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Contextual Constraints on the Comprehension of Relative Clause Sentences in Chinese: ERPs Evidence*

Chin Lung Yang and Charles A. Perfetti
University of Pittsburgh

This paper reports two event-related potentials (ERPs) studies designed to test the universal and language-specific characteristics of cognitive mechanisms and their neurocognitive substrates during the real-time processing of sentence integration in Chinese. Native Chinese (Mandarin) speakers read sentences with different kinds of relative clauses (RC, subject-/object-extracted) when the RC modified the grammatical subject of the matrix clause (Experiment 1a) and the grammatical object of the matrix clause (Experiment 1b). The between-subject Modifying Type (subject-/object-modifying) factor varies on the syntactic constraints of the initial contextual phrase. While Experiment 1a uses contextual phrase of optional adjunct that is constraint-free for syntactic mapping, Experiment 1b uses contextual phrase of an essential sentence mapping that provides strong processing expectation for sentence integration. Cross-experiment comparisons of convergent ERP results on the embedded RC words indicate distinctive morphology and scalp topography of related ERPs that vary with the contextual constraints. While both experiments found a working memory ERP (bilateral anterior negativity) for keeping the filler-gap dependency meaningfully tractable, the integration ERP effects (N400 & P600) were found only when the RCs were under strong contextual constraints in meaning in Experiment 1b. This context effect occurs as early as the processed RC words being encountered (~200ms) for the identification of word class. In addition, the results also indicate an ERP effect, the N400-P600 complex, that may be related to a language-specific property of Chinese reading. In a nutshell, the context-dependent lexical effect (~200ms) and the N400-P600 complex suggest an interactive model of sentence processing in Chinese. This model is compatible with the linguistic observation that the comprehension of a Chinese text relies heavily on semantically-derived information based on the initial guidance of syntactic mapping.

Key words: relative clauses, ERPs, contextual constraints, working memory

1. Introduction

How the semantic integration of a sentence containing multiple nouns and verbs

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gets accomplished has been an important topic in the research of sentence comprehension. Indeed, successful comprehension of this kind of sentence requires appropriate use of semantic and syntactic information in memory that demands orchestration of cognitive activities managed by the processing support system (working memory) during moment-to-moment integration (Gibson 1998, Just & Carpenter 1992, Just, Carpenter, Keller, Eddy & Thulborn 1996). A particularly interesting example concerns the processing of subject-extracted (SR) and object-extracted (OR) relative clauses (RCs) as shown below:

(1) a. SR: [[The reporter$_i$ that [e_i attacked the Senator]] stole the ballots].
b. OR: [[The reporter$_i$ that [the Senator attacked e_i]] stole the ballots].
(The e_i in both sentences (1a) and (1b) indicates the unexpressed logical NP in the RC that coindexes with its modified NP, *the reporter$_i$*, in the matrix clause.)

Examples (1a) and (1b) demonstrate the contrast between the subject-extracted RC (SR) and object-extracted RC (OR) when the RCs modify the grammatical **subject** of the matrix clause. The critical contrast is that the modified noun phrase description (NP; i.e., *the reporter$_i$*) functions as the unexpressed logical subject of the verb of the embedded clause (i.e., *attacked*) in the subject-extracted RC; whereas, this NP functions as the unexpressed logical object of the verb of the embedded clause in the object-extracted RC. The object-extracted RCs are found to be more difficult to comprehend than the subject-extracted RCs. Such **object-subject processing differences** have been demonstrated by a variety of behavioral measures such as reading-time (Gordon, Hendrick & Johnson 2001, King & Just 1991), probe tasks (Wanner & Maratsos 1978), accuracy by children in enacting the meaning of sentences (MacWhinney 1982), comprehension by aphasic patients (Caramazza & Zurif 1976), as well as neuroimaging measures of brain activity (Caplan, Alpert & Waters 1998).

A variety of theoretical frameworks have been developed for explicating these object-subject RC differences and related complexity effects (Gibson 1998, Gordon, Hendrick & Johnson 2001, MacWhinney 1977). One is the "memory-load" account that attributes the object-subject processing differences to the fact that the semantically unintegrated sentence fragment must be kept in memory longer in the object-extracted RC than in the subject-extracted RC. One can see in example (1) that while the SR has no intervening content word between the modified NP and its corresponding unexpressed logic NP (e_i), the OR has two intervening content words. This account

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associates the processing difficulty of OR structures with the increase in memory load (Ford 1983, Gibson 1998).

The memory-load account obtains support from the ERP studies by Kutas and her colleagues (King & Kutas 1995, Muller, King & Kutas 1997, Weckerly & Kutas 1999). King & Kutas (1995) used ERP measures to examine the processing of different RC sentences in English similar to those shown in example (1a) and (1b) in a word-by-word reading task. A left anterior negativity (LAN) was elicited by the verb of the matrix clause in the OR sentence, a condition presumably taxed with the greatest memory load, as compared to that in the SR sentence. In addition, the processing of OR sentences elicited a sustained negativity at the central-frontal site, as compared to SR, from the initial word of the RC through the processing of the matrix clause. This slow brain potential was also found in other studies that used processing tasks taxed with heavy demands on working memory (Rosler, Heil & Hennighausen 1995, for a review). Other ERP studies showed similar results when the sentence material was presented in auditory modality (listening comprehension; Muller et al. 1997) and when lexical features of the major noun phrase arguments within the relative-clause sentence were systematically varied (Weckerly & Kutas 1999).

The current available evidence, both cognitive and neurocognitive, suggests that working memory plays a major role in modulating the relative ease of processing RC sentences during sentence integration. Nevertheless, it is far from clear to what extent and in what way the findings established in the studies of English can be generalized to other languages as well. To illustrate, as shown in Table 1, the structural contrast between SR and OR in Chinese induces an opposite prediction based on the memory-load account. One can see in Table 1 that there are two new discourse entities introduced (*gōngjí* 攻擊 'attacked', and *zhèngkè* 政客 'politician') in the **subject-extracted** RC, but not in the **object-extracted** RC. Thus, according to the memory-load account, it would be the subject-extracted RC to be more difficult to process than the object-extracted RC. Because the unintegrated sentence fragment 'the lawyer$_i$' (*nèi-ge lǜshī* 那個律師$_i$) must be kept in memory longer in subject-extracted RC than in object-extracted RC.

Furthermore, different language systems have different morphosyntactic systems that shape the interactive network properties of the language subsystems. Accordingly, the processing of sentence integration in different language systems will reflect language-specific characterizations in the orchestration of cognitive mechanisms to achieve the appropriate representation of meanings. Indeed, the parsing property of Chinese RC construction (next section) instantiates processing contrasts where the pattern of RC embeddedness (subject-/object-modifying) determines the ease of processing related to the use of semantic and syntactic information due to the head-final property of RC construction in Chinese. Yang and his colleagues have demonstrated this phenomenon in both behavioral measures (Yang, Gordon & Perfetti 2004) and brain activity measures (Yang, Perfetti & Liu, under review).

The current study conducted two ERP experiments of sentence comprehension in Chinese (Mandarin) to further examine the timecourse of integration processes of RCs sentences in Chinese as a function of the contextual constraints. Participants were native Chinese speakers and were asked to comprehend Chinese sentences containing different types of RC in a word-by-word reading task while their brain activities were recorded over the scalp. ERPs allow detailed timing information (temporal resolution), and provide a closer link to the neural firing that occurs in the brain during task performance. Specifically, some ERP effects have been very useful in studying the cognitive mechanisms exploited in information processing during language comprehension (e.g., N400, P600, and left anterior negativity (LAN)).

The N400 is a negative deflection with a central-parietal topographic distribution observed between 250 and 500ms after the stimulus onset. The less a word fits into the semantically established context, the larger the N400's amplitude (Federmeier & Kutas 2001, Kutas & Hillyard 1980, Van Petten & Kutas 1990). At the higher-level comprehension, enhanced negativity of N400 was associated with a more effortful integration process during sentence comprehension (King & Kutas 1995, Weckerly & Kutas 1999) and text comprehension (St. George, Mannes & Hoffman 1997, van Berkum, Zwitserlood, Brown & Hagoort 2003). The P600 is a positive deflection observed between 600 to 800ms post-stimulus onset with a central-parietal topographic distribution. It is elicited by morphosyntactic violations (Hagoort, Brown & Groothusen 1993, Osterhout 1994). Under certain circumstances, P600 can reflect a general reintegration process (Coulson, King & Kutas 1998, Kaan, Harris, Gibson & Holcomb 2000). Finally, the LAN is a late negative deflection observed between 300 to 700ms at the anterior sites over the left hemisphere. It was found to associate with linguistic circumstances that demand differing degrees of working memory capacity (King & Kutas 1995, Muller et al. 1997, Ruchkin, Johnson, Canoune & Ritter 1990). These ERP effects are used as indicators of the way the cognitive system provides processing support (e.g., working memory, LAN) to the processing and representation in memory of semantic (N400) and syntactic (P600) information over the course of sentence integration.

1.1 The contrast of RC sentences in English and Chinese

While the canonical word order in Chinese, as in English, is SVO (subject-verb-object, Sun & Givon 1985), the syntactic parsing of the Chinese RC construction bears a **head-final** property while the English RC construction is **head-initial**. Table 1 illustrates two types of RC constructions in both Chinese and English. Note that while

English has post-nominal RCs (the RC comes after the head NP, *the lawyer*, that is being modified), Chinese has pre-nominal RC (the RC comes before the head NP that is being modified), with *-de* as a relative clause indicator occurring later within the RC structure. Accordingly, while in English the processing of matrix and embedded materials can be temporally segregated by the occurrence of complementizer, *that*; in Chinese the interpretation of the RC embedded materials and that of the matrix clause can be easily confounded.

To illustrate, in Chinese OR of example (2b), the initial RC materials of *the politician attack(ed)* (N-V-) are naturally interpreted as the matrix subject and verb before encountering the relativizer, *-de*. This is especially true when the RC is under greater structural constraints (e.g., when the RC modifies the matrix object as shown in Table 2 where the initial linguistic materials (N-V-) preceding the embedded RC materials commands a canonical parsing (N-V-N) of matrix clauses as shown in example (3c) and (3d).

(3) Subject-modifying RCs:
   a. Chinese-SSR: $[V_r\ N_r$ *-de* $N_{(m,\ r)}]_{RC}\ V_m\ \ N_m$
   b. Chinese-SOR: $[N_r\ V_r$ *-de* $N_{(m,\ r)}]_{RC}\ V_m\ \ N_m$

   Object-modifying RCs:
   c. Chinese-OSR: $N_m\ \ V_m\ \ [V_r\ N_r$ *-de* $N_{(m,\ r)}]_{RC}$
   d. Chinese-OOR: $N_m\ \ V_m\ \ [N_r\ V_r$ *-de* $N_{(m,\ r)}]_{RC}$
   (Subscripts are used to indicate the clause status, matrix clause (m) & relative clauses (r); thus, in the following example, V_r indicates the verb in the RC and V_m the verb in the matrix clause, N: noun, *-de*: marker of RC construction.)

Consequently, the processing of the RC material for both OSR and OOR induce reinterpretation of the matrix clause up to that point. As shown in Figure 1 of the object-modifying RCs (Experiment 1b), the processing of the embedded verb of OSR is predicted to induce P600 and LAN, due to the processing difficulty related to the syntactic remapping (P600) and the assignment of multiple thematic roles (LAN) for the double transitive verb construction (N_m V_m $\mathbf{V_r}$…).[1] On the other hand, the processing of

[1] In the current study, we used typical transitive verbs that require immediate attachment of NP arguments in both matrix and embedded clauses in the stimuli (Table 1). This made it unlikely that the construction of double transitive verbs in the OSR condition would be directly interpreted as a sensible serial verb construction. The absence of ERP differences for the processing of the relativized marker *-de* also indicates that the reinterpretation process was not delayed due to a possible interpretation of serial verb construction for the double transitive verb. Were that to be true, then we should expect ERP differences occurred later in the sentence (*-de*) rather than in the embedded materials.

embedded verb of OOR is predicted to induce N400, because the occurrence of a transitive verb after the essential mapping of a matrix clause (N_m V_m N_r **Vr**…) induces a reinterpretation of the sentential semantics. These ERP patterns have been demonstrated in Yang et al. (under review). In the current study, we systematically compared the RC processing differences under different contextual constraints (subject-/object-modifying). Figure 1 indicates the predicted ERP effects related to the RC processing differences as a function of the modifying type of RCs (subject-/object-modifying). Note that for the subject-modifying RCs, the initial adverbial phrase (ADVP) does not provide constraints on the syntactic meaning and thematic role assignments for the RC materials, thus the integration difficulties of N400 and P600 with the object-modifying RCs will not occur. The LAN, however, is predicted to associate with the processing of SSR RC-words because the maintenance and storage of unintegrated sentence fragment represented by the argument structure of the initial transitive verb (*attack(ed)*, 攻擊, with null subject) demands processing support from working memory. One can see in example (2) of Table 1 that, for Chinese RCs, it is the SR that has more intervening content words between the unintegrated sentence fragment and its lexical NP counterpart. In contrast, King & Kutas (1995) found the LAN induced by the processing of object-extracted RCs (OR).

Table 1: Sample sentences demonstrating different kinds of RC construction for Chinese and English from Yang et al. (under review). As can be seen, the Chinese RC structures lead opposite prediction in terms of the object-subject processing differences as compared to what has been observed in English RCs. The arrows indicate the integration distance between the modified head noun (律師$_i$, *lawyer$_i$*) and the unexpressed logic NP (e_i) (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

Overall, although the memory-load account predicts that it would be the Chinese SRs that induce processing difficulty, the fact that an appropriate interpretation of a Chinese RC sentence requires multiple-rules for parsing operations (head-final for the embedded RCs and head-initial for the matrix clauses) results in processing complexity of integration more than just an effect of memory operation. This contrasts with the processing of English RC sentences and Japanese RC sentences (Babyonyshev & Gibson 1995, Yamashita, Stowe & Nakayama 1993) where the memory-load account has obtained supporting evidence. Both English and Japanese require single-rule parsing operation in the interpretation of the RC sentences (head-initial for English and head-final for Japanese).

2. Experiment 1a and b

We adopted sentences from Yang et al. (under review) for our study (Table 2). As can be seen, we vary the contextual constraints on the interpretation of RC materials and test the ease of integration through ERPs measured from the first content word of the RC region (Figure 1). This context manipulation tested how the cognitive system provides processing support in the timecourse of recruitments of different kinds of linguistic information during sentence integration. This is achieved by analyzing the linguistic materials related to the interpretation of the meaning of RCs that includes the embedded NP and embedded verb of the RCs at "the RC Region". The four variant conditions of each sentence include one within-subject variable and one between-subject variable. We used Chinese sentences with different types of RCs (SR vs. OR) when the RCs modified the grammatical **subject** of the matrix clauses (Experiment 1a) and when the RCs modified the **object** of the matrix clause (Experiment 1b).

Table 2: Sample sentence with different kinds of RCs when the RC modifies the subject NP (*the reporter*, 記者) of the matrix clause (Experiment 1a) "*The reporter introduced the Senator to the public before the meeting.* 召開會議前, 那個記者介紹那個議員給公眾認識." and when it modifies an object NP (still, *the reporter*, 記者) of the matrix clause (Experiment 1b) "*The Senator introduced the reporter to the general public of Taipei.* 那個議員介紹那個記者給台北的一般民眾認識."

Experiment 1a (Subject-modifying RCs)

Subject-modifying Subject-extracted RC **(SSR)**

召開 會議 前, 攻擊 政客 的 那個 記者
Calling meeting before, *e(i)* attack(ed) politician] *-de* that *reporter (i)*]
介紹 那個 議員 給 公眾 認識。
introduce(d) that Senator to public known
"The reporter who attacked the politician introduced the Senator to the public before the meeting."

Subject-modifying Object-extracted RC **(SOR)**

召開 會議 前, 政客 攻擊 的 那個 記者
Calling meeting before, politician attack(ed) *e(i)* *-de* that *reporter (i)*
介紹 那個 議員 給 公眾 認識。
introduce(d) that Senator to public known
"The reporter who the politician attacked introduced the Senator to the public before the meeting."

Experiment 1b (Object-modifying RCs)

Object-modifying Subject-extracted RC **(OSR)**

那個 議員 介紹 攻擊 政客 的 那個 記者
that Senator introduce(d) *e(i)* attack(ed) politician] *-de* that *reporter (i)*
給 台北 的 一般 民眾 認識。
to Taipei *-de* general public known
"The Senator introduced the reporter who attacked the politician to the general public of Taipei."

Object-modifying Object-extracted RC **(OOR)**

那個 議員 介紹 政客 攻擊 的 那個 記者
that Senator introduce(d) politician attack(ed) *e(i)* *-de* that *reporter (i)*
給 台北 的 一般 民眾 認識。
to Taipei *-de* general public known
"The Senator introduced the reporter who the politician attacked to the general public of Taipei."

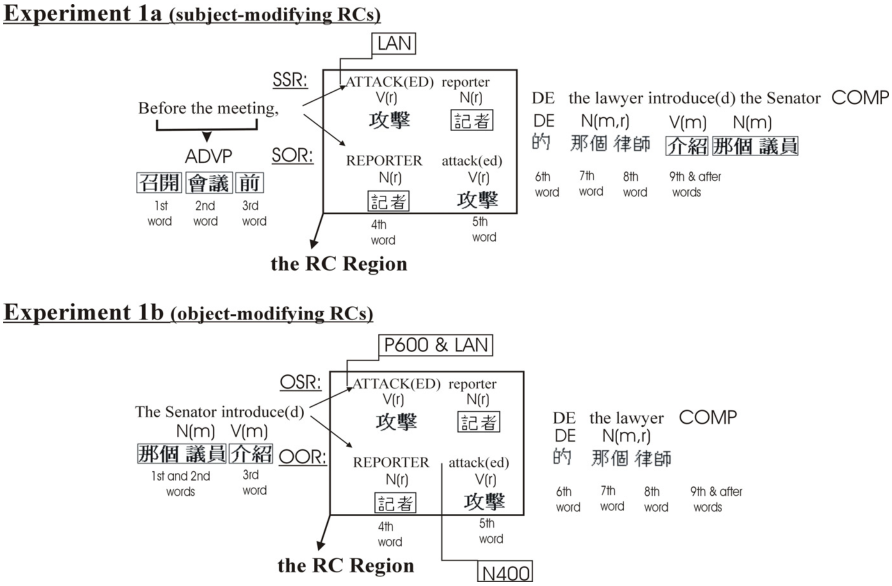


Figure 1: The predicted ERP components of Experiment 1a and 1b elicited by the processing differences between linguistic materials of subject-extracted and object-extracted RCs at the RC Region. Note that, in Experiment 1a, an adverbial phrase (ADVP) precedes the RC region that does not provide constraints upon syntactic mapping[2] and semantic meaning for interpreting the meaning of the subsequent RC materials. In contrast, in Experiment 1b, the materials preceding the RC Region are: "NP + Verb" that commit to the processing of a canonical word order of N-V-N. This provides strong constraints of both syntactic and semantic interpretation while integrating the upcoming linguistic materials within the RC Region. The sequential order of word-by-word reading is also indicated at the bottom text for each word (COMP: complement).

The hierarchical structure of Chinese RCs in Table 2 provides a centered-embedded pattern of RCs preceded by an adverbial phrase (ADVP) in Experiment 1a, and a matrix subject NP and matrix verb in N-V- order in Experiment 1b. This center-embedded pattern resembles the centered-embedded structure of RCs used in English study (King & Kutas 1995). The crucial contrast in Chinese, then, is that without a pre-RC relativized

[2] We use "syntactic mapping" on the aspect of representation rather than on the aspect of processing. We refer to the mental representation associated with the states of affairs characterized by the morphosyntactic information conveyed by the items being processed. This information will be transformed into meanings in the representation in the end. Thus, what is important is that the processing result from this mapping process is a sensible representation with specified thematic roles for each referent.

marker as compared to the English RCs (*-de* in Chinese as analogous to 'that' in English), the interpretation of the embedded RC materials is modulated by the syntactic constraints and semantic meaning of preceding context. For subject-modifying RCs (Experiment 1a), the initial adverbial phrase does not provide syntactic and semantic constraints on the interpretation of the upcoming RC materials. Thus, the ERPs will reflect only the memory effect related to resources constraints for items maintenance and storage. In contrast, for the object-modifying RCs (Experiment 1b), the initial matrix NP and verb provide strong syntactic and semantic constraints in the interpretation of the RC materials. Accordingly, the ERPs will reflect both the memory effect and the integration effects of N400 and P600 as a function of utilizing semantic and syntactic information in memory to manage the relative processing-differences of RC materials (Figure 1).

Comparison of the results of Experiment 1a and 1b provides a between-participants view of how the constraints of incremental processing affect the comprehension of the RC material with differential contextual constraints, and how the cognitive system provides processing supports in this integration process. It is worth noting that Experiment 1b resembles Yang et al. (under review), with the addition of three words to the sentence-final complement of the experimental sentences to balance the word length with Experiment 1a. The comparison of Experiment 1b and Yang et al. (under review) allows us to examine the generality of the findings across variations in the comprehension of types of trials, and in the individual differences that might induce different reading strategies. Thus, Experiment 1b can add additional generality to the evidence regarding to the RC processing-differences of object modifying RCs.

2.1 Methods and materials

2.1.1 Participants

Eighteen and 16 participants were tested in Experiments 1a and 1b, respectively. Fourteen participants in Experiment 1b were graduate students of Rice University and the remaining were all graduate students of the University of Pittsburgh. Participants were all native Chinese (Mandarin) speakers with normal or corrected-to-normal vision. Participants had acquired bachelor's degrees at Universities in Taiwan and had started English education from junior high school. Their years of graduate study range from 1 to 6 years (mean, 2.65; SD, 1.45). They were all right-handed (9 had left-handed first-degree relatives).

2.1.2 Stimuli and tasks

Experiment 1a and 1b employed a set of 32 experimental sentences adapted from Yang et al. (under review). As illustrated in Table 2, the RC modifies the **subject** NP of the matrix sentence in Experiment 1a, while it modifies the **object** NP of the matrix sentence in Experiment 1b. Appropriate changes were made for each experiment so that the length of the sentences remained the same across experiments and the target words for ERP analysis are all positioned from the 4^{th} through the 6^{th} words within a sentence. Four instances of each experimental sentence were constructed by varying the RC Type (subject-/object-extracted, within-subject factor) and the Modifying Type factors (subject-/object-modifying, between-subject factor). Each sentence has three definite descriptions relating to human roles (e.g., lawyer, politician, senator, etc.) as the arguments of the verbs in the matrix and embedded clauses. Note that the subject-/object-extracted RCs have identical linguistic constituents that only differ in the word order of the 4^{th} and the 5^{th} words. A set of 90 filler sentences that did not include restrictive relative clauses was used to increase the variation of sentences read for comprehension.

2.1.3 Design and procedure

There were two sessions in both Experiments 1a and 1b, and each session included 32 experimental sentences and 45 filler sentences. In each experiment, two versions of experimental sentences were divided by the RC Type condition and assigned to two sets of materials respectively. Two sets of 77 sentences (45 were filler sentences) each constituted the reading task and each set was used in a single experimental session. Participants read only one version of the experimental sentence within a session and across two sessions they read both versions of the experimental sentences. The sequence of the two sets of materials 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 300ms with a stimulus-onset asynchrony (SOA) of 700ms. A fixation mark preceded each trial to orient participants' attention before the trial started. Participants initiated a trial by pressing the space bar. Participants were instructed to remain as still as possible with their eyes on the center of the computer screen throughout the sentence to reduce the artifacts. They were told that they could rest before initiating the next trial. Each word was presented in the center of a 2cm high × 4cm wide column with white text in front of a black background. A true-or-false comprehension task appeared after each sentence. Participants were asked to make a true-or-false response based on the meaning of the sentence they had just read and were given immediate feedback on the accuracy. Half of the comprehension questions were true, and half were false. For the experimental sentences, correctly answering the questions required understanding of the semantic/syntactic relationship between NPs and the matrix verbs or embedded verbs in the RCs. Approximately half of the comprehension questions involved matrix verbs and the remaining half involved embedded verbs in the relative clauses.

2.1.4 Apparatus

The electroencephalogram (EEG) was recorded using the 128 channel Electrical Geodesics system (Tucker 1993) consisting of Geodesic Sensor Net electrodes, Netamps, and Netstation software running on an Apple Macintosh 1000 MHz. PowerPC G4 class computer with Mac OS 9.2.2. (Apple Computer, Cupertino, CA). The data were recomputed off-line against the average reference, the vertex (Lehmann & Skrandies 1980). Impedances were maintained below 50 kΩ, an acceptable level for electrode and amplifier used (Ferree, Luu, Russell & Tucker 2001, Tucker 1993). The EEG was amplified and analog filtered with .1 Hz to 100 Hz bandpass filters, referenced to the vertex, and a 60 Hz notch filter then digitized at 250 Hz. Six eye channels were used to monitor the trials with eye movement and blinks. The EGI Net Station also recorded all event onset times, and accuracy for later analysis. The experimental trials were controlled by the Eprime (Psychology Software Incorporation, Pittsburgh, Pennsylvania), to present the trials and to record relevant trial information. Eprime also sent event information to the electroencephalogram (EEG) recording system (Net Station, Electrical Geodesics Inc., Eugene, Oregon).

2.1.5 ERP recordings

We recorded raw electroencephalogram (EEG) data continuously, referenced to the vertex, at 250 samples per second. The EEG data were segmented off-line into 2400ms epochs that included 400ms pre-stimulus and 2000ms post-stimulus for the critical words. Data were digitally screened for artifact (eye movements/blinks, subject movement, or transient electronic artifact) and contaminated trials were removed. 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 noise, baseline corrected over the 400ms pre-stimulus period, and re-referenced to an average reference frame to remove topographic bias that can result from the selecting of a reference site (Dien 1998). The subject-averaged ERPs were averaged together to produce the mean waveform across subjects, the grand average waveform for each condition. The statistical analyses were performed on the subject-averaged ERPs for the two RC Type conditions.

The waveform plots were performed on the grand average data. For comparison purposes, Figure 2 shows both the location of the recording sensors over the scalp surface of the 128 channel Geodesic Sensor Net and the corresponding commonly-used recording sensors of 10/20 system.

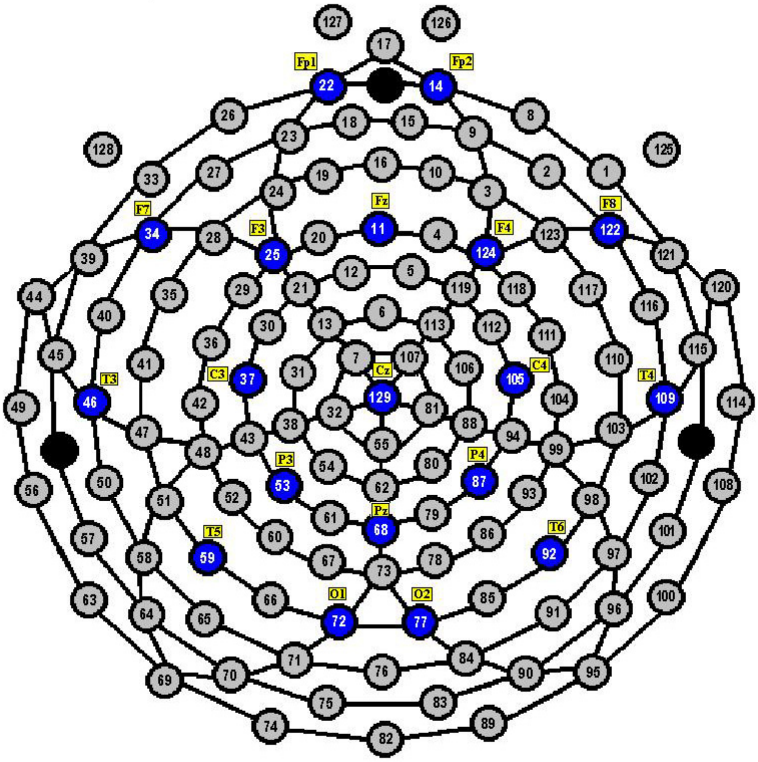


Figure 2: The location of the recording sensors over the scalp surface of the 128 channel Geodesic Sensor Net. The vertex is at the center of the map (electrode 129), the nose at the top, the occiput at the bottom, and the ears at the sides. The global circle represents the cantho-meatal line, the inferior boundary of the recording space. The commonly-used 19 recording sensors of 10/20 system are shown by blue circles for comparison.

2.1.6 ERP data analysis strategies

Our strategy was to acquire a converging view of the ERP results. We used temporal PCA to identify temporal factors and their corresponding scalp locations associated with the experimental effect. Further tests on mean amplitude differences related to experimental factors were conducted at regions of interest (ROI) identified by PCA to provide specific temporal information of the ERP effects. Note that the ERP analysis was conducted on a multiple-scale base, with epoch of multiwords in the PCA and epoch of a single-word in the ROI analysis. King & Kutas (1995) showed that multiple-scale EPR analysis on the RC materials made it possible to examine different aspects of working memory function, with multiword analysis related to storage/maintenance of items in memory and with single-word analysis related to the computational/integrative function on the immediate processing of items.

2.1.6.1 Principal Component Analysis (PCA)

A temporal Principal Component Analysis (PCA) was conducted to allow theory-free, data-driven ERP patterns to emerge. The PCA provides a quantitative analysis of the data and was carried out on subject averages, based on 250 8-ms time samples spanning from the onset of the target word to 2000ms post-stimulus (0-2000ms). PCA extracts independent components based on the covariance matrix of all sample points and thus provides a way to visually identify pre-defined temporal shifts in the ERP waveform. Because the variance of the full data pattern defines the components, PCA allows cognitively important components to emerge in the context of the overall variance pattern (Chapman & McCrary 1995, Dien & Frishkoff 1995, van Boxtel 1998). Each temporal factor can be considered to represent a particular pattern of temporal activity (e.g., a time window) associated with a specific underlying cognitive activity during the sentence integration. Thus, PCA provides a quantitative identification of a specific time window of related cognitive activity. Based on such temporal as well as spatial information from PCA analysis, an analysis of region of interest (ROI) that used the subject-averaged ERPs was further conducted to examine the modulated factors of related cognitive activities. The PCA data set consisted of the ERP averages at each electrode site in all the experimental conditions for each subject. Using the covariance matrix with Promax rotation (Picton, Bentin, Berg, Donchin, Hillyard, Johnson, Miller, Ritter, Ruchkin, Ruggs & Taylor 2000), five temporal factors were extracted (98% explained variance) in Experiment 1a and nine temporal factors were extracted (96% explained variance) in Experiment 1b. The use of Promax rotation maximizes the amount of variance associated with the smallest number of variables.

2.1.6.2 Statistical Analysis (ANOVAs)

All statistical analyses were repeated-measures ANOVAs. To examine the hemispheric difference as a function of experimental conditions, two separate ANOVAs were conducted on each prominent ERP component. One ANOVA tested the three medial electrode sites (Fz, Cz, and Pz) and the other tested 10 lateral electrode sites (F7-

F8, F3-F4, C3-C4, P3-P4, and T3-T4). The separation of the lateral electrodes from the medial electrodes made it possible to test the hemispheric differences in experimental effects because the ERP effect at the medial electrodes would be hard to attribute to hemisphere differences. For the PCA, the ANOVAs were conducted on the component score of each temporal component identified by PCA. The ANOVAs for PCA components used two within-subjects factors: RC Type (subject-/object-extracted RC) and Electrodes (3 for medial sites ANOVA and 5 pairs for lateral sites ANOVA) and the ANOVA of lateral sites includes an additional within-subject factor of Hemisphere (Left vs. Right). For the analysis of ROIs, the ANOVAs were conducted on mean voltage amplitudes, extracted from specific time windows, of clustered electrodes that represented the ROI. The ANOVAs for the ROI analysis used primarily the within-subjects factor of RC Type while the Hemisphere factor would be used wherever the ERP analysis called for lateralized comparisons. All probability values reported for effects with more than two degrees of freedom were adjusted with the conservative Geisser-Greenhouse correction for deviations from sphericity in the data.

2.2 Results

Two participants in Experiment 1a were rejected due to equipment failure during experiment runs. Sixteen participants in each experiment provided valid behavioral and EEG data for further analysis.

2.2.1 Behavioral results

The mean accuracy was 88% (SD, 7.3) for Experiment 1a and 77% (SD, 11.5) for Experiment 1b. The mean accuracy for each condition follows. Experiment 1a: subject-extracted RC (SSR: 89%), object-extracted RC (SOR: 88%); Experiment 1b: subject-extracted RC (OSR: 78%), object-extracted RC (OOR: 75%). A repeated measures ANOVA was conducted to test the generality of this pattern. The ANOVA used the RC Type (subject-/object-extracted) as a within-subject factor and the Modifying Type (subject-modifying vs. object-modifying) as a between-subject factor. The main effect of RC Type did not reach significance ($F(1,30)=1.39$, $p=0.25$) and did not interact with Modifying Type ($F(1,30)=0.47$, $p=0.50$). However, the between-subject factor of Modifying Type reached significance ($F(1,30)=11.69$, $p<0.005$). The results indicated that the RC-sentences were more difficult to comprehend when the mapping and interpretation of the embedded RC materials were under strong contextual constraints (when RC modifies the grammatical object of the matrix sentence) that caused integration difficulty due to the violation of processing expectation.

2.2.2 ERP results

2.2.2.1 PCA components

The PCA extracted 5 temporal factors that accounted for 98% of the total variance in the data set of Experiment 1a (left panel, Figure 3) and 6 major temporal factors that accounted for 94% of the total variance in the data set of Experiment 1b (right panel, Figure 3). For Experiment 1a, statistical tests indicated that only component 4 (peaking at 640 and 1192ms) and component 5 (peaking at 208ms) were effected by the experimental factor. Other components were not influenced by experimental factor (component 1, peaking at 1736ms; component 2, peaking at 40ms; and component 3, peaking at 312ms). For Experiment 1b, statistical tests indicated that only components 2 (peaking at 600ms), component 4 (peaking at 400ms), and component 6 (peaking at 1104ms) were effected by the experimental factor while other components were not (component 1, peaking at 1848ms; component 3, peaking at 96ms; and component 5, peaking at 224ms). The component 1 in both Experiment 1a and 1b indicates a slow-wave component that is widely found in PCA on ERP. It is sometimes a result of the autocorrelated nature of ERP data (Wastell 1981). Other insignificant components in both Experiment 1a and 1b all have very early peaks that reflect exogenous components. Note that "component" in this section refers to PCA component, not to voltage shifts. Table 3 outlines the results of ANOVAs for the prominent PCA components related to the experimental manipulations.

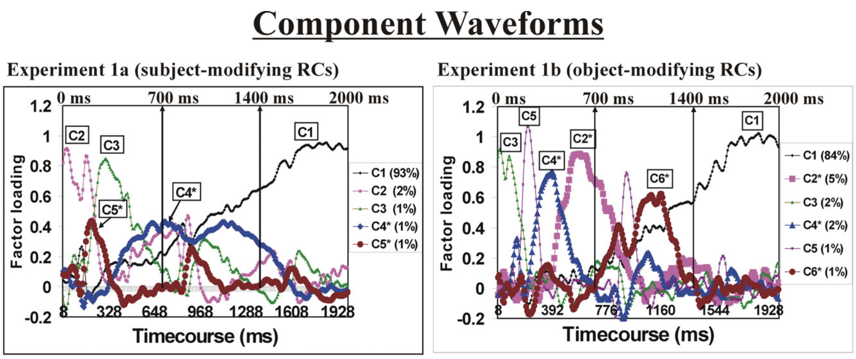


Figure 3: Component waveforms of extracted PCA components for Experiment 1a & 1b. For the component waveforms, the text boxes within the plot area indicate the corresponding components and their explained variance are shown in the legend box. Note that the 0ms, 700ms and 1400ms on the upper X axis indicate the onset of the 4th word, of the 5th word, and of the 6th word, respectively. In each figure, components with asterisks are those related to the experimental manipulation.

Table 3: Analyses of Variance (ANOVAs) of Experiment 1a and 1b on the component score of each prominent temporal factor extracted from PCA. The Geisser-Greenhouse correction was applied when the variance sphericity assumption was not met. The corrected *P* values are reported. (Note: RC=RC-Type. The medial ANOVA used 3 midline electrodes (Fz, Cz & Pz) while the lateral ANOVA used 5 pairs of bilateral electrodes (F7-F8, F3-F4, C3-C4, P3-P4, & T3-T4)). *p<.05.

Source		**Experiment 1a**			
		Component 4 (~640 to ~1192ms)		**Component 5 (208 & 912ms)**	
		Medial ANOVA		***Medial ANOVA***	
	Df	*F*	*P*	*F*	*P*
RC	(1, 15)	2.60	0.13	0.43	0.52
RC *Electrodes	(2, 30)	11.10	0.001*	3.09	0.08
		Lateral ANOVA		***Lateral ANOVA***	
	Df	*F*	*P*	*F*	*P*
RC	(1, 15)	13.19	0.002*	3.84	0.07
RC *Electrodes	(4, 60)	5.39	0.006*	4.60	0.007*
RC *Hemisphere	(1, 15)	2.01	0.18	0.51	0.49
RC *Electrodes *Hemisphere	(4, 60)	0.39	0.76	0.89	0.46

Source		**Experiment 1b**					
		Component 2 (600ms)		**Component 4 (400ms)**		**Component 6 (1100ms)**	
		Medial ANOVA		***Medial ANOVA***		***Medial ANOVA***	
	Df	*F*	*P*	*F*	*P*	*F*	P
RC	(1, 15)	3.77	0.07	3.47	0.08	7.91	0.01*
RC *Electrodes	(2, 30)	2.11	0.16	0.48	0.62	3.57	0.04*
		Lateral ANOVA		***Lateral ANOVA***		***Lateral ANOVA***	
	Df	*F*	*P*	*F*	*P*	*F*	*P*
RC	(1, 15)	1.12	0.31	1.52	0.24	1.02	0.33
RC *Electrodes	(4, 60)	3.67	0.04*	2.63	0.06	8.29	0.001*
RC *Hemisphere	(1, 15)	0.12	0.74	0.23	0.64	0.55	0.47
RC *Electrodes *Hemisphere	(4, 60)	0.04	0.91	0.83	0.46	0.19	0.82

2.2.2.1.1 Experiment 1a

Component 4, a slow wave component, rose slowly from ~450ms and reached the peak at 640ms. The average component scores were negative for central and parietal sites, and positive for frontal and temporal sites. As shown in Table 3, statistical tests indicated that this component was modulated by the RC Type factor at both medial and lateral sites. There was a significant interaction effect of RC Type x Electrodes for the medial site ANOVA, and significant effects of both RC Type and interaction of RC Type x Electrodes for the lateral sites ANOVA. Planned contrasts indicated that the sources of the effect are located at the bilateral frontal sites (F7, $t(15)=2.21$, $p<0.05$; Fz, $t(15)=2.47$, $p<0.05$; F4, $t(15)=2.53$, $p<0.05$; F8, $t(15)=2.31$, $p<0.05$), the left parietal sites (P3, $t(15)=-3.18$, $p<0.01$; Pz, $t(15)=-4.09$, $p<0.01$), and the right temporal site (T4, $t(15)=2.88$, $p<0.05$). The subject-extracted RC (SSR) elicited more negativity than the object-extracted RC (SOR) at the frontal and temporal sties (F7, Fz, F4, F8 & T4). However, at the parietal sites (P3 & Pz) the subject-extracted (SSR) condition was more positive than that of the object-extracted (SOR) condition.

Component 5 had peak loadings of 208ms, 912ms and 1608ms. These time points corresponded to ~200ms peaks relative to the onset of each processed word (e.g., the 4th word, 208ms; the 5th word, 212ms; the 6th word, 208ms). The average component scores were positive at the frontal, central, and parietal site, and negative at the temporal sties. Statistical test indicated that this component was modulated by the RC Type factor at the lateral sites. ANOVAs (Table 3) indicated a significant interaction of the RC Type x Electrodes. Planned contrasts indicated that the sources of the effect are located at the right frontal site (F4, $t(15)=2.26$, $p<0.05$), left parietal site (P3, $t(15)=-2.54$, $p<0.05$), and the right temporal site (T4, $t(15)=3.64$, $p<0.005$). Similar to component 4, the subject-extracted RC induced more negativity than the object-extracted RC at the right frontal and temporal sites (F4 & T4), and more positivity than the object-extracted RC at the parietal site (P3). Interestingly, the peak and shape of this component matched the N100-P200 complex that represents a typical ERP for visually presented material. An early component of this kind was also found in Experiment 1b (component 5, right panel of Figure 3) that was not sensitive to the RC Type factor. It is a surprise that the current experiment found such early effect related to the experimental factor. This suggests that the lexico-semantic information may be available very quickly, as soon as the words are encountered, to distinguish the class of the words while the embedded RC materials are under weak contextual constraints. The implication of this finding will be discussed later.

2.2.2.1.2. Experiment 1b

Component 2, with a peak loading at ~600ms. The average component scores were negative for the central, parietal, and temporal sites and positive for the frontal site. Statistical tests (Table 2) indicated that this component was modulated by the RC Type factor at the lateral sites ANOVA that there was a significant interaction effect of RC Type x Electrodes. Yet, the main effect of RC Type reached marginal significance in the medial site ANOVA. Planned contrasts indicated that the locus of the RC Type effect were at the frontal and central-parietal sites. The subject-extracted RC (OSR) induced more positivity than the object-extracted RC (OOR) at the central-parietal sites (Cz, $t(15)=-1.90$, $p=0.08$; P3, $t(15)=-1.91$, $p=0.08$; Pz, $t(15)=-2.20$, $p<0.05$), while more negativity than the OOR at the frontal site (F8, $t(15)=2.54$, $p<0.05$). This component was called P600 because its peak, latency, and topographic distribution (central-parietal site) were similar to the P600 effect reported in the literature.

Component 4, with a peak loading at ~400ms. The average component scores were negative over the scalp distribution. Statistical tests (Table 2) suggested that this component was modulated by the RC Type factor at both the medial and lateral sites. Both the main effect of the RC Type for the medial site ANOVA and the interaction effect of the RC Type and Electrodes for the lateral sites ANOVA reached marginal significance. Planned contrasts indicated that the OSR condition elicited more negativity than the OOR condition at the Cz, though it just reached significance ($t(15)=2.13$, $p=0.05$). This component was called N400 because its peak, latency, and topographic distribution (central-parietal site) resembled the N400 effect reported in the literature.

Component 6, with a peak loading at ~1100ms. This timeframe indicates the 400ms post-onset of the 2nd word of this 2000ms epoch (the 5th word of the sentence). Accordingly, this component reflects processing differences of the 5th word of the sentence. The average component scores were positive for the frontal site, and negative for the central, parietal and temporal sites. The ANOVAs indicated that this component was modulated by the RC Type factor at both the medial and lateral sites. For the medial site ANOVA, the main effect of RC Type and its interaction with the Electrodes were found significant. For the lateral site ANOVA, only the interaction of RC Typex Electrodes reached significance. Planned contrasts showed that the processing of the OOR word induced more negativity than the OSR word at the central-parietal sites (Cz, $t(15)=-3.12$, $p<0.01$; P3, $t(15)=-3.22$, $p<0.01$; P4, $t(15)=-4.32$, $p<0.005$). Yet, the left frontal site showed an opposite pattern that the OOR word induced more positivity than the OSR word (F7, $t(15)=2.57$, $p<0.05$). This component was N400 (relative to the onset of the 5th word) because its peak, latency, and topographic distribution (central-parietal site) were similar to the N400 effect reported in the literature.

2.2.2.2 Region of Interest (ROI) Analysis

Figures 4 and 5 show the brain waveforms of the scalp location related to the experimental effect for Experiments 1a and 1b, respectively. These locations were identified by the PCA. While drawing ROI for each ERP effect, each electrode is represented by clustering with adjacent electrodes. Figure 6 shows the clustered electrodes of regions that correspond to commonly used electrode sites in the international 10-20 system (F7-F8, F3-Fz-F4, C3-Cz-C4, P3-Pz-P4, and T3-T4). For statistical tests on brainwave amplitudes at the ROIs, we used the mean amplitudes of electrode clusters (as identified by PCA) by averaging the mean voltage amplitude of all channels within each clustered region. The ANOVAs used two within-subject factors of RC Type and Hemisphere. Because the PCA has identified significance differences for the selected scalp electrodes, the tests of the ROI were used to provide finer temporal sources of the experimental effects, not as an additional test of whether there were differences.

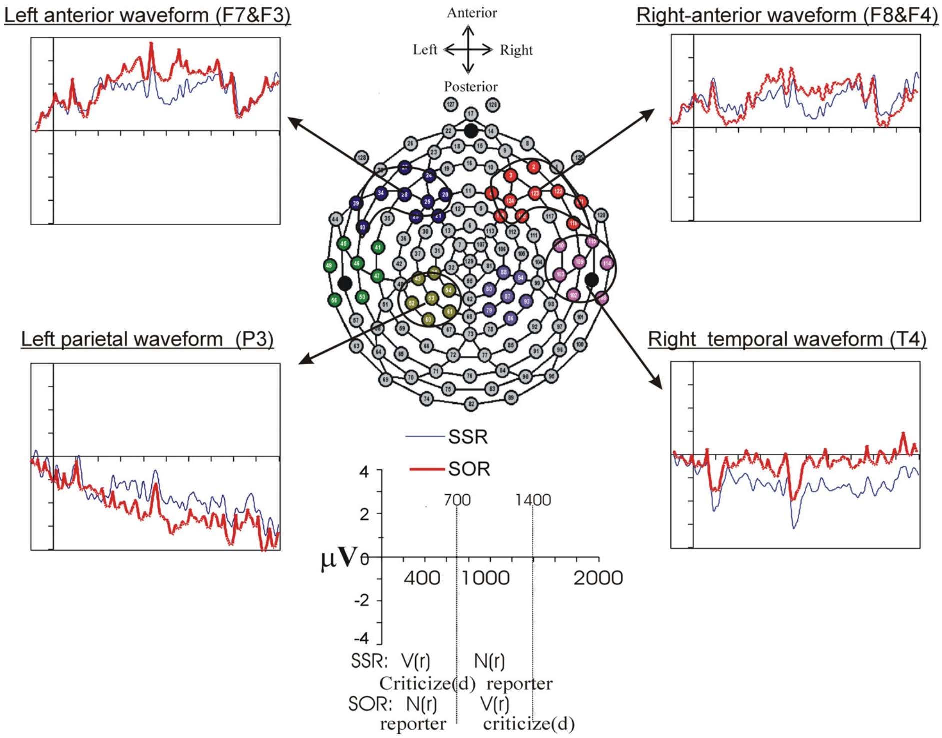


Figure 4: Top view of the ROI mapping for scalp location related to the experimental manipulations as identified by the PCA in Experiment 1a. These include bilateral anterior sites (F7, F3, F4 & F8), the left parietal site (P3), and the right temporal site (T4). The brain waveform of each ROI was plotted by averaging the grand average reference ERPs to the RC Typeover electrode clusters. The selected electrode clusters are marked by colored circles. The hemispheric distinction (left & right) are marked with different colors.

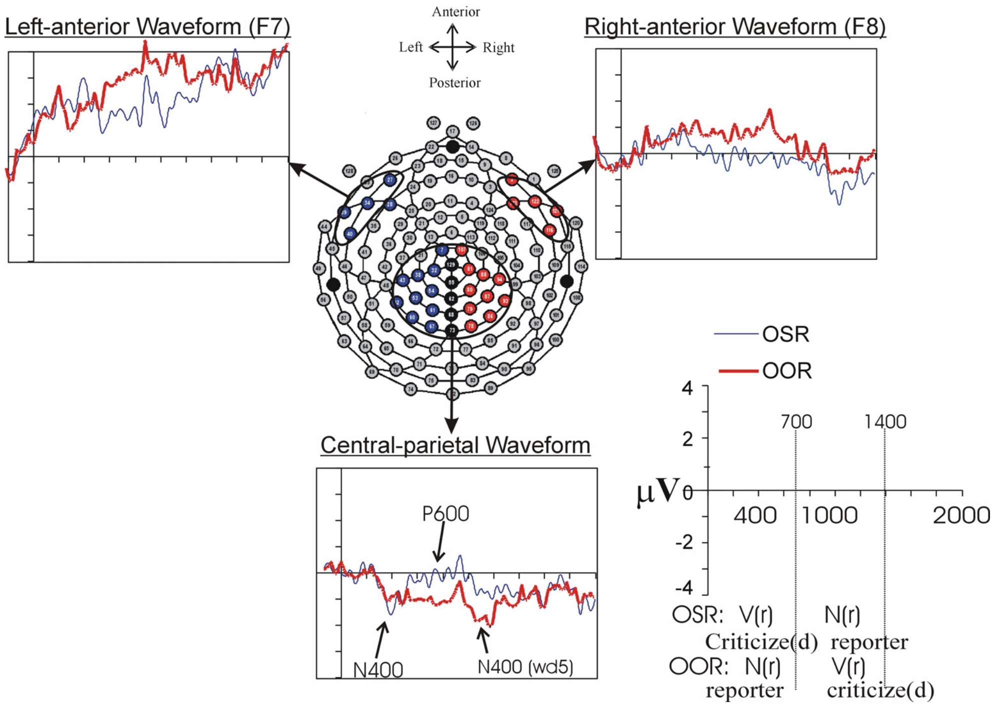
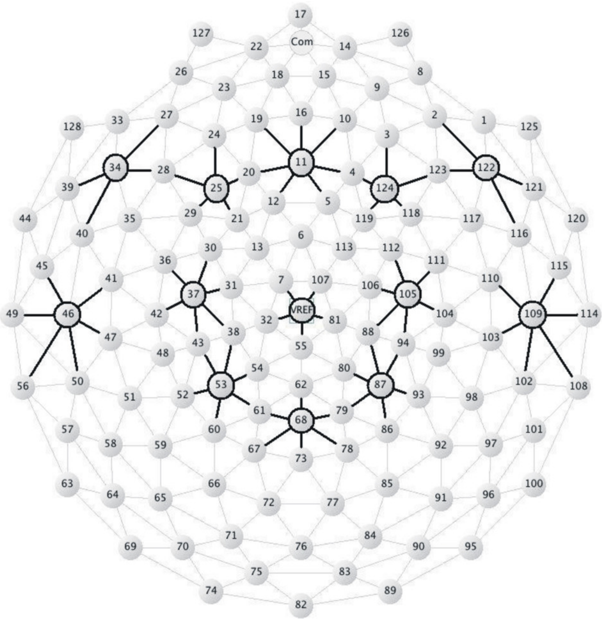
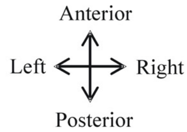


Figure 5: Top view of the ROI mapping for scalp location related to the experimental manipulations as identified by the PCA in Experiment 1b. These include bilateral anterior sites (F7 & F8) and the central-parietal site (Cz, P3, Pz & P4). The brain waveform of each ROI was plotted by averaging the grand average reference ERPs to the RC Typeover electrode clusters. The selected electrode clusters are marked by colorful circles. The hemispheric distinction (left, middle, and right) were marked with different colors.





Cluster Locations	
10/20 System	EGI 129
F7	34
F8	122
F3	25
Fz	11
F4	124
C3	37
Cz	129 (VREF)
C4	105
P3	53
Pz	68
P4	87
T3	46
T4	109

Figure 6: The clustered channels that correspond to the most commonly used electrode sites in the international 10-20 system (F7-F8, F3-Fz-F4, C3-Cz-C4, P3-Pz-P4, T3-T4) for the ANOVA of the ROI analysis.

2.2.2.2.1 Experiment 1a

According to the PCA analysis, the bilateral anterior sites (F7, F3, F4 & F8), the left parietal site (P3), and the right temporal site (T4) are the primary regions of interest to test the *a priori* hypothesis in terms of the ERPs effect as a function of the relationship between working memory and structure mapping. Component 4 identifies sustained negativity related to the working memory operation and component 5 identifies early effect that may relate to a lexico-semantic processing in distinguishing word class of visually-presented words.

2.2.2.2.1.1 Bilateral Anterior ROI

The bilateral Anterior ROI was a slow wave component identified by component 4 of PCA. One can see in Figure 4 that the processing of the SSR word elicited sustained negativity at the bilateral anterior region with a temporal epoch extending from the 4th through the 5th word. The anterior negativity has been shown to relate to working memory that supports the integration processes (King & Kutas 1995, Kluender & Kutas

1993). The ANOVA of this bilateral anterior negativity (time windows, 600 to 1300ms) showed that the processing of the SSR word induced more negativity than that of the SOR word ($F(1,15)=5.71$, $p<0.05$). This pattern was consistent at both hemispheric sites as no significant interaction of the RC Type x Hemisphere ($F(1,15)=0.19$, $p=0.67$) was found.

2.2.2.2.1.2 Right Temporal ROI

This ROI was identified by component 4 of PCA. The ANOVA of this temporal negativity used a time window of 600 to 1300ms and included its left lateral counterpart, T3. The results indicate that there is more negativity associated with the processing of the SSR word than that of the SOR word only at the right hemisphere. The interaction between RC Type and Hemisphere was significant ($F(1,15)=7.83$, $p<0.05$). However, the main effect of RC Type was not significant ($F(1,15)=0.79$, $p=0.39$).

2.2.2.2.1.3 Left Parietal ROI

This region was identified by component 4 of PCA as well. Interestingly, this region indicated similar timecourse with opposite polarity pattern of RC processing differences to the previous two ROIs. Again, the ANOVA of this parietal effect used a time window of 600 to 1300ms and included its right lateral counterpart, P4. The results indicate that there is more sustained negativity associated with the processing of the SOR word than that of the SSR word at both hemispheres. The main effect of RC Type was significant ($F(1,15)=5.97$, $p<0.05$). No significance was found for the interaction of RC Type x Hemisphere ($F(1,15)=0.14$, $p=0.71$).

2.2.2.2.2 Experiment 1b

According to the PCA, the bilateral anterior sites (F7 & F8) and the central parietal site (Cz, P3, Pz & P4) are the regions of interest to test the *a priori* hypothesis in terms of the ERP effects as a function of the relationship between working memory, syntactic mapping, and semantic integration.

2.2.2.2.2.1 Central-parietal ROI

In this region, PCA demonstrates the spatiotemporal dynamics of how different levels of linguistic information (semantic and syntactic) are recruited and processed as the sentence integration is temporally unfolded. The PCA showed an N400-P600 complex for the OSR condition while processing the 4th word, and an N400 effect for the OOR condition while processing the 5th word. Figure 5 demonstrated the brain waveforms of these locations identified by the PCA.

2.2.2.2.2.1.1 N400-P600 complex (for the 4th word)

The brainwave form showed an enhanced N400 and P600 for the processing of the OSR embedded verb. However, the ANOVA on the N400 effect (time windows, 350 to 450ms) indicated only marginal significance for the RC Type factor ($F(1,15)=3.44$, $p=0.08$). No interaction of RC Type x Hemisphere was found ($F(1,15)=0.01$, $p=0.93$). On the other hand, the ANOVA on the P600 (time windows, 500 to 800ms) showed that the processing of OSR word significantly induced more positivity than the OOR word ($F(1,15)=16.17$, $p<0.005$). The interaction of RC Type x Hemisphere did not reach significance ($F(1,15)=0.08$, $p=0.79$).

2.2.2.2.2.1.2 N400 (for the 5th word)

For the N400 elicited by the OOR embedded verb, the EEG data were segmented off-line into 1200ms epochs spanning 200ms pre-stimulus to 1000ms post-stimulus for the 5th word of the sentence. The procedures of data extraction for the subject-averaged ERPs were the same as described above. The ANOVA showed a reliable N400 reduction for the OSR word ($F(1,15)=8.01$, $p<0.05$). No interaction was found for the interaction of RC Type x Hemisphere ($F(1,15)=0.12$, $p=0.73$).

2.2.2.2.2.2 Bilateral Anterior ROI

The bilateral anterior ROI was identified from component 2 and component 6 of PCA. One can see in Figure 5 that, similar to Experiment 1a, the processing of OSR word induced sustained negativity that extended over the processing of the subsequent word, the 5th word, at the bilateral anterior regions. Note that this anterior negativity is more locally distributed than that of Experiment 1a. While it occurred only in the prefrontal area (F7 and F8) in the current experiment, it occurred in a broader area that covered both prefrontal and frontal sites (F7-F3 and F8-F4) in Experiment 1a. The ANOVA of this bilateral anterior negativity (time windows, 600 to 1300ms) indicated that the processing of the OSR word induced reliably sustained negativity than the OOR word ($F(1,15)=4.93$, $p<0.05$). This effect was not influenced by Hemisphere factor ($F(1, 15)=1.33$, $p=0.27$). Consistent with Experiment 1, the anterior region ERPs indicated working memory operations during sentence integration.

3. Discussions

The present ERP study examined how universal and language-specific factors modulate the processing and representation of syntactic and semantic information in memory over the course of sentence integration. As Chinese has an impoverished morphosyntactic writing system, the processing of language comprehension relies heavily on the sequential and syntactic organization of the linguistic structure (Yang, Gordon, Hendrick & Hue 2003, Yang, Gordon & Perfetti 2004, Yang et al., under review). With the use of multiple analyses of ERP recordings on an epoch that extends to the processing of series of RC words, we have obtained a convergent picture of the word-by-word integration processes during the comprehension of RC sentences with structural complexity in Chinese. This picture showed that each word is immediately integrated into the reader's representation of the sentence as being encountered, and that this integration process is guided primarily by the sequential and syntactic organization of a language. The nature of these two aspects, immediate integration and sequential organization, predicts that differential ERP effects will be obtained that reflect differences in the ease of integration as a function of contextual constraints.

Our test of this used the Chinese RCs that varied the grammatical status and hierarchical structure of the head NP the RCs modified. The use of context constrains processing expectation based on its syntactic status upon the processing of embedded RCs materials. In Experiment 1a, the adverbial phrase that precedes the subject-modifying RCs is an optional adjunct. In contrast, in Experiment 1b, the matrix NP and verb in an N-V- order that precede the object-modifying RCs impose an essential structural mapping for sentence integration. Accordingly, the processing differences of RCs reflect simply a working memory effect when the RCs are preceded by an optional adverbial phrase, while both integration and working memory effects when the RCs are preceded by a mapping of matrix clause.

The convergent ERP results indicated that readers were responsive to preceding context while interpreting the meaning of the RC words. When the preceding context provides optional syntactic attachment, the ERP indicates a bilateral, sustained anterior negativity that reflects working memory function for items storage and maintenance while resolving filler-gap dependency. In contrast, when the context represents essential mapping of syntactic and semantic information, the ERP shows both a bilateral anterior negativity, and crucially integration effects that reflect the use of syntactic and semantic information in memory while resolving processing difficulty for the series of RC words. Note that the ERP analyses of both Experiment 1a and 1b were on identical lexical items. Nevertheless, the convergent results indicated both similar and differential ERP effects on amplitudes and scalp distribution. The bilateral anterior negativity that reflects working memory operations is essential for both Experiment 1a and 1b because the processing of the subject-extracted RC (SR) words necessarily involves item storage and maintenance that demands supports of working memory. On the other hand, the integration ERPs related to the use of different kinds of linguistic information were found only in Experiment 1b where the preceding context of object-modifying RCs induced integration difficulty due to the violation of processing expectation.

Furthermore, the cross-experiment comparison suggests that the contextual constraint has an effect on early lexico-semantic processing. In Experiment 1a, the component 5 of PCA identified an early temporal factor (~200ms post-stimulus onset for the processed words) related to the RC Type factor. Note that the comparison of words of different RC Type involves different lexical items in reverse order. This suggests that the lexico-semantic information can be available as soon as the word being encountered for the identification of word class. However, Experiment 1b also indicated this early ERP effect identified by PCA (component 5), but with no significant relation to the experimental manipulation. Similarly, previous ERP studies of the processing of English RCs (King & Kutas 1995) and Chinese RCs (Yang et al., under review) provide evidence of distinctive ERP patterns as a function of the RC Type that is not consistent with the prediction of the lexical-processing artifact. This is confirmed with the absence of the early effect in Experiment 1b while Experiment 1b bears close resemblance to Yang et al. (under review).

The question becomes why the ERP reaction to the processing of lexical parsing of word class occurs only when the preceding context did not provide strong processing expectation of word class in Chinese sentence processing. One possibility is that the lexical identification of word class in Chinese is flexible and context-dependent within a sentence environment. Thus, the earliness of class distinction occurs when the preceding context provides context-free information, but disappears when the context provides essential processing expectation. Were this true, then we face a theory of Chinese sentence integration that is in line with the interactive viewpoint of sentence processing (MacDonald, Perlmutter & Seidenberg 1994, Bates & MacWhineey 1989, Taraban & McClelland 1988).

Indeed, Chinese has an impoverished morphosyntactic system that does not have subject-verb agreement, case marking, inflectional system, and morphological transformation (Li & Thompson 1981). These characteristics lead to a linguistic consequence that the appropriate class information of a word would be identified only after examining the lexical and semantic relations between neighbouring characters in a character string. Quite often, a word form can be used to represent different word class depending on the combination of its neighboring words within a sentence. Cognitively speaking, this suggests an interactive processing system that draws a variety of linguistic information (e.g., lexical, semantic, and syntactic) at both the single-word and the discourse level in the processing of word-class identification during sentence integration. In this view, the finding of the context-dependent early effect on the processing of word-class identification accords with a processing consequence of this linguistic property of Chinese.

Additional ERP evidence also indicates that the context-dependent effect on word-class identification may result from an interaction of contextual constraints and the lexico-semantic information carried by the processed word as well. In this view, the identification of different word class during sentence integration depends on whether the lexico-semantic information of processed words substantiates appropriate use of the processed words within the sentence context. In the current study, the word-class distinction occurred when the context did not provide processing constraints for the use of the processed word (verb (SSR) vs. noun (SOR)), but disappeared when the context provides processing expectation of inappropriate use of the processed words (e.g., for OSR, the context expected a noun when the initial RC word is a transitive verb). This is consistent with Federmeier, Segal, Lombrozo & Kutas (2000) who found that the occurrence of a left, frontal positivity associated with the use of unambiguous verbs in a sentence depends on the contextual constraints of syntactic expectation. The left, frontal positivity occurred only when the unambiguous verb was used in an appropriate context (e.g., when used as a verb in the sentence) but disappeared when the unambiguous verb was used in an inappropriate context (e.g., when used as a noun in the sentence).

It is worth noting that the serial verb construction in Chinese raises an additional possibility that the absence of early effect on word-class distinction in the OOR condition may be due to an integration process that assimilate the double transitive verbs into a sensible serial verb construction. However, the fact that we used transitive verbs that demanded immediate attachment of NP argument made this implausible. In addition, the ERP analysis did not support this possibility as it showed processing difficulty at the embedded verb of the OOR condition, but not at the subsequent relativized marker *-de*. Were the double transitive verbs able to assimilate into a sensible serial verb interpretation, it would be the relativized marker *-de* that showed processing differences on the reinterpretation process.

Consistent with Yang et al. (under review), Experiment 1b found a N400-P600 complex at the central-parietal site that provides supporting evidence for the role syntactic organization plays in Chinese sentence processing. The N400-P600 effect was induced by the OSR word where a processing of syntactic reinterpretation is expected. The occurrence of a transient N400 preceding the P600 suggests that a lexico-semantic process occurs while resolving syntactic difficult. This lexico-semantic process may relate to a lexical-selection process needed in determining the appropriate lexical parsing of word class for the processed word. In Chinese, after all, the appropriate use of lexico-semantic information of a processed word within a sentence is determined by the processing constraint of the sentence context. In this view, the occurrence of a N400-P600 complex in the current study accords with a linguistic observation that Chinese readers tend to use more of the semantic relationship between linguistic constituents than of their structural mappings in deriving a coherent representation during language comprehension (Li & Thompson 1981).

In sum, the results of the current study are in line with the interactive viewpoint that the real-time sentence processing makes use of all available information in the analysis to derive a semantically coherent representation for comprehension (MacDonald et al. 1994). More specifically, the N400-P600 complex, which reflects a general lexically-based process, suggests that the semantic and syntactic information are interdependent to each. This also implies that the processing resources used for managing different kinds of linguistic information (lexical/semantic/syntactic) are from the same resource pool during the real-time processing of Chinese sentence. This implication is not consistent with the modular approach that semantic and syntactic information are independent to each other and are analyzed in different levels (Clifton & Frazier 1988, Frazier 1989)

3.1 Working memory and sentence integration

Working memory plays an important role in providing processing supports to the real-time cognitive activities during language comprehension. In the current study, we adopted multiword ERP analysis (King & Kutas 1995) to examine the function of working memory during sentence integration in Chinese. In general, LAN and the slow potential over the frontal cortex have been related to working memory functions during the processing of sentence comprehension. The LAN has been related to the processing of filler-gap dependency and thematic-role assignment during sentence integration (King & Kutas 1995, Kluender & Kutas 1993). The slow wave pattern over the frontal area has related to working memory operations during the processes of sentence comprehension (King & Kutas 1995, Muller et al. 1997), and in tasks that demand recruitment of additional resources for cognitive operations (Rosler et al. 1995, Ruchkin, Johnson, Mahaffey & Sutten 1988).

The current study found a bilateral, sustained anterior negativity elicited by the RC conditions (SSR and OSR) taxed with heavy memory load in item storage and maintenance. The temporal coverage of the sustained negativity coincides with the fact that the process of storage tended to spread out in time that extends across regions of multiple linguistic constituents. This is consistent with Yang et al. (under review) that analyzed both single-word and multiword ERP epochs. However, only the multiword

ERP analysis found a sustained, bilateral anterior negativity that was statistically reliable. Both ERP studies of Chinese RCs failed to find a left lateralized and temporally localized negativity that indexes integrative and computational processes for thematic-role assignment and syntactic mapping (King & Kutas 1995, Kluender & Kutas 1993). This contrasts with King & Kutas (1995) where both the multiword and single-word ERP analyses on the RC words in English indicated ERPs related to different aspects of working memory function: While the multiword analysis found sustained negativity associated with the OOR condition at the frontal sites, the single-word analysis found left-lateralized anterior negativity (LAN) associated with the OOR condition.

Thus, while the ERP sentence studies in Indo-European languages found the anterior, sometimes left lateralized sites to be a primary locus that signifies the cognitive mechanisms of working memory; the current study, however, found ERP evidence of working memory mainly related to the ease of processing, storage, and maintenance (slow frontal wave potential), and no reliable indication related to the integrative aspect of working memory (LAN). This suggests that working memory function may be less functionally differentiated during the processing of language comprehension in Chinese as compared to that in English. The different aspects of working memory function (computational/integrative vs. storage/maintenance) may be executed by similar cognitive mechanisms. This implied an additional possibility that the subgroups of neurogenerators responsible to different aspects of working memory are less functionally differentiated in their cortical organization. We need to entertain the possibility that certain language-specific properties of Chinese, both at the lexical and the sentence levels, may play a role in shaping the cortical organization of the relationship between cognitive architecture and its neurocognitive substrates during language development (Gandour, Wong, Dzemidzic, Lowe, Tong & X. Li 2003, Li, Jin & Tan 2004, Tan, Spinks, Feng, Siok, Perfetti, Xiong, Fox & Gao 2003). Further studies are needed to examine which specific properties of the Chinese language system may play such a role in shaping the neural correlates of working memory and those cognitive mechanisms exploited in the integrative processes of language comprehension

4. Conclusion

Sentence comprehension is an instance of complex information processing and therefore its successful achievement relies on how different levels of linguistic information are sufficiently processed and integrated into a coherent mental representation. The current study indicates that Chinese readers process each incoming word incrementally to map the referents into a semantically-interpreted mental representation during sentence integration. As in English, this integration process is modulated by the sequential and syntactic organization of linguistic structure. In addition, the ERP results also indicate some language-specific properties of the Chinese sentence that may play a role in orchestrating the relationship of cognitive architecture and the neurocognitive substrates. Both the context-dependent lexical effect related to word-class identification and the N400-P600 complex in resolving syntactic difficulty suggest a processing consequence of impoverished morphosyntactic system and of a semantically-driven process in deriving the meaning of a sentence. In all, the current study suggests that Chinese readers, like English readers, use the sequential and syntactic structure of a language in the word-by-word reading process to map the referent into mental representation. This mapping process exploits all available information in subsequent analyses to derive a semantically coherent representation for comprehension.

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Chin Lung Yang
Learning Research and Development Center
University of Pittsburgh
3939 O'Hara Street, Room#413
Pittsburgh, PA 15260
USA
cyang@pitt.edu

語料情境限因對於中文關係子句理解歷程的影響：腦電波生理證據

楊金龍　　Charles A. Perfetti
匹茲堡大學

本論文報導兩個事件相關電位 (event-related potentials, ERPs) 之研究，用以探討中文關係子句處理歷程之認知機制及其神經認知基礎。本研究中我們操弄兩個變項：關係子句之種類（受試者中變項）及關係子句之語料情境（語境）限因（受試者間變項）。本實驗操弄關係子句之前置語料作為語境限因之變異基礎。實驗 1a 中，關係子句中之前置語詞為不具語法限因之附屬詞句（例如：“今天一大早，…”）。相對而言，實驗 1b 則使用具有高限因語法表徵之主語語料（例如：用“名詞 (N)-動詞 (V)”語序以表徵“主詞-動詞-”之限制）作為關係子句的前置語料。兩實驗對於關係子句的語料處理之比較分析顯示語境限因因素在不同的實驗中引導出不同之事件相關電位之模式。實驗 1a 及 1b 之相關電位分析均顯示：“工作記憶”(working memory) 這個認知機制在關係子句之語料的意義整合上有重要功能。相對而言，只有在具高度語境限因之實驗 1b 中，事件相關電位之分析才會顯示語義 (N400) 及語法 (P600) 之句義整合效果。更進一步分析則指出，語境限因之效果對早期之中文語詞種類之辨識即有影響（約 200 ms）。再者，此效果的分析亦發現一個複雜效果 (N400-P600)。本複雜效果對中文閱讀之特性有其獨特之意義。整體而言，本實驗之主要發現：語境制約之語詞種類效果以及句義整合之複雜效果，顯示中文句之處理歷程是依循訊息互動模式的理論基礎。中文篇章之理解歷程是依賴各種不同之語言訊息之交互支持作用。其中，中文篇章之理解歷程是高度依賴於語義；然而，本研究結果亦指出語料所具呈之語法表徵為語義衍生之基礎。這樣的現象符合一般語意學對中文篇章理解之看法。

關鍵詞：中文關係子句，事件相關電位，語境限因，工作記憶