set of materials and the other version was assigned to a second set. Each material set had 32 experimental sentences along with 45 filler sentences. Participants read only one version of the experimental sentence within a session and across two sessions they read both versions of the experimental

[3] It is important to note that the ERP effects at each processing increment of the RC Region were assessed via the comparison of two structural mapping conditions which necessarily involved comparing different words. The alternative of measuring the same verb form across different structures would result in a complication of confounds that would make the assessment much more difficult and less comparable to other similar studies of RC processing in different languages, as most of the prior research involving varying paradigms seldom made such direct comparisons. The complications of these confounds include: First, a systematic confound of processing latency because the OOR embedded verb is always one-increment farther than the OSR embedded verb and prior research has indicated that the amplitude of an ERP effect is modulated by the sentence position of the target word (Kutas, Federmeier, Coulson, King, & Mute, 2000; Nagy & Rugg, 1989). Second, various confounds would result from the fact that the direct contrast of embedded verbs in different conditions is actually comparing different reintegration processes (revision vs. reanalysis) at distinct levels of linguistic/information processing, one dealing with local phrasal attachment and the other dealing with global propositional meaning. Our comparison strategy allows us to limit the confounds to one single dimension of lexical differences and to address the issue of universality and particularity in sentence reading across studies that used the comparable materials strategies. Note that the possible confound of lexical factors is intrinsic to the syntax of RC sentences across languages. However, in our analyses, we evaluate the extent to which lexical differences would contribute to the effects and conclude the effects we report are robust enough to weigh against the lexical-driven alternative.

sentences. Participants took a break of approximately 5–10 min between sessions. The sequence of the two material sets was randomly assigned for each participant.

The EEG was recorded as the participants read each Chinese sentence for comprehension. Each sentence was presented one word at a time on the center of the computer screen for a duration of 300 ms with a stimulus-onset asynchrony (SOA) of 700 ms. A fixation mark preceded the trial to orient participants' attention before they initiated a trial by pressing the space bar. Each word was presented in the center of a 2 cm height × 4 cm width column with black text in front of a white background. A comprehension question followed each sentence. Participants made a true-or-false response based on the meaning of a sentence they just read and were given immediate feedback. Half of the comprehension questions were true, and half were false. For experimental sentences, correctly answering the questions required an understanding of the semantic/syntactic relationship between NPs and the main-clause verbs or the embedded verbs. Approximately two fifths of the comprehension questions related to the main-clause verbs and the remaining questions related to the embedded verbs in the relative clauses.

To reduce recording artifacts, participants were instructed to remain as still as possible with their eyes on the center of the computer screen throughout the sentence. They were requested to refrain from blinking as much as possible when stimuli were presented, but were told that they could rest before initiating the next trial. Participants were tested for 70–90 min in a quiet and comfortable environment, while the experimenter monitored the ERP recordings and experimental events in an adjacent room. Participants were seated and adjusted so that their eyes were about 55 cm from the center of the 15-in. CRT monitor screen at their eye level.

2.1.5. ERP recording and pre-processing

The raw electroencephalogram (EEG) was recorded continuously at 250 samples per second by a 128-channel Electrical Geodesics system consisting of Geodesic Sensor Net electrodes, Netamps, and Netstation software (Electrical Geodesic Inc., Eugene, Oregon) running on a Macintosh G4 computer with Mac OS 9.2.2. Impedances were maintained below 50 kΩ before each run (Ferree, Luu, Russell, & Tucker, 2001). The EEG was amplified and analog filtered with .1–100 Hz bandpass filters, referenced to the vertex, and a 60 Hz notch filters then digitized the signals at 250 Hz by a 12 bit A/D converter. Six eye channels were used to monitor trials with eye movement and blinks. All materials were presented on a 15-in. CRT monitor working with a 60 Hz refresh rate. The experimental trials were controlled by Eprime (Psychology Software Incorporation, Pittsburgh, Pennsylvania) to present trials, record relevant trial information and send event information to the EEG recording system. The EEG data were segmented off-line into epochs of interest for the words of the critical regions to examine the ERP patterns as a function of RC-Type. We first examined the epochs of multiwords extracted from the onset of the initial word of each critical region to identify ERP effects related to each processed increment. Furthermore, for the ERP effects identified to be related to each processed increment, we resegmented and rebaselined the epoch from the onset of each word of interest to examine the nature of the effects. Prior research (Kutas and her colleagues, 1995, 1997) has indicated that this multidimensional approach (multiwords and individual word) is useful to reveal different aspects of memory functions (e.g., storage/maintenance vs. integrative/computational). This approach is particularly useful in the present study, because, as we have emphasized, the processing differences of different types of RC in Chinese reading reflects the interactive dynamics of memory operations and information integration as sentence integration temporally unfolds.

Data were both visually and digitally screened for artifacts (eye blinks or movements, subject movements, or transient electronic artifacts) and contaminated trials were removed. Overall, 8.4% of trials were rejected (between 0 and 3 per subject), leaving no subject with fewer than 29 good trials in any condition. Remaining data were sorted by condition and averaged to create the ERPs. Averaged ERP data were digitally filtered at 20 Hz lowpass to remove residual high-frequency electrical noise, baseline corrected by the pre-stimulus period, and re-referenced to the average reference to remove topographic bias that can result from the selecting of a reference site (Lehmann & Skrandies, 1980). The subject-averaged ERPs were averaged together to produce the mean waveform across subjects (the grand average) for each condition, which was used to plot waveform and topographic distribution. The statistical analyses were performed on the subject-averaged ERPs. Topographic maps of the voltage field across the surface of the scalp were created by interpolating from the recorded values using spherical splines (Perrin, Pernier, Bertrand, & Echallier, 1989).

2.1.5.1. Statistical analysis. All statistical analyses on ERPs were conducted on two separate repeated-measures ANOVAs. One tested the mean amplitudes of the ERPs for the three medial electrodes (Fz, Cz, and Pz) and the other tested those for 10 lateral electrode pairs (F7–F8, F3–F4, C3–C4, P3–P4, and T3–T4). These thirteen electrodes were selected to provide sufficient coverage to examine the ERP shifts related to syntactic, semantic and referential effects during sentence integration. Each ANOVA has two within-subject factors: RC-Type (OSR vs. OOR) and electrode site (three for medial AVOVA and five pairs for lateral ANOVA). The ANOVA of each lateral site had an additional within-subject factor of Hemisphere (Left vs. Right). All probability values reported for effects with more than two degrees of freedom were adjusted using the Greenhouse–Geisser correction for deviations from sphericity in the data. The corrected P values are reported.

2.1.5.2. Spatial analysis of EEG. Low Resolution Electrical Tomography (LORETA) was used to locate the spatial source of significant ERP components. Converging with the temporal information provided by the ERP, the analysis of LORETA is informative in localizing the possible neurocognitive sources related to the significant ERP components of interest. LORETA provides an algorithm to solve the inverse problem of EEG by assuming that neighboring grid points are more likely to be synchronized than grid points that are far from each other. In mathematical terms, the task is to find the "smoothest" of all possible solutions that is consistent with the scalp distribution (Pascual-Marqui, Michel, & Lehmann, 1994). A particular advantage of LORETA is that it does not require any assumptions about the number and location of possible sources. The solution space of LORETA consists of 2394 pixels (cubes) with a 7 mm resolution. The LORETA-KEY software (Pascual-Marqui, 1999) was used in the analysis (from http://www.unizh.ch/keyinst/loreta.htm, March, 2004). The version used was registered to the Talairach brain atlas (Talairach & Tournoux, 1988). In addition, the weights for computing solutions (transformation matrix) were computed based on the positions of electrodes on the recording net in our lab by using a tool provided with LORETA-KEY. LORETA was employed to determine the spatial maps of ERP sources, subjecting differences to statistical parametric mapping (SPM) based on pixel-wise t-tests. Several studies have successfully applied parametric statistical tests using LORETA maps with either ROI (region of interest) or pixel-by-pixel tests (Pizzagalli, Lehmann, Koenig, Regard, & Pascual-Marqui, 2000; Strik, Fallgatter, Brandeis, & Pascual-Marqui, 1998). Because t-tests assume Gaussian distributions of pixel activation, a log transform of the value of each LORETA pixel was carried out to produce more Gaussian-like distributions for each ERP component under examination. The second assumption of SPM, smoothness across neighboring pixels, is satisfied directly by the LORETA output. The t-test threshold was set to $p < .05$ and cluster size was set to ⩾3 pixels (1000 mm^3 volume size), as is common in PET and fMRI studies. Although simulations have shown that LORETA localization performed better than some other localization methods, LORETA, as with all ERP localization algorithms, has accuracy limitations (Pascual-Marqui, 1999). Thus, the statistical tests for LORETA were not aimed at finding significant experimental effects. Instead, the LORETA statistics on the brain regions in the present study were examined only when scalp electrode ERP effects were statistically significant, and importantly their functional interpretation are applied in the context of previous findings and theoretical inferences.

2.2. Results

Eighteen participants contributed data set for analysis, following the elimination of data for three participants, two for low accuracy (53%) and one for lab equipment failure.

2.2.1. Behavioral results

The mean accuracies across participants ranged from 70% to 95% (mean, 79%; SD, 8.9), with a mean accuracy of 81% for the subject-extracted RC (OSR), and 76% for the object-extracted RC (OOR). This difference between OSR and OOR was significant according to a repeated-measures ANOVA ($F(1, 17) = 6.34$, $p < 0.05$, MSE = 33.5).

2.2.2. ERP results

The critical multiword segments were divided into two non-overlapping regions, the RC Region and the Head Noun Region (see Fig. 1). The ERPs of the pre-RC Region (the main-clause subject and verb) did not show RC processing differences.[4] Figs. 2A and 3A plot the grand average reference ERP waveform for different types of RC of the RC Region and the Head Noun Region, respectively.

Table 3 outlines the results of ANOVAs for the mean amplitude of each multiword ERP region. For the RC Region, the RC-Type effect was observed only in the lateral analysis, with OSR more negative than OOR ($t(17) = -2.37$, $p < 0.05$). In addition, the interaction of RC-Type × Electrodes was significant, indicating a bi-lateralized, enhanced negativity for the OSR condition only at the pre-frontal (F7–F8, $t(17) = -2.26$, $p < 0.05$) and temporal (T3–T4, $t(17) = -2.35$, $p < 0.05$) sites. For the Head Noun Region, the lateral ANOVA showed a marginal significance for the interaction of RC-Type × Hemisphere ($p = 0.06$), and a significant three-way interaction of RC-Type × Electrodes × Hemisphere. The OSR condition induced enhanced and sustained negativities relative to the OOR condition mainly at the right-lateralized pre-frontal site (F8) ($t(17) = -2.59$, $p < 0.05$). The observed ERP differences at the temporal sites were not statistically reliable (T3 and T4, max. $t(17) = 0.70$, $p = 0.493$). Thus, both multiword processing regions consistently demonstrated ERP effects in the form of enhanced negativities, consistent with memory support for storage and maintenance of referents (King & Kutas, 1995). However, their topographic contrast may suggest detailed differences in the mechanisms and knowledge sources recruited to provide such support, a topic to which we return in the Discussion.

2.2.2.1. ERPs of the critical words.

The RC Region: Fig. 2A identifies two salient features of waveforms related to RC processing differences on a word-by-word basis. First, for the initial word of the RC Region, an enhanced positivity elicited by the OSR embedded verb from ~600 to 800 ms was found at the central (Cz) and parietal (P3, Pz and P4) sites. This OSR-elicited P600 was preceded by a transient negativity from ~360 to 460 ms, peaking up at 400 ms. Second, for the second word of the RC Region, the processing of the OOR embedded verb elicited negativities from ~290 to 500 ms post-onset at the central–parietal sites (Cz, C4, Pz and P4). Fig. 2B plots the waveforms of the RC-Type factor by averaging over the representative electrodes[5] at the central–parietal region.

To test the generality of these observed ERPs, ANOVAs were conducted for the critical *words*. Table 4A outlines the results of the mean amplitude analysis of each critical word. For the OSR-elicited P600, the ANOVAs were conducted on mean amplitudes of 600–800 ms post-onset of the initial word of the RC Region. The medial site ANOVA showed a significant main effect of RC-Type in that the OSR was more positive than the OOR ($t(17) = 3.39$, $p < 0.005$). The RC-Type did not interact with Electrodes ($F < 2$). The lateral site ANOVA indicated a significant interaction of RC-Type × Electrodes in that the OSR was significantly more positive than the OOR only at the central and parietal sites (Cz, Pz, P3–P4; min $t(17) = 2.20$, $p < 0.05$).

For the transient, OSR-elicited N400 effect, the ANOVAs were conducted on mean amplitudes of 370–500 ms post-onset of the initial word.[6] The lateral site ANOVA showed a significant main effect of RC-Type in that the OSR was more negative than the OOR ($t(17) = -2.29$, $p < 0.05$). This pattern was consistent over the scalp (RC-Type × Electrodes, $F < 1$; RC-Type × Hemisphere, $F < 1$).

Finally, for the OOR-induced N400 effect at the 2nd word of the RC Region, new segmenting and new baselining were conducted to extract the ERPs from the *onset* of the 2nd word of the RC Region, with 1000 ms post-stimulus duration and 200 ms baseline. The ANOVAs were conducted on mean amplitudes of 300–500 ms post-onset. The medial site ANOVA showed a significant main effect of RC-Type in that the OOR was more negative than the OSR ($t(17) = -2.36$, $p < 0.05$). No significant interaction of RC-Type × Electrodes was obtained ($F < 2$). The lateral site ANOVA indicated no significant main effect of RC-Type ($F < 1$). Crucially, a significant interaction of RC-Type × Electrodes showed that the OOR induced significant greater negative deflection than the OSR only at the central and parietal sites (Cz, C4, P3–P4; min $t(17) = -2.31$, $p < 0.05$).[7]

The Head Noun Region: The ANOVAs on the determiner (*that*, 那個: the first word of the Head Noun Region) did not find reliable ERP pattern with respect to the RC-Type. In contrast, the processing of the head noun (*lawyer*, 律師) in the OOR condition induced enhanced negativities over the Fz and Cz sites that diverged at ~250 ms and sustained over the processing of the following word (see Fig. 3). To test the effect of OOR-elicited, central–frontal sus-

[4] The fact that no ERP effect was observed in the pre-RC region was established both linguistically and statistically. As show in Table 2 and Fig. 1, the words in the pre-RC region are all the same across different experimental conditions. Specifically, with our rigorous design, participants would not be able to be primed to anticipate incoming experimental condition. Indeed, no ERP effect occurred as a function of experimental manipulations as verified by the same statistical test conducted on other ERP effects in the study.

[5] These "representative" electrodes were selected due to their shared ERP characteristics of polarity shifts, latencies, and time-courses over the target epoch for demonstration purposes. The same rule was applied to both Figs. 2B and 3B.

[6] Experimental effects for this ERP component did not emerge when tested with the conventional interval of 50 ms. On the other hand, the reported time window of this component that showed the experimental effect was identified by examining the relative differences between experimental conditions from the grand average reference ERP and topographic maps of difference waves.

[7] An issue related to the OOR-elicited N400 effect found at the 2nd embedded word of the RC region is whether the enhanced positivity elicited by the preceding OSR word may have a crucial contribution to the magnitude of measured differences in the test. To examine this, we conducted an additional test for the OOR-elicited N400 by using a re-baselining that extended into the first 250 ms after the onset of the tested word (the 2nd embedded word) to reduce the possible impact of enhanced positivity from the preceding OSR word. The results were largely the same. For the medial ANOVA: main RC-Type effect, $F(1, 17) = 3.62$, $p = 0.07$, MSE = 1.02. For the lateral ANOVA: RC-Type × Electrodes, $F(4, 68) = 3.84$, $p < 0.05$, MSE = 2.09; RC-Type × Hemisphere, $F(1, 17) = 4.34$, $p = 0.053$, MSE = 1.52. Again, the OOR induced significant greater negative deflection than the OSR only at the central and parietal sites (Cz, C4, P3–P4; min. $t(17) = -2.30$, $p < 0.05$).

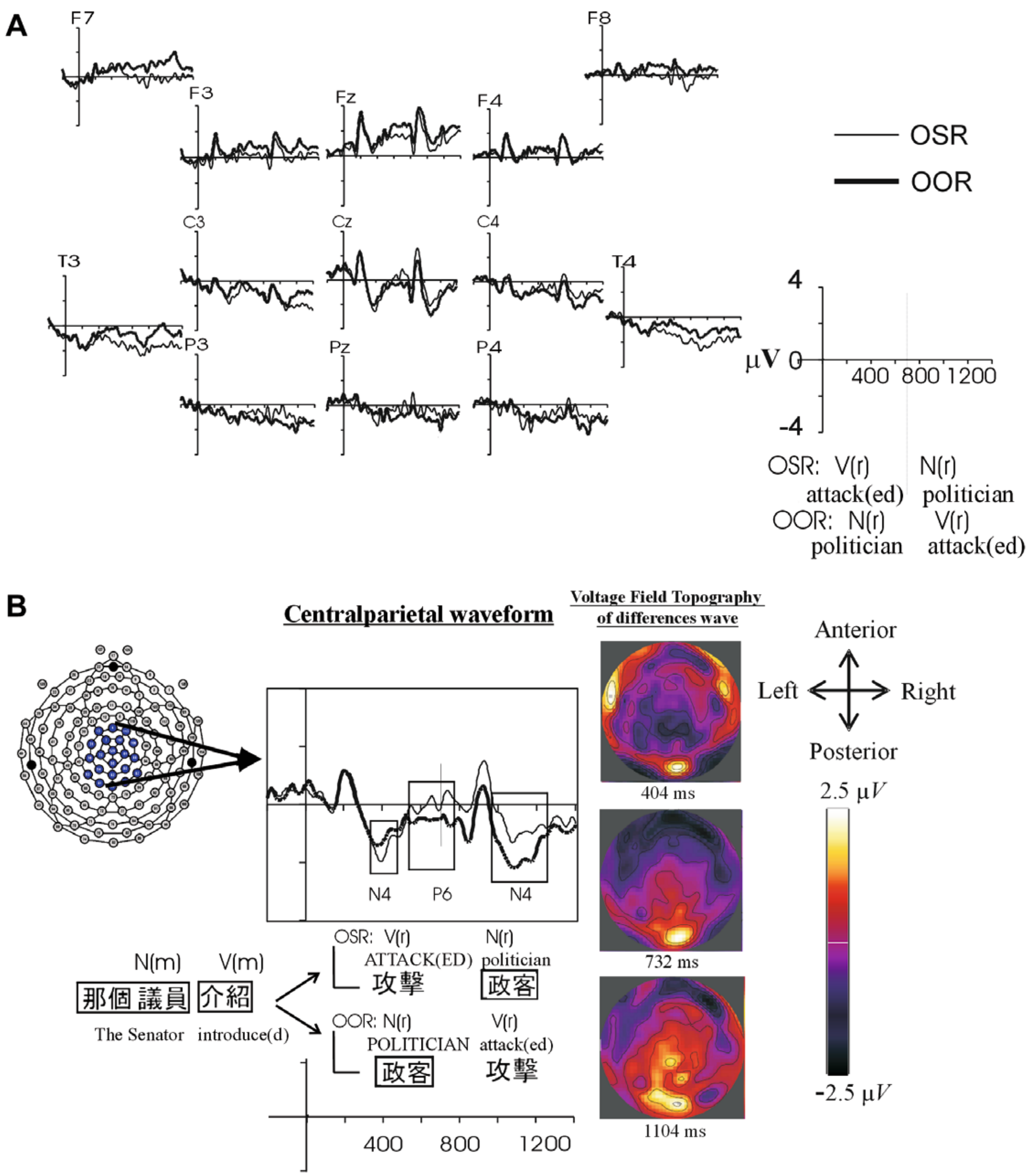

Fig. 2. A. Grand average reference ERP for the subject-extracted and object-extracted RCs sentences of the RC Region. ERPs were extracted from the onset of the initial word of the RC Region (the 4th word). For this and following figure, each hash-mark represents 200 ms and the vertical calibration bar represents 8 μV. B. The waveforms of different RC-Types at the central–parietal site of the RC Region that were plotted by averaging over the representative electrodes (blue dots) for the upper left scalp. The rightmost column shows the temporal-sequenced topographic maps of the difference waves (calculated by subtracting the OOR wave from the OSR wave) across RC-Types. For this and following figure, note that the vertex is at the center of the map (electrode 129), the nose at the top, the occiput at the bottom, and the ears at the sides.

tained negativity at the head noun (*lawyer*,律師), new segmenting and new baselining were conducted to extract the ERPs from the onset of the head noun, with a 1000 ms post-stimulus duration and a 200 ms baseline. The ANOVAs were conducted on mean amplitudes of 250–800 ms post-onset of the *exact* head noun. Table 4B outlines the results of the mean amplitude analysis. The medial ANOVA indicated a main effect of RC-Type in that the OOR was more negative than the OSR ($t(17) = -3.55$, $p < 0.01$). In addition, the lateral ANOVA indicated a significant interaction of RC-Type × Electrodes in that the OOR induced more negative deflection than the OSR only at the frontal and central sites (F3–F4, Fz and Cz; min $t(17) = -2.32$, $p < 0.05$).

2.2.3. Source analysis (LORETA)

A set of four LORETAs (N400 and P600 on the OSR embedded verb, N400 on the OOR embedded verb, and central–frontal sustained negativity on the modified head noun) was conducted to identify the functional neuroanatomy associated with the time-course of sentence integration. Each examined ERP component showed a peak in Global Field Power (Lehmann & Skrandies, 1980) that matched the ERP waveform peaks. The results from each subject were computed separately. For all subjects, 129 electrodes were submitted to LORETA. Then, pixel-by-pixel paired *t*-tests (within subjects) were performed on the four comparisons (No correction for multiple comparisons was performed because the scalp electrodes showed significant differences; again the LORETA tests were used only to identify the source of differences, not as an additional test of whether there were differences.). Table 5 summarizes the results of the LORETA analysis. Fig. 4 indicates the sources for the RC-Type processing differences identified by the ERP effects at each processed increment. The figure is a threshold *p* map of the *t*-test results mentioned above. For

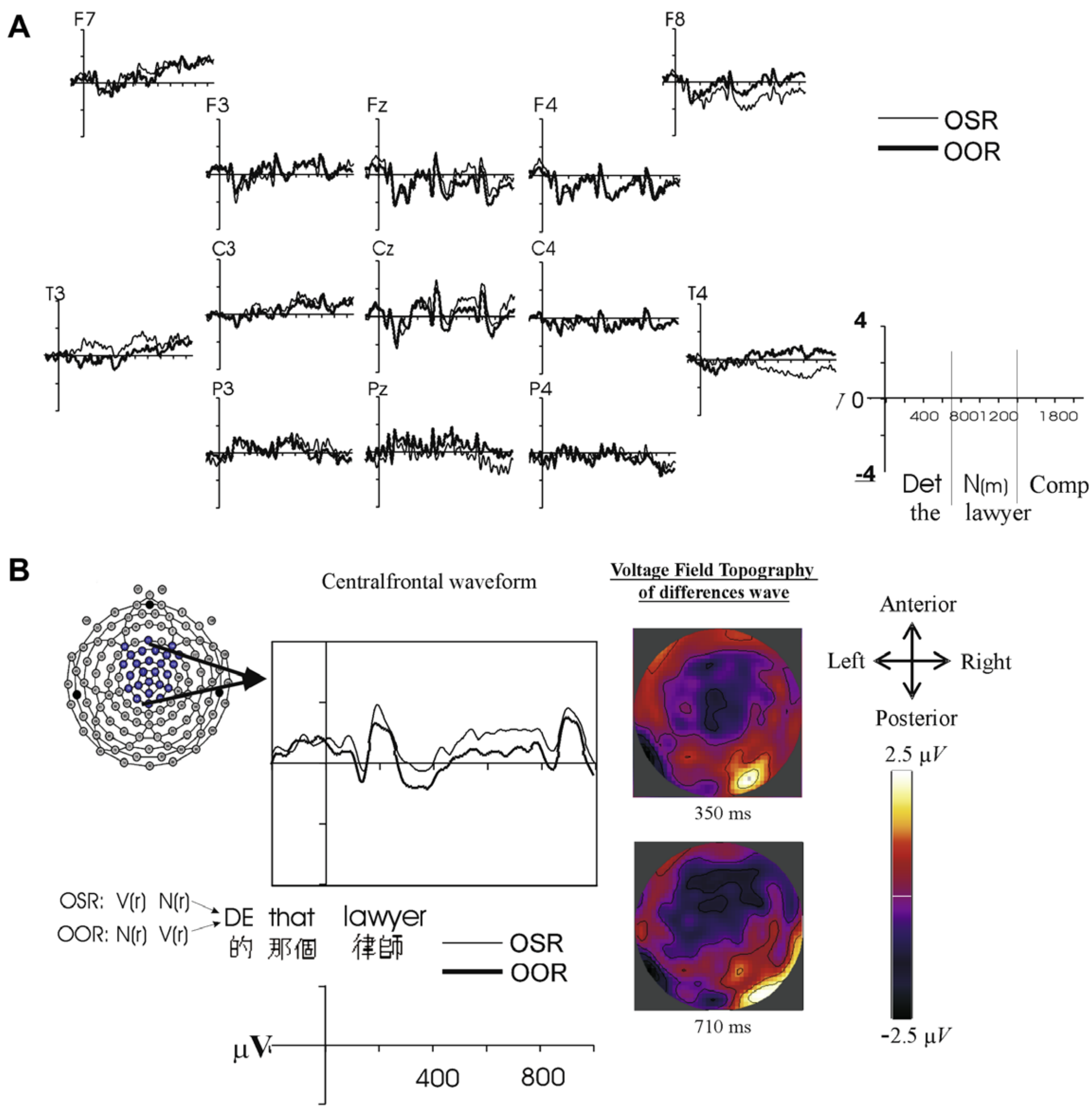

Fig. 3. A. Grand average reference ERP for the subject-extracted and object-extracted RCs when the ERPs were extracted from the onset of the *determiner* (*that*, 那個) of the head noun phrase. B. The waveforms of different RC-Types at the central–frontal site when the ERPs were taken from the onset of the exact *head noun* (*lawyer*,律師). The waveforms were plotted by averaging over the clustering electrodes at the central and frontal sites, shown by the blue dots within the upper left scalp figure. The rightmost column showed the temporal-sequenced topographic maps of the difference waves (calculated by subtracting the OSR wave from the OOR wave) across RC-Types.

Table 3
Analyses of Variance (ANOVAs) for the multiword ERP regions (Note: The medial ANOVA used 3 midline electrodes (Fz, Cz, and Pz) while the lateral ANOVA used 5 pairs of bilateral electrodes (F7–F8, F3–F4, C3–C4, P3–P4, and T3–T4)).

Source	Df	RC Region			Head Noun Region		
		Medial ANOVA			Medial ANOVA		
		F	*MSE*	*p*	*F*	*MSE*	*p*
RC-Type	(1, 17)	0.23	1.31	0.636	0.04	0.88	0.841
RC-Type × Electrodes	(2, 34)	1.53	2.66	0.232	1.23	2.68	0.306
		Lateral ANOVA			Lateral ANOVA		
RC-Type	(1, 17)	5.60	1.61	0.030*	0.01	6.99	0.994
RC-Type × Electrodes	(4, 68)	2.86	1.95	0.044*	0.39	1.92	0.817
RC-Type × Hemisphere	(1, 17)	0.60	4.09	0.449	4.16	2.38	0.057
RC-type × Electrodes × Hemisphere	(4, 68)	0.42	1.64	0.791	2.65	1.30	0.041*

* $p < .05$.

2394 cortex pixels (non-cortex pixels are in Gray), each pixel has three possible values: 0 for $p > 0.05$ (White pixels in Figures); 1 for $p \leqslant 0.05$ with a positive mean difference to indicate significantly greater activation for the processing of the OOR word than the OSR word (red pixels in figures, circled for easy reading); −1 for $p \leqslant 0.05$ with a negative mean difference to indicate signifi-

Table 4
A. Analyses of Variance (ANOVAs) for the mean amplitude of single-words at the RC Region. B. Analyses of Variance (ANOVAs) for the mean amplitude of the modified head noun at the Head Noun Region.

Source	Df	The first word (the 4th word)						The second word (the 5th word)		
		N400 (370–500 ms)			P600 (600–800 ms)			N400 (300–500 ms)		
		Medial ANOVA			Medial ANOVA			*Medial ANOVA*		
		F	*MSE*	*p*	*F*	*MSE*	*p*	*F*	*MSE*	*p*
(A) RC Region										
RC-Type	(1, 17)	3.19	1.31	0.092	11.51	1.08	0.003*	5.55	1.14	0.031*
RC-Type × Electrodes	(2, 34)	0.05	2.20	0.956	1.44	2.00	0.251	1.59	1.77	0.219
		Lateral ANOVA			Lateral ANOVA			Lateral ANOVA		
RC-Type	(1, 17)	5.53	1.37	0.031*	0.05	1.80	0.820	0.09	2.05	0.768
RC-Type × Electrodes	(4, 68)	0.44	1.81	0.779	3.73	2.32	0.025*	4.86	2.87	0.006*
RC-Type × Hemisphere	(1, 17)	0.01	1.99	0.932	2.48	2.63	0.134	4.42	2.37	0.051
RC-Type × Electrodes × Hemisphere	(4, 68)	0.74	1.46	0.570	0.16	1.29	0.859	0.16	2.89	0.865

Source	Df	The modified head noun (the 8th word) Sustained negativity (250–800 ms) Medial ANOVA		
		F	*MSE*	*p*
(B) Head Noun Region				
RC-Type	(1, 17)	12.57	0.93	0.002*
RC-Type × Electrodes	(2, 34)	1.61	1.44	0.214
		Lateral ANOVA		
RC-Type	(1, 17)	0.86	2.25	0.367
RC-Type × Electrodes	(4, 68)	2.66	1.90	0.040*
RC-Type × Hemisphere	(1, 17)	0.19	2.48	0.672
RC-Type × Electrodes × Hemisphere	(4, 68)	0.33	1.90	0.761

* $p < .05$.

Table 5
Stereotactic coordinates and corresponding Brodmann areas for regions showing significant activation for ERPs components as a function of the processing differences of different types of RC. The volume size of each voxel is 343 cubic millimeters.

Region of Interest (ROI)		ERPs	Regions activated	BA	Coordinates (*X*, *Y*, *Z*)	Voxels no.	Vol. mm^3
RC Region	The 4th word	N400	Left superior/middle temporal gyrus	22, 39, 19	(−52, −63, 12)	9	3087
			Right middle frontal gyrus	9	(46, 10, 36)	3	1029
		P600	Medial inferior frontal gyrus	11, 10	(−7, 49, −20)	4	1372
					(4, 49, −20)	2	686
			Precuneus	31	(−10, −71, 22)	5	1715
					(8, −71, 22)	3	1029
			Right inferior frontal gyrus	44, 45	(53, 17, 22)	3	1029
	The 5th word	N400	Medial inferior frontal gyrus	11, 10	(−7, 45, −13)	5	1715
					(4, 45, −13)	3	1029
			Right anterior cingulate	32	(11, 45, −6)	1	343
			Left superior/transverse temporal gyrus	42, 41	(−59, −25, 15)	3	1029
Head Noun Region	The 8th word (OSR/OOR: head noun)	Sustained negativity	Left inferior frontal gyrus	47	(−35, 17, −17)	4	1372
			Left superior temporal gyrus	38	(−49, 17, −17)	4	1372
			Precuneus	7	(−7, −46, 50)	2	686
					(4, −46, 50)	1	343

cantly greater activation for the processing of the OSR word than the OOR word (blue pixels in figures).

2.2.3.2. Transient N400 component of the OSR embedded verb. As can be seen in Fig. 4A, no areas showed more activation for the OOR word than for the OSR word (absence of red pixels). However, more activation for the OSR word than for the OOR word (blue pixels) are observed at areas of left superior and middle temporal gyrus (Brodmann area (BA) 22/39/19, x = -52, y = -63, z = 12, 9 pixels), and of right middle frontal gyrus (BA 9, x = 46, y = 10, z = 36, 3 pixels).

2.2.3.3. P600 component of the OSR embedded verb. Fig. 4A indicates more activation for the OSR word than for the OOR word (blue pixels) at medial inferior frontal gyrus (BA 11/10, $x = -7$, $y = 49$, $z = -20$, 4 pixels; $x = 4$, $y = 49$, $z = -20$, 2 pixels), precuneus (BA 31, $x = -10$, $y = -71$, $z = 22$, 5 pixels; $x = 8$, $y = -71$, $z = 22$, 3 pixels) and right inferior frontal gyrus (BA 44/45, $x = 53$, $y = 17$, $z = 22$, 3 pixels).

2.2.3.4. N400 component of the OOR embedded verb. Fig. 4B indicates that the red areas at left superior and transverse temporal gyrus (BA 42/41, $x = -59$, y = -25, $z = 15$, 3 pixels) show *more* activation for the OOR word than for the OSR word. In contrast, more activation for the OSR word than for the OOR word (blue pixels) is observed at medial inferior frontal gyrus (BA 10/11, $x = -7$, $y = 45$, $z = -13$, 5 pixels; $x = 4$, $y = 45$, $z = -13$, 3 pixels) and right anterior cingulate (BA 32, $x = 11$, $y = 45$, $z = -6$, 1 pixels).

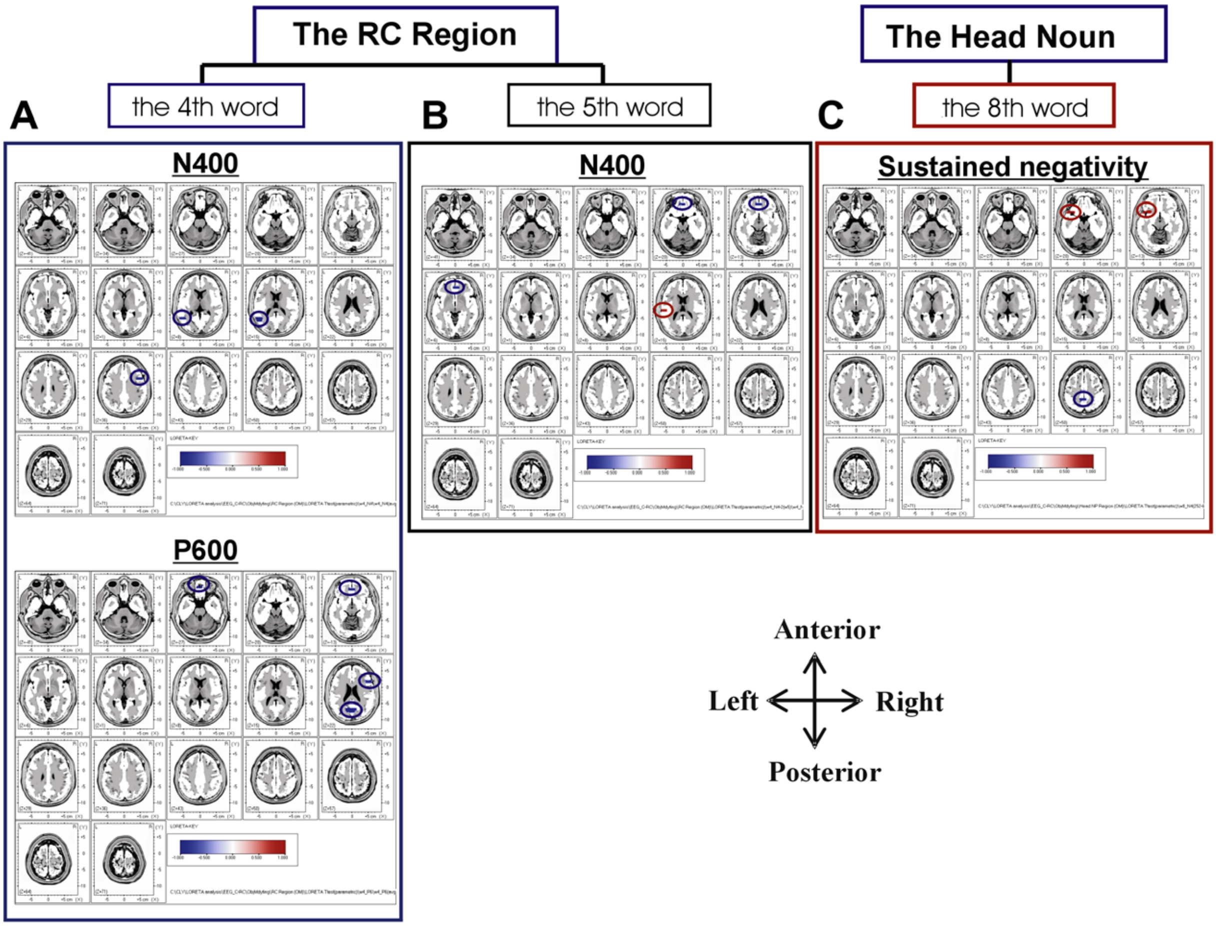

Fig. 4. Top views of the low resolution electromagnetic tomography (LORETA) *p* map for prominent ERPs of OOR vs. OSR words at the RC Region (the 4th and 5th words) and at the Head Noun Region (the head noun of modified RCs) ($p < .05$). Gray = non-cortex; white = $p > .05$ cortex; blue = $p \leqslant .05$ cortex with a negative value to indicate significantly greater activation for the processing of the OSR word than the OOR word; red = $p \leqslant .05$ cortex with a positive value to indicate significantly greater activation for the processing of the OOR word than the OSR word (circled for easy identification). L = left, R = right.

2.2.3.5. Sustained central–frontal negativity of the OOR head noun. Fig. 4C shows that the red area at left inferior frontal (BA 47, $x = -35$, $y = 17$, $z = -17$, 4 pixels) and left superior temporal gyrus (BA 38, $x = -49$, $y = 17$, $z = -17$, 4 pixels) indicates *more* activation for the OOR word than for the OSR word. Conversely, the blue area at the precuneus (BA 7, $x = -7$, $y = -46$, $z = 50$, 2 pixels; $x = 4$, $y = -46$, $z = 50$, 1 pixels) indicates more activation for the OSR word than for the OOR word.

2.3. Discussion

The results indicate that the processing (accessibility, recruitment, and usage) of different kinds of information during the real-time incremental integration in structure and in meaning of Chinese reading, by and large, parallel those of other language systems. This was demonstrated from the convergent picture of our ERP analysis, with multiple scales (e.g., multiwords and single word) and multi-dimensions (e.g., temporal and spatial LORETA). Below we first discuss how the ERP data supports this general picture and then discuss the implications of the results for general accounts of sentence integration.

2.3.1. The universality of information processing and recruitment dynamics

The straightforward evidence comes from the temporal and spatial EPRs that indicate each processed increment produced ERP components associated with distinctive linguistic and cognitive processes that are subject to the contextual constraints of the preceding representation. These findings are interpretable by the sort of structure-dependent cognitive processing previously shown in Indo-European languages. For the RC Region, a P600 effect was found when the linkage of the OSR embedded verb to a developing configuration of a main-clause verb phrase led to a restructuring processing in the local phrasal configuration.[8] Additionally, an N400 effect was elicited when the linkage of the OOR embedded verb to the representation of a message-level proposition demanded reanalysis and restructuring processing in meaning derivation of a sentence. Both the P600 and N400 effects had a topographic distribution of central–parietal dominance. Although this shared topography is consistent with the possibility that syntactic reanalysis and meaning integration are similar processes with shared neuroanatomy, strong localization conclusions are not warranted. Nevertheless, our LORETA results below provide an opportu-

[8] A factor that should be considered regarding the P600 effect elicited by the OSR embedded verb is, as Kaan and Swaab (2003) suggested, that the posterior P600 positivity may reflect processes involved both in revision of a non-preferred continuation and in repair of an ungrammatical continuation. Nevertheless, the fact that the OSR sentences were accurately comprehended about 81% of the time seems to suggest that a repair process of an ungrammatical continuation in the integration of the OSR embedded verb is unlikely to be the case in the present experiment. This accuracy instead suggests that revision of a non-preferred continuation is not difficult in the di-transitive verb construction. This is especially true when compared with classical garden-path sentences such as "*The boat floated down the river sank.*" that received an acceptability rating of only 4–12% (Osterhout, 1997).

nity to assess the strength of the association between localization conclusion and shared scalp topography.

Accompanying the OSR-elicited central–parietal P600 is an enhanced and sustained negativity at the bi-lateralized pre-frontal and temporal sites that has the same latency as the P600 effect, particularly at the pre-frontal site. Prior studies suggest two possibilities for anterior negativities in the time window observed here. One is referential processing, associated both with the left-lateralized LAN, which begins at about 250 ms and is interpreted as reflecting linguistic load that influences referent binding operations (King & Kutas, 1995; Kluender & Kutas, 1993) and also with the bilateral frontally-distributed negativity interpreted as indicating the establishment of reference in a situation model (Van Berkum et al., 2007). Second, an even earlier negativity at the left-lateralized sites is associated with violations of syntactic category (Friederici, Hahne, & von Cramon, 1998; Friederici, Pfeifer, & Hahne, 1993; Hahne & Friederici, 1999; Neville, Nicol, Barss, Forster, & Garrett, 1991). Such negative deflection usually occurs with around 125–250 ms and is thus referred to as ELAN (Early Left Anterior Negativity). The second of these two possibilities is not likely for the present results because of the discrepancies in latency and topography. The ELAN is earlier and strictly left-lateralized, whereas the negativity in the present results was later (~560 ms) and bi-lateral in pre-frontal and temporal sites. Further evidence against the possibility of ELAN is shown at the processing of the subsequent increment, the OOR embedded verb. As shown in the norming study (page 13), continuation of a bare transitive verb from a canonical S–V–O-sentence context was so rare (only 3%) that the reading of an OOR embedded verb in our stimuli might as well constitute a violation of word category; nevertheless no similar negative deflection at the pre-frontal sites was found. Thus, the OSR-elicited bi-lateralized negative deflection bears little resemblance to the ELAN that may reflect a sheer processing of word-category violation.

The fact that the latency of this bi-lateralized negativity synchronized with that of the P600 and was sustained across the processing of consecutive embedded words suggests that it was functionally related to the configuration of a di-transitive verb phrase. As mentioned above, configuration of a di-transitive verb construction would require memory resources to support the tracking of multiple thematic roles of referents predicated by each of the transitive verb. Prior research (King & Kutas, 1995) indicated a pattern of enhanced frontal negativities at the region of *object-extracted* RC in English ("Early Relative Clause (ERC))" that would demand memory support to track multiple thematic roles. It appears that both Chinese and English produce frontal negativity in response to cognitive processes that require high memory load associated with the structure that is more difficult for thematic role assignment, whether the processing of the *object-extracted* RC words in English or *the subject-extracted* RC words in Chinese. These results are in accordance with the argument that the integration of sentence fragments over long-distance dependency requires high demands on memory resources before the integration takes place (Gibson, 1998). The temporal synchrony of enhanced negativities with the P600 effect (~560 ms) reinforces this interpretation, because such synchronization indicates that the establishment of multiple references does not take place until the syntactic mapping of a di-transitive verb construction is identified.

The analysis using LORETA maps provides complementary information on the cortical sources of the ERP effects, allowing an examination of the functional neuroanatomy associated with the temporal integration processes (see Fig. 4). The Hagoort (2005) Memory, Unification and Control (MUC) model provides an explicit account of functional neuroanatomy of how different levels of processing (e.g., semantic, syntactic and phonological) take place in parallel in a *unifying* operation. The Hagoort (2005) MUC model distinguishes differential cortical sources related to the core components for language processing (memory, unification and control). The left posterior temporal cortex is involved in lexico-semantic (Damasio, Grabowski, Tranel, Hichwa, & Damasio, 1996; Hickok & Poeppel, 2000) and lexico-syntactic processing (Indefrey, 2004) and thus is important for the memory functions of retrieval and storage of the syntactic frames in the lexicon. On the other hand, the left pre-frontal cortex is involved in information maintenance over time and thus is important for the unification function that demands computational resources for binding multiple lexico-syntactic frames together thorough the integration dynamics of phrasal configuration (Hagoort, 2005). The specific functional neuroanatomy of these cortical sources has been suggested by other researchers as well (Kuperberg, Lakshmanan, Caplan, & Holcomb, 2006; Mason & Just, 2006). The MUC model, however, provides an especially interesting perspective on the present results. In a Chinese RC, the threats to integration come from several sources and a unifying process, postulated in the MUC, would operate across the different levels of information to bring about integration.

The LORETA results found separate sources specific to structural building and information processing at each processed increment. For the RC Region, the LORETA traces the OSR-elicited P600 effect to right frontal areas (BA 44/45), and the OOR-induced N400 effect to left temporal BA 42/41. Activation of inferior frontal regions has been implicated in the processing of syntactic complexity in English sentences (Caplan, Alpert, & Waters, 1999; Caplan, Alpert, Waters, & Olivieri, 2000; Caplan et al., 1998; Just et al., 1996). In connection with the MUC model, the activation of inferior frontal is important to provide computational resources for binding lexico-syntactic frames, a processing characteristics critical to a configuration of a di-transitive verb phrase while integrating the OSR embedded verb. Additional evidence reinforcing this interpretation is shown in the activation of medial inferior frontal BA 10/11 specific to the processing of OSR embedded words. One can see in Fig. 4A and B that LORETA traces shared activation for the consecutive OSR embedded words of the RC Region to the medial inferior frontal BA 10/11. Part of the medial frontal BA 10/11 has been implicated in the processing of visual–spatial analysis in reading Chinese characters that has not usually been found in alphabetic language systems (Liu & Perfetti, 2003; Siok, Perfetti, Jin, & Tan, 2004; Tan et al., 2001). However, the fact that greater activation in this area was observed only in the processing of OSR embedded words, and not in the processing of the head noun (see Table 5 and Fig. 4), suggests that the activation of this region in the present study is functionally related to the cognitive demands in the configuration of a di-transitive verb phrase. Although the function of this region in reading is not completely clear, in the research on sentence/text processing the function of BA 10/11 region has been linked to the processing of multiple referents at the level of situation model. Lepage, Ghaffar, Nyberg, and Tulving (2000) associated the pre-frontal regions with episodic memory in retrieving the spatial relation of perceived objects from their mental representations. Specifically, the medial frontal gyrus has been implicated in the theory of mind processes in the action of characters within a narrative (Fletcher et al., 1995), in the identification of thematic roles within a story (Nichelli et al., 1995) and in the processing of reference establishment when there are ambiguous antecedents within the context for an anaphor (Nieuwland, Petersson, & Van Berkum, 2007). Taken together, these findings suggest that this region may be related to establish referents, a process in which a model of multiple referents is updated on the basis of appropriate specification of multiple thematic roles. In the case of the word-to-referent integration in Chinese reading, the multiple thematic-role specification in the mapping of a di-transitive verb construction is supported by a neural network that not only provides computational resources for structure building, but it also supplies an episodic memory system for building semantic representations from the thematic relations among the NPs.

On the other hand, the left superior temporal region (BA 42/41), identified with an N400 effect induced by the OOR embedded verb, is known to be involved in lexical processing (Indefrey & Cutler, 2003), syntactic/semantic processing in sentence comprehension (e.g., Broca's area), and increasing processing demands that reflect sentence complexity while comprehending English RC sentences (Just et al., 1996). Thus, the activation of this region, according to the MUC model, implicates the retrieval of syntactic frames from memory that would apply to the structural integration of the OOR embedded verb, because the embedded NP must be reinterpreted from a main-clause object to a subject of the embedded RC, requiring retrieval of an extended syntactic frame. Thus, the temporal and spatial ERPs converge to indicate distinctive cognitive processing and functional neuroanatomy of information recruitment and usage in the processing of structural building and meaning integration for each reading increment of the RC Region.

Note that although specific lexical differences may be associated with the subject–object processing differences, the present results are difficult to reconcile with such lexical-driven account. The evidence of brain activities from both temporal and spatial (LORETA) indicates remarkably different activity patterns on the consecutive processed increments of embedded RC words. One can see clearly in Figs. 2 and 4A and B that brain activities at the RC Region indicate patterns that are functionally specialized to the cognitive demands in the reinterpretation processing contingent on the embedded structure of RC verbs. This is consistent with RC studies in various paradigms in English (Caplan et al., 1998; King & Just, 1991; King & Kutas, 1995; Muller et al., 1997) and Chinese (Yang & Perfetti, 2006). These results provide robust evidence that the underlying cognitive processes exploited in the two consecutive reading increments of the RC Region reflect distinctive processing of information recruitment and usage in the structural mapping and meaning derivation that are subject to the contextual constraints of the preceding representation. Thus, in agreement with other research that suggests that integration processes are affected by contexts beyond specific words and structures (Ledoux, Camblin, Swaab, & Gordon, 2006; Swaab, Camblin, & Gordon, 2004), the present study found that in some circumstances the language context can override lexical and syntactic sources.

An additional point to consider is the role of memory in integration processes. English-based theoretical frameworks that explain RC processing (Gibson, 1998; Gordon, Hendrick, & Johnson, 2001; MacWhinney & Pleh, 1988) have emphasized the role of memory. In fact, some ERP studies have reported *only* memory effects in the referent maintenance/integration of referential bindings; e.g., the frontal negativity associated with the object-extracted structure (King & Kutas, 1995; Muller et al., 1997). In contrast, our findings for Chinese, which has contrasting linear ordering between an unexpressed logical NP and the modified head noun, clearly indicate *both* memory and integration effects that depend on the embedded structure of the RCs. The memory effect, consistent with King and Kutas (1995) and Muller et al. (1997), was shown in the form of enhanced frontal negativity associated with the structure—the subject-extracted RC—that places great demands on memory resources. However, the integration effect was indicated in the P600 and N400 effects that reflect structure building as a function of the embedded structure of the RC verbs. The results indicate that integration in Chinese reading by and large conforms to the assumption that both semantic and syntactic information are used in sentence processing in all languages. Contrary to suggestions (Chu, 1998; Li & Thompson, 1981) that tend to smear the distinction between the usage of semantic and syntactic information in the cognitive system of Chinese reading, Chinese readers appear to use distinct sources of linguistic information in relative clause processing, as is observed in other languages.

This conclusion is consistent with recent ERP studies that provide evidence to the distinction of semantic and syntactic processing in real-time Chinese reading (Ye, Luo, Friederici, & Zhou, 2006; Yu & Zhang, 2008). These studies report ERP effects differentially associated with semantic violations (central–parietal N400 elicited by a semantically incongruent verb) compared with syntactic violations (enhanced negativity at the anterior site from as early as 50 ms) (Ye et al., 2006) and in enhanced positivity of P600 at the central–parietal sites (Yu & Zhang, 2008) elicited by the processing of a syntactically-incongruent constituent. The fact that these studies used non-canonical pre-verbal *ba* sentence construction (a S–O–V mapping), which provides semantic relationships among referents (e.g., agent and patient) to support meaning derivation of a sentence (Chao, 1968; Li & Thompson, 1981), makes their convergence with the present results (based on the canonical S–V–O orders) especially compelling.

Beyond the implication of universality in structure building, the ERP shifts observed in this study also track a lexico-semantic process that may be a language-specific property of Chinese. The ERP at the OSR embedded verb induced a transient, sharp N400, preceding the P600 (an N400–P600 complex). The LORETA traces this transient N400 to left superior temporal areas (BA 22/39/19), separable from the syntactic P600 (right frontal BA 44/45). We interpret this transient N400 to reflect lexico-semantic processes needed to resolve syntactic difficulty. Chinese has a large number of class-ambiguous words that can be used as both nouns and verbs (like *paint* in English) but without any morpho-phonological indicators of which syntactic category (Guo, 2001; Hu, 1996). The N400 may reflect the processing needed to identify the form as a possible verb in order for structure mapping and meaning processes to proceed.

Indeed, relevant for the need for this early lexico-semantic processing is the synchrony we observed between the OSR-elicited bilateralized frontal negativity and the P600 component of the N400–P600 complex. The sharp N400 to the OSR embedded verb may reflect its identification as a transitive verb, which would trigger a revision of the phrasal configuration of the di-transitive verb construction. This in turn would require additional memory resources to post or "open" the multiple thematic roles predicated by each transitive verb. Thus these findings suggest a way that Chinese reading may indeed be more dependent on lexico-semantic processes for sentence comprehension. However, these processes are in the service of structure building, not a substitute for it, consistent with a constraint-based model of sentence processing (MacDonald et al., 1994), in which semantic, probabilistic lexical information and lexically-derived syntactic information guide each increment of comprehension.

2.3.2. From word-to-referent to referent-to-model Integration

We made two assumptions about the processing of modified head nouns in the introduction: (1) processing a modified head noun entails the updating of thematic roles and establishes reference; (2) these processes require long-distance binding for the OSR types and a restructuring of multiple NPs for the OOR types. These assumptions appear to be validated by the differential ERP effects elicited by the head nouns of different RC-types: a central–frontal sustained negativity elicited by the OOR head noun and a right-lateralized sustained negativity induced by the OSR head noun. The fact that the OOR type (76%) was more difficult to comprehend than the OSR type (81%) suggests that the negativity at the OOR head noun reflects difficulty in integrating this word with the sentence meaning, resembling the classical effect of N400. The central–frontal distribution and the sustained nature of this effect leave open the possibility that it is instead related to the negativity that has been linked to referent-tracking at the level of situation model (Van Berkum et al., 2007) or to cognitive demands for recruitment of additional memory resources (Rosler, Heil, & Hennighausen, 1995; Ruchkin, Johnson, Mahaffey, & Sutton, 1988).

The LORETA traces this OOR-elicited central–frontal negativity to greater activation of left superior temporal BA 38 and frontal BA 47 (Fig. 4C). In the MUC model (Hagoort, 2005), the synchronous activation of these two regions reflects a concurrent operation of the left frontal–temporal networks in the retrieval and binding of multiple syntactic frames that would be required by unification operations. Such processes maintain, construct, and integrate information into the readers' understanding of the text, playing an important role in a situation model of a text (Mason & Just, 2006). In this context, the temporal and spatial ERPs suggest combined effects in the OOR head noun sustained negativity: an N400 meaning integration effect and a frontally dominant shift reflecting cognitive and memory operations that establish and bind references. Both of these processes are essential to support the meaning derivation of a referentially-specified model for an appropriate comprehension of a sentence.

It is worth noting that ERP studies of other languages with head-final construction of the RC (e.g., Japanese and Korean) have consistently indicated major processing difficulty associated with the processing of the OR head noun as compared to that of the SR head noun (Kwon, Kluender, Polinsky, & Kutas, 2007; Ueno & Garnsey, 2008).[9] At a general level, these patterns echo our analysis that for languages whose RC structures precede the modified head noun. Greater processing cost, and thus risk to comprehension, occurs at the head noun because intermediate representations associated with multiple NPs must be maintained on-line until the integration of a referentially-specified model takes place at the head noun. Comprehension could be impaired because intermediate representations may not be maintained and subsequently retrieved due to constrained memory resources. The fact that our Chinese readers had significant lower accuracy of overall comprehension on an OOR than an OSR sentence provides evidence for this possibility. In a nutshell, this implicates in that languages with typological differences in the constituent ordering exploit universal processing mechanisms in the real-time integration process of reading. However, to what extent and in what ways the morphosyntactic system of a language can provide processing hints to the on-site thematic-role specification, constituent ordering and etc. determine the processing specificity at each processed increment. In the case of our present Chinese study, the fact that the Chinese RC occurs before the head noun it modifies—and the absence of thematic markers and the late occurrence of a relative marker—creates a potential for structural ambiguity that is much higher than in English and many other languages. Such structural ambiguity could induce enduring cost at the processing of the head noun where an integrative thematic relationship among multiple referents can be ultimately formed.

Our finding of an OSR-elicited right-lateralized anterior negativity suggests greater memory demands in the maintenance and reactivation of unintegrated referents in the processing of long-distance dependencies. This interpretation is consistent with the association of lateralized anterior negativities with linguistic variables that affect the need for memory resources in referent integration (King & Kutas, 1995; Kluender & Kutas, 1993) and with the notion that activities of right hemisphere are functionally related to the coherence maintenance during high-order language integration (Roberston et al., 2000). The LORETA results reinforce this conclusion, showing (see Fig. 4) greater activation in response to the OSR words in the medial–parietal precuneus region across both the RC Region and the Head Noun Region (e.g., Fig. 4A: BA 31, the OSR embedded verb of the RC Region; Fig. 4C: BA 7, the OSR head noun of the Head NP Region). The precuneus is situated in a brain region that has extensive links to the network of other cortical regions that are implicated in memory processes, specifically in verbal work memory (Fiez, Raichle, Balota, Tallal, & Petersen, 1996) and in sentence processing in English (Caplan et al., 1999) and Chinese (Chee et al., 1999). In light of these associations, the precuneus may play a mediating role in resource allocation managed by the central executive system of working memory to support the increasing demands on cognitive resources based on the immediate task demands in time (Braddley, 1986).

For an integrated interpretation of the cognitive dynamics implied by these ERP effects, we must consider the cognitive task of word-by-word reading. In this task, readers integrate the RC words with a memory representation of the preceding context. This integration unfolds rapidly as readers identify the word's form class and its meaning, select the context-relevant meaning and integrate it, based on an anticipation formed from a developing representation. This integration process can be disrupted in relative clauses when the embedded verbs have alternative phrase attachments that are preferred over the RC reading. Adding to this disruption is a lingering effect from the head noun, which has multiple possibilities for NP structures that can remain unresolved as the remainder of the RC is encountered. The ERP shifts track these processes in that both the temporal and spatial ERPs show posterior dominance at the RC Region and of anterior dominance at the Head Noun Region. The finding of posterior dominant ERP shifts in the current study accords with prior studies in which the ease of integrating an immediate linguistic constituent depends on the degree of semantic relatedness to the contextual meaning (Kutas & Hillyard, 1980; Van Berkum, Brown, Zwitserlood, Kooijman, & Hagoort, 2005) and on the degree of syntactic well-formedness (Hagoort et al., 1993). ERP shifts in frontal areas have been related to memory processing reflecting referent integration (King & Kutas, 1995; Kluender & Kutas, 1993; Van Berkum et al., 2007), and to cognitive demands for recruitment of additional resources for mental operations (Rosler et al., 1995; Ruchkin et al., 1988). In a nutshell, while the dominant posterior ERP effects at the RC Region present basic evidence of word-to-referent integration, the anterior dominance of ERP effects at the Head Noun Region provides evidence for a referent-to-model building process that demands memory and cognitive resources.

3. Conclusions

Our ERP evidence demonstrates temporal and cognitive processes of information integration that are quite general across writing systems. These processes immediately recruit different, but related kinds of linguistic information, according to the processing demands at each processing increment. They rely on the ongoing support of memory mechanisms to track thematic relations and hold onto referent information. The immediacy of these ERP effects suggests that different types of information are available very quickly to comprehension. Our results also allow a picture that brings together the temporal dynamics of processing with its functional neuroanatomy. Posterior regions support the

[9] In Japanese, different types of RCs (subject-/object-extracted) are of the same word orders of the identical linguistics constituents, with different morphosyntactic marker attached to the pre-verbal NPs to specify the thematic-role matrix. In contrast, in Chinese, the subject-/object-extracted RCs differ in the word order of the embedded verb and noun, with no on-site thematic markers to specify the thematic roles of main and embedded clause. Thus, for the Japanese RCs, processing demands are discussed in their relation to the memory resource required by the resolution of referential dependency (Ueno & Garnsey, 2008), while for the Chinese RCs, we discussed processing demands to relate to a processing complexity that was jointly determined by the reanalysis effect incurred by the RC words and the available memory resources constrained by the processing of reanalysis.

word-to-referent integration processes in a developing sentential representation, whereas anterior regions provide cognitive and memory resources of a referent building process in the construction of a referentially-specified model. Importantly, the medial–parietal precuneus functions to mediate resource allocation in this referent building and integration process. These patterns imply that, in Chinese sentence reading, both the use of information sources and the recruitment of appropriate neural network of reading are influenced by the developing representation and the supporting cognitive resources in ways similar to what has been observed in other languages.

In addition to these generalizations across languages we see language-specific functional specialization in the timing and cortical sources of processes for reading Chinese sentences: The anterior medial BA 10/11 areas that function in character reading (Siok et al., 2004) appear also to function in sentence processing when multiple nouns must be mapped to multiple themes. Although the exact role that this region plays is not yet clear, its involvement in Chinese reading at both word and sentence levels implies that Chinese reading has adapted at more than one level to the memory functions it supports. Our study is one of the very few on the real-time processing and functional neuroanatomy of sentence integration in Chinese reading. It leads us to conclude that Chinese sentence reading uses a neural network that is sensitive to the sequential and hierarchical organization of linguistic inputs, reflecting a universal property of language processing. We believe that cross-linguistic studies of real-time integration of sentence comprehension in neurocognitive paradigms will be important to test and refine the theoretical framework of sentence processing we have explored here, and to more sharply distinguish its universal features from its language-specific features.

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