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When embeddedness matters: Electrophysiological evidence for the role of head noun position in Chinese relative clause processing

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ABSTRACT

This ERP study of Chinese subject- and object-modifying relative clauses (RCs) aimed at investigating how sentence context (embeddedness) temporally interacted with relativization in terms of processing load. In stead of adotping a static view of processing costs of RCs, we focused on the dynamic modulation of processing load by sentence context at two critical words–the relative marker *de* and head noun. Using cluster-based permutation analyses of ERPs, our study found an early relativization effect (110–220 ms) followed by an embeddedness effect (411–441 ms) and a late interaction effect (540–620 ms) at the relative marker *de*. The main effect of relativization as an early left anterior negativity suggests a transitory processing advantage of subject-relativization independent of sentence context. The sentence context was processed just 410 ms after word onset as a late left-lateralized anterior negativity for the center-embedded RCs, indicating increased working memory load introduced by sentence context constraints. A late centro-posterior positivity registered for object-relativization RCs with preceding sentence context due to structural reanalysis. An early anterior negativity (73–123 ms) reflecting the embeddedness effect at the head noun suggests the complexity of information encoded in phrase markers when semantic contents of verb arguments are instantiated. Our results indicate that it is necessary to adjust the account of RC processing beyond a universal processing advantage for subject-relativization to integrate the effects of sentence context cross-linguistically.

1. Introduction

Relative Clauses (RCs) constitute a major prism through which the human sentence processing mechanism has been examined (see the review of Carreiras, Duñabeitia, Vergara, de la Cruz-Pavía, & Laka, 2010). RC processing is complex, involving the modification of a noun phrase by a predicate derived from a clause via a process of relativization. Relativization can involve a movement process in which a *wh*-expression is displaced as in English. Relativization via a process of displacement is subject to island constraints (Frazier, 1979, 1999; Frazier, 1987; Mitchell, 1994). Relativization can also involve a non-movement process in which a (null) pronoun is bound without the same island effects as in Chinese, Korean, and Japanese (Hoshi, 1998; Murasugi, 2000; Perlmutter, 1972; Yang, 2008).

Studies in different languages have consistently observed a processing advantage for subject-relativization over object-relativization (English: Ford, 1983; King & Just, 1991; Hakes, Evans, & Brannon, 1976; Traxler, Morris, & Seely, 2002; Dutch: Mak,

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Vonk, & Schriefers, 2002; French: Holmes & O'Regan, 1981; German: Lipka, Kopp, & Pechmann, 2000) and this advantage was also found in typologically more distinct languages like Japanese and Korean, both of which are head-final SOV languages with pre-nominal relative clauses (Japanese: Ishizuka, 2005; Ueno & Garnsey, 2008; Korean: Kwon, Polinsky, & Kluender, 2006; Kwon, Kluender, Kutas, & Polinsky, 2013).[1]

Several theoretical models of sentence processing have been proposed to explain the observed processing loads in RC processing. They can be broadly categorized as working memory models (Gibson, 1998), experience-based models (Wu, F., Kaiser, E., & Vasishth, S., 2018) and phrase-structure models (Traxler et al., 2002; Hsiao & Gibson, 2003). Variants of working memory models that focus on processing costs induced by memory processes and attention related to processing linear or hierarchical syntactic structures make different predictions as a function of their stance on the central nature of the processing task (Gibson, 1998; Gibson & Wu, 2013; O'grady, 2007). Thus, the Dependency Locality Theory (DLT) proposed by Gibson (1998) assumes that working memory storage costs increase as the number of maintained syntactic heads increases so that integration costs depend on the linear distance of the dependency between two constituents. The longer the distance is, the higher the integration costs are and the heavier the working memory load is. The DLT predicts greater processing loads for object-relativization of English RCs due to longer filler-gap linear distance. Structural proposals, in contrast, such as the Phrase Structural Distance Hypothesis (SDH) of O'grady (2007), posit that processing costs are influenced by structural distance—the number of syntactic nodes involved in a dependency. Subject-relativization is less demanding for working memory resources because fewer intervening syntactic nodes need to be maintained between filler and gap.

Experience-based models encompass different versions of frequency-based theories and expectation (or surprisal)-based theories (see detailed discussions in Wu, Kaiser, & Vasishth, 2018). Frequency-based accounts and the theory of Noun Phrase Accessibility Hierarchy (Keenan & Comrie, 1977) suggest a subject-relativization processing advantage that reflects the typological fact that subject-relativization is more frequent than object-relativization. Expectation/surprisal theories further propose that online sentence processing constantly updates the conditional probability of upcoming input based on expectation, frequency or plausibility (Hale, 2001, 2003; Levy, 2008). Higher surprisal values imply more difficulties in integrating a word.

RC parsing preferences have also been characterized on the basis of phrase structure computations (Traxler et al., 2002; Hsiao & Gibson, 2003). The parser will incorporate the incoming string into a partial phrase marker being constructed with as few nodes as possible and without generating unnecessary nodes. Irrespective of whether a *wh*-movement process is at play as in English or whether a pronominal binding process is involved as in Japanese, processes of memory and attention should interact with the structuring of the input guided by economy-based parsing principles of Late Closure and Minimal Attachment in incremental interpretation (Frazier, 1979, 1999). Recent research in this vein suggests that a hyperactive human sentence processor seeks to resolve dependencies quickly by anticipation (Omaki, Lau, Davidson White, Dakan, Apple, & Phillips, 2015), as evidenced by strategies such as the Active Filler Strategy (Fodor, 1978) for filler-gap dependencies and by Theta Attachment (Pritchett, 1992) for garden paths, inter alia. As the following English examples show, greater processing costs arise in parsing object-relativization 2) than subject-relativization 1), because in processing 2) the parser automatically links *who* to the closest argument position (the subject position), much as the parser does in 1), before quickly revising this initial analysis when the incoming noun phrase subject *the lawyer* is encountered. This processing advantage of subject-relativization has been reported in terms of shorter response time (Ford, 1983; King & Just, 1991), lower accuracy (Hakes et al., 1976; King & Just, 1991), and fewer eye-fixations and regressions (Traxler et al., 2002).

English examples:

1) The senator$_i$ [$_{RC}$ who_$_i$ irritated the lawyer a lot] called the banker. (subject-relativization)
2) The senator$_i$ [$_{RC}$ who the lawyer irritated_$_i$ a lot] called the banker. (object-relativization)

[1] The following Japanese and Korean examples were taken from Kwon et al. (2013).
Japanese examples:
1) [RC__i giin – ga hinanshita] kishai – ga ayamari–o mitometa
senator–ACC attacked reporter – NOM error–ACC admitted
The reporter who attacked the senator admitted the error. (subject – relativization)
2) [RC giin – ga __i hinanshita] kishai – ga ayamari–o mitometa
senator–NOM attacked reporter – NOM error–ACC admitted
The reporter who the senator attacked admitted the error. (object – relativization)
Korean examples:
3) [RC__i uywon – ul kongkyekha – n] kicai – ka silswu–lul siinhayssta
senator–ACC attack – AND reporter – NOM error–ACC admitted
The reporter who attacked the senator admitted the error. (subject – relativization)
4) [RC uywon – i __i kongkyekha – n] kicai – ka silswu–lul siinhayssta
senator–NOM attack – AND reporter – NOM error–ACC admitted
The reporter who the senator attacked admitted the error. (object – relativization)
Reanalysis for resolving temporary ambiguity also occurs in Japanese object – relativization RCs, which are initially parsed as a main sentence as a result of minimal attachment of hinanshita 'attacked' to giin–ga 'senator – NOM' (Ishizuka, 2005)

Apart from a range of general factors and principles which have been proposed to explain RC processing loads, the particular properties of each grammar in terms of word order, head-final modification, and the information encoded morphologically in the relativizer have also been shown to play a non-trivial role in shaping the processing. Additionally, the sentence context which determines the phrase-structure based expectations in parsing also plays a role. In the following sections, we first discussed how the sentence context interacts with relativization under the guidance of general parsing principles for Chinese RCs. The claim is that the null argument attribute of Chinese entitles the parser to adopt an economy-driven strategy of delaying relativization until the relative marker *de* is encountered. We then presented a study of Chinese RCs using the event-related electrophysiological potential (ERP) technique by manipulating two factors: sentence context (sentential embeddedness) and subject- vs. object-relativization to reveal the ERP components on the relativizer *de* and the following head noun. Their relative timing provides crucial information that has hitherto not received the full attention that it deserves (cf. Yang and Perfetti, 2006, Yang, Perfetti & Liu, 2010), At *de*, we show a temporal sequence of ERP effects for subject- vs. object-relativization, sentential embeddedness (partially determining initial processing steps), and their subsequent interaction as the RC and its predicted nominal head are integrated into the full sentence-level analysis. The discussion focused on the significance of the sequencing of the effects for models of RC processing with a special focus on Chinese.

2. Studies of Chinese relative clauses

Parsing does not only reflect general principles, but also the specifics of each grammar. As the examples below show, Chinese RCs have four distinctive grammatical features: pre-modification, i.e. a relative clause pre-modifies its head noun, a feature similar to Korean and Japanese (Kwon et al., 2013), but different from English; a detached right-edged relative marker *de*, a unique feature different from English, Japanese and Korean and critical in disambiguating the thematic roles of the unspecified agents or arguments of verbs in both relative clauses and main sentences (Packard, Ye, & Zhou, 2010); a reversed filler-gap sequence determined by the pre-nominal word order of Chinese syntax (Kwon et al., 2013); morphological unmarked noun phrases with case interpretations dependent on sentence context. These examples show two pairs of Chinese subject- and object-relativization RCs in two embeddedness scenarios: subject-modification and object-modification. Consider subject-modifying RCs in 3a and 3b with the head noun *jiaoshou* 'the professor' as the subject in each sentence. 3a is a subject-modifying subject-relativization (SS) RC, since the subject of the relative clause constitutes a null argument position before the RC verb *tuijian* 'recommended'. 3b is a subject-modifying object-relativization (SO) RC because the null argument is the object of the RC verb. In the same vein, object-modifying RCs 4a and 4b with the head noun *jiaoshou* 'the professor' as the object in each matrix sentence have the *huanzhe denghou* 'patient waited-for' as the local sentence context preceding the RCs. 4a is an object-modifying subject-relativization (OS) RC and 4b is an object-modifying object-relativization (OO) RC with internal structures of the relative clauses same as 3a and 3b.

Subject-modifying RCs:						
3a)	[$_{RC\_i}$ tuijian	yisheng	de]	jiaoshou$_i$	denghou	huanzhe
	[$_{RC\_i}$ recommended	the doctor	REL]	the professor$_i$	waited for	the patient
The professor who recommended the doctor waited for the patient (**subject-relativization–SS**).						
3b)	[$_{RC}$ yisheng	tuijian_ $_i$	de]	jiaoshou$_i$	denghou	huanzhe
	[$_{RC}$ the doctor	recommended_$_i$	REL]	the professor$_i$	waited for	the patient
The professor who the doctor recommended waited for the patient (**object-relativization–SO**).						
Object-modifying RCs:						
4a)	huanzhe	denghou	[$_{RC}$ _$_i$ tuijian	yisheng de]	jiaoshou$_i$	
	the patient	waited for	[$_{RC}$ _$_i$ recommended	the doctor	REL]	the professor$_i$
The patient waited for the professor who recommended the doctor (**subject-relativization–OS**).						
4b)	huanzhe	denghou	[$_{RC}$ yisheng	tuijian_$_i$	de]	jiaoshou$_i$
	the patient	waited for	[$_{RC}$ the doctor	recommended_$_i$	REL]	the professor$_i$
The patient waited for the professor who the doctor recommended (**object-relativization–OO**).						

In English relativization, a filler-gap search is expected in a *wh*-movement dependency (Frazier, 1979). The displaced *wh*-expression must have a point of origin, where the thematic relation is expressed. However, as Yang (2008) notes, the 'gap' in Chinese is a pronoun unrealized phonologically and stands in a construal with the head noun, because it does not show sensitivity to the island constraints as a 'true' *wh*-movement gap does. In a null-argument language dependent on context like Chinese, a gap does not immediately signal the need for relativization. Minimal Attachment as a prohibition of vacuous nodes excludes relativization until the relativizer *de* is encountered; therefore, the grammar of Chinese RCs is expected to present a different parsing problem. In fact, regarding the claim of a processing advantage for subject-relativization, the existing literature of Chinese RCs provides rather conflicting findings.

A survey of 16 most relevant studies of Chinese RCs in Table 1 lists results on words where significant differences between subject- and object-relativization were reported. Some researchers found subject-relativization RCs are easier to process (*self-paced reading:* Lin & Bever, 2006; Vasishth, Chen, Li, & Guo, 2013; *eye-tracking:* Jäger, Chen, Li, Lin, & Vasishth, 2015; *ERP:* Zhang & Jiang, 2010; Bulut, Cheng, Xu, Hung, & Wu, 2018 only on *de*), while other researchers have reported a processing preference of object-relativization (*self-paced reading*: Hsiao & Gibson, 2003; Chen, Ning, Bi, & Dunlap, 2008; Lin & Garnsey, 2011; Gibson & Wu, 2013; *eye-tracking*: Sung, Tu & Lin, 2016; *ERP:* Packard et al., 2010; Sun et al., 2016; Zhang & Yang, 2010; Bulut et al., 2018 only on the head noun).

Table 1
Summary of 16 studies of Chinese relative clauses.

Paradigm	Studies	Types of Relative Clauses	Critical Words	Processing Preferences
Self-paced reading	Hsiao and Gibson (2003)	SS/SO	The first two words within relative clauses	Object-relativization
	Gibson and Wu (2013)	SS/SO	*de*; head noun	Object-relativization
	Chen et al. (2008)	SS/SO	The first two words within relative clauses	Object-relativization
	Vasishth et al., (2013)	SS/SO	*de*; head noun	Object-relativization on *de*; Subject-relativization on the head noun
	Lin and Bever (2006)	SS/SO; OS/OO	*de*; head noun	Subject-relativization
	Jäger et al. (2015)	SS/SO; OS/OO	The first two words within relative clauses	Subject-relativization
	Li, Zhang, and Wei (2010)	SS/SO; OS/OO	head noun	Subject-relativization
Eye-tracking	Sung et al., (2016)	SS/SO	The first word within relative clauses; head noun	Object-relativization
	Jäger et al. (2015)	SS/SO; OS/OO	The first two words within relative clauses	Subject-relativization
ERP	Zhang and Jiang (2010)	OS/OO	The second word within relative clauses; *de*; head noun	Subject-relativization
	Zhang and Yang (2010)	SS/SO	The second word within relative clauses; *de*; head noun	Object-relativization
	Yang and Perfetti (2006), Yang et al. (2010)	SS/SO; OS/OO	The first two words within relative clauses; head noun	Ambiguous
	Sun et al (2016)	SS/SO; OS/OO	The first two words within relative clauses; *de*; head noun	Object-relativization
	Packard et al. (2010)	SS/SO; OS/OO	*de*; head noun	Object-relativization
	Bulut et al. (2018)	OS/OO	*de*; head noun	Object-relativization on *de*; Subject-relativization on the head noun

The theoretical models discussed above make different processing load predictions for Chinese RCs. The DLT predicts greater processing load for Chinese subject-relativization RCs due to the longer linear gap-filler distance compared to object-relativization. The proposal has been empirically supported by a number of self-paced reading studies, which reported longer reading times on the first two words within the relative clause region, the relative marker and the head noun (Hsiao & Gibson, 2003; Chen; et al., 2008; Lin & Garnsey, 2011; Gibson & Wu, 2013). In contrast, SDH proposes greater processing costs for object-relativization RCs, since the object gap is hierarchically more deeply embedded in the syntactic structure and hence less accessible to the filler. The self-paced reading study by Lin and Bever (2006) lent support to the structural claim and reported significantly longer reading time at both the relative marker and head noun.

Experience-based models predict a processing advantage for Chinese subject-relativization due to its higher occurrence rate than object-relativization (Pu, 2007). The claim is backed by the findings of Vasishth et al. (2013) and Li, Q., Zhang, J., & Wei, Y. (2010), who observed that longer reading times on the relativizer and head noun of object-relativizations were in line with the distributional pattern of the two structures found in large Chinese corpora. Direct evidence supporting expectation/surprisal models was reported by Jäger et al. (2015), who found that the predicted higher surprisal values for object-relativization could be associated with longer reading times, regression duration, and higher regression probability on the first two words within the relative clause region.

Compared with the above psycholinguistic studies using the behavorial measurements, the high temporal resolution of the electrophysiological technique offers a more sensitive tool for researchers to investigate online sentence processing at the scale of the millisecond. In the past decade, continuous efforts have been made to investigate what linguistic processes drive the different processing load between subject- and object-relativization by examining ERP components related to filler-gap dependency, of which the most commonly reported neural signatures include a left/bilateral anterior negativity, a centro-parietal negativity (N400) (King & Kutas, 1995; ; Münte, Schiltz, & Kutas, 1998; Vos, Gunter, Kolk, & Mulder, 2001) and a late centro-medial positivity (P600) (Fiebach, Schlesewsky, & Friederici, 2002; Gouvea, Phillips, Kazanina, & Poeppel, 2010; Kaan, Harris, Gibson, & Holcomb, 2000).

The left/bilateral anterior negativity observed in a time window between 300 and 600 ms after word onset with the largest topographical distribution in the anterior region of the scalp is associated with increased working memory load (King & Kutas, 1995). A sustained slow variant of the negativity spanning multiple words have also been found to be associated with heavy working memory load (see the review of Rosler, Heil, & Hennighausen, 1995; Kwon et al., 2013). Münte et al. (1998), for example, reported that sentences more demanding of working memory to build up discourse representations elicited a sustained left anterior negativity from the onset of the first word. The N400 component observed between 350 and 500 ms (Bulut et al., 2018; Sun et al., 2016; Zhang & Jiang, 2010; Zhang & Yang, 2010) is considered to reflect lexical retrieval from semantic memory (Brouwer, Crocker, Venhuizen, & Hoeks, 2017). The P600 component is a late posterior positivity with a time course between 500 and 800 ms after the stimulus onset (Hagoort, Brown, & Groothusen, 1993; Osterhout et al., 1994). It has been found to be related with both syntactic anomaly and difficulties in syntactic integration such as filler-gap dependency in *wh*-questions with variant onset time (Kaan et al., 2000; Gouvea et al., 2010; Fiebach et al., 2002).

These three ERP components have been taken by researchers of Chinese RCs to index high processing costs on different aspects of sentence processing. Packard et al. (2010), Sun et al. (2016) and Zhang and Yang (2010) argued that the N400/P600 effect observed for subject-relativization RCs indicated increased processing load for semantic retrieval and/or syntactic integration, while Zhang and Jiang (2010) suggested that sustained negativity at the relative marker and an N400/P600 effect at the head noun of object-relativization implied more demanding working memory load interacting with lexical-syntactic processing. Mixed results were obtained by Bulut et al. (2018) and Yang and Perfetti (2006), Yang et al. (2010). Bulut et al. (2018) found an N400-P600 complex on the relative marker *de* for OO RCs, but a P600 effect on the head noun for OS RCs. Yang and Perfetti (2006), Yang et al. (2010) reported a sustained negativity of subject-relativization RCs irrespective of subject- or object-modification, an N400 effect for OO RCs on the first two words within the RC region and a right-lateralized sustained negativity of OS RCs on the head noun.

So far, like the large cohort of behavioral studies of Chinese RCs, the ERP studies have failed to provide a consistent picture for the processing advantage in relativization. Moreover, the same conclusion is often derived from observations of different ERP components charactererzing distinct underlying neuronal processes. For example, although both Sun et al. (2016) and Packard et al. (2010) reported the processing advantage for object-relativization RCs, Sun et al. (2016) found N400 effects at both the relative marker and the head noun of SS RCs, while Packard et al. (2010) found a P600 effect at the relative marker and no effect at the head noun.

In general, the present literature of ERP studies have revealed that the processing of Chinese RCs is rather intricate with phrase structure integration and prediction at play simultaneously and no single theoretical model of sentence processing seems to satisfactorily account for the complexities that are observed (Bulut et al., 2018; Sun et al., 2016). The common interpretations often rely on a combination of working memory approaches, the expectation-based approaches and/or the integration-based approaches (Frazier, 1979, 1999), in which integration cost and structural ambiguity play a critical role in determining processing difficulties.

3. Embeddedness and Chinese relative clauses

Object-modifying RCs as 4a and 4b include a local sentence context *huanzhe denghou* 'patient waited-for' preceding the RCs. Obviously, the sentence context influences the downstream processing of RC regions. But what are the ERP effects of this influence? In the previous research, very few manipulations have examined how sentence context interacts with relativization temporally and what sentence processing mechanisms underlie the interaction.

Yang and Perfetti (2006), Yang et al. (2010) have attempted to address the issue of 'sentence constraints' on the processing of Chinese RCs and found that the sentence context before the RCs in object-modifying RCs elicited more complex ERP patterns than subject-modifying RCs without preceding constituents. Using temporal principal component analysis (PCA), Yang and Perfetti (2006) extracted temporal factors representing different ERP components and found object-modifying RCs, under the constraints of sentence context, showed an N400-P600 complex effect for OS RCs at the first word and an N400 effect for OO RCs at the second word within the RC region. Similar results were also reported in their second study using the typical ERP analysis method (Yang, Perfetti, & Liu, 2010). In addition, a sustained negativity was observed at the head noun of OO RCs.

The results of these two studies revealed that the preceding sentence context (embeddedness) significantly interacted with the processing of Chinese RCs on words downstream such as the head noun, but their analysis missed the relative marker *de*, which was assumed not to contribute to interpreting the meanings of the RCs. However, linguistically speaking, the relative marker *de* marks the derivation of a predicate from a formed clause, allowing the modification. It plays a critical role in coordinating semantic and syntactic integration of Chinese RC processing under the constraint of working memory. The modification particle *de* is obligatory with Chinese RCs. It introduces a predication relation with a head noun (Simpson, 2002). In terms of memory processes, *de* signals an upcoming noun phrase. Several Chinese RC studies (Table 1) have observed effects related to RC types at *de* with different approaches (Bulut et al., 2018; Gibson & Wu, 2013; Lin & Bever, 2006; Packard et al., 2010; Sun et al., 2016; Vasishth et al., 2013; Zhang & Jiang, 2010; Zhang & Yang, 2010). A large number of reports of the longer reading time, sustained negativity, N400 and N400-P600 effects at *de* across different RC types suggest that the relativization function of *de* interact with various linguistic processes.

Yang and Perfetti (2006) only included subjects, spatial topography, and conditions as sources of variance in the PCA analysis, but the subject- and object-relativization conditions also crucially differ in both gap-filler dependency and word order. Within the RC region, object-relativization has a canonical N + V sequence, whereas subject-relativization has a non-canonical V + N order. The temporal PCA used in the study, compared to the parametric PCA which is more sensitive to the modulations of stimulus parameters, cannot exclude the possibility that the N400 and P600 components on the two words were induced by the word order difference instead of gap-filler integration. The results were also based on the comparison of the subject- and object-modifying RCs between different groups of subjects, which introduced another level of variability.

4. The current study

The present ERP study sought to circumvent the issues of Yang and Perfetti (2006), Yang et al. (2010) by provding empirical evidence of the effect of the sentence context (embeddedness) at the relativizer and head noun of Chinese RCs.[2] There are four research questions we are interested in.

1) What is the temporal sequence by which sentence context (embeddedness) interacts with relativization? (RQ1)
2) Whether there is a processing advantage of subject-relativization for Chinese RCs? (RQ2)
3) What effect does embeddedness have on processing costs? (RQ3)
4) How sentence context (embeddedness) interacts with the processing of Chinese RCs and modulates the neuronal processes underlying higher processing costs? (RQ4)

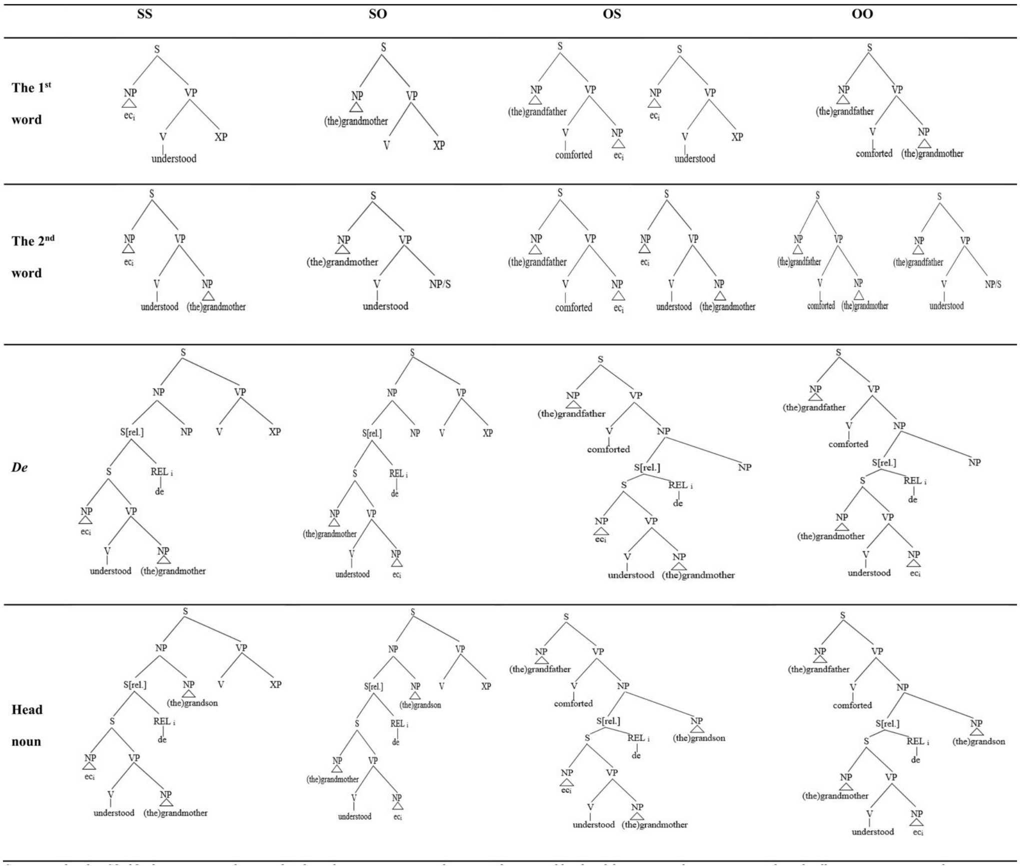
We propose that the garden-path theory (Frazier, 1979, 1999; Frazier, 1987) and its related Minimal Commitment models of sentence parsing (Frazier & Rayner, 1982; Just & Carpenter, 1980; Mitchell, 1994) best characterize how relativization interacts with embeddedness in Chinese RCs. In ambiguous regions, the parsing process may be delayed, leading to 'incomplete, low-level analysis' (Mitchell, 1994). The parsing difficulty is more salient in disambiguating regions which can trigger intricate updating procedures. Based on the theoretical framework of the models, the tree diagrams in Table 2 illustrate hypothesized incremental parsing processes of the four types of Chinese RCs at each word in the critical region (from the first word in the relative region to the head noun). Before the critical disambiguating point *de* in OS and OO RCs, the parser resorts to an economical online processing strategy of building up simple structural representations with minimum commitment (Frazier & Rayner, 1982). The N + V + V + N and N + V + N + V sequences could be entertained incrementally with simpler root clausal representations until the relativizer *de* is encountered. The add-on procedure continues until the parser, cued by *de,* must resolve the ambiguity as hierarchically more complex relativization structure.

At the initial parsing stage of *de*, the parser is guided by a Minimal Attachment strategy, which attaches a constituent to a phrase marker with as few nodes as possible, and by a late closure strategy, which tends to attach the constituent to the phrase currently parsed (Frazier, 1979). The relativizer should be attached to the local RC structure enabling gap-filler dependencies that allow for the modification of the head noun, so that the RC can be subsequently incorporated into the main sentence. According to these computations, in response to RQ1, we hypothesize that at the relative marker *de*, the relativization effect will be observed at an earlier time window than the embeddedness effect. ERP components indexing higher working memory load (LAN or sustained negativity) (Fiebach, Schlesewsky, & Friederici., 2001; King & Kutas, 1995; Münte et al., 1998, Vos et al., 2001) are expected for both effects because previous studies have already shown that the components contribute to establishing filler-gap dependency (Fiebach et al., 2001) and working memory modulates the ease of integration of RCs with sentence context (Traxler, 2007).

For the RQ 2, we propose that object-relativization might be more resource consuming than subject-relativization as predicted by

[2] Although Yang et al. (2010) argued that the problem of comparing two structures: V + N in subject-relativization and N + V in object-relativization would not override the main results of their study, other research has shown that Chinese nouns and verbs elicited distinct ERP patterns and topographies (Xia, Wang, & Peng, 2016; Zhang, Ding, Guo, & Wang, 2003). The present study mainly reported the results at the relativizer and head noun to avoid the conflation of lexical difference in our interpretations.

Table 2
The tree diagrams of the four types of relative clauses (SS/SO/OS/OO) at each word of the critical region.



S–sentential nodes; S[rel.]–the syntactic mechanism whereby a close sentence is turned into a predicate capable of modifying a noun phrase; ec_i – topic-bound null arguments represented as empty categories.

Phrase Structural Distance Hypothesis (SDH) of O'Grady (2007), because the object gap is structurally more embedded than the subject-gap so that the number of intervening syntactic nodes between the gap and filler is greater. In line with the claims of Frazier (1979, 1999), the assumption is that phrase structure parsing is insensitive to the linear distance between gap and filler. With a heavier working memory load for maintaining and computing the invernening nodes, increased LAN or sustained negativity effects may be observed for object-relativization RCs at *de*.

As for the effect of embeddedness on RC processing (RQ3), it is hypothesized that object-modifying RCs will show greater ERP effect due to the integration into matrix sentences than subject-modifying RCs, which have a null preceding sentence context. At the head noun, an effect of embeddedness is expected because only the semantic contents of the null argument will be instantiated by the head noun as predicted.

In response to RQ4, it is hypothesized that embeddedness will interact with relativization at the relative marker *de* in terms of increased late posterior positivity ERP component (P600/Syntactic Positive Shift) (Hagoort et al., 1993, 2000, 2003) related to the syntactic reanalysis of OO RCs. In sentence 4b, the noun phrase *yisheng* 'doctor' in the string *huanzhe denghou yisheng* 'The patient waited-for the doctor' is automatically integrated as the object of the verb *denghou* 'waited-for'. This analysis needs to be, however, undone as soon as the relative marker *de* is detected, and the noun *yisheng* 'doctor' must be reassigned as the subject of the verb. The temporary parsing ambiguity is expected to lead to a structural reanalysis, increasing processing costs.[3] Additionally, the interaction

[3] An anonymous reviewer notes that *tuijian* 'recommended' can be interpreted as a noun in 'the recommendation of the doctor' because Chinese lacks inflectional morphology to distinguish nouns and verbs. This possibility seems to us rather disfavored compared with the first one, since *de* is usually needed between *yisheng* 'doctor' and *tuijian* 'recommendation' to indicate possessive relationship in Chinese. The results of a sentence completion task of all the 48 OO sentences used in the ERP experiment supports this claim. Five subjects who did not participate in either the plausibility judgement task or the ERP experiment were asked to complete the OO sentences with the relative marker *de* and head noun left out. In

Table 3
An exemplar quadruple of experimental stimuli and probes.

	C1	C2	C3	C4	C5	C6	Probe
SS	了解 understood	奶奶 grandmother	的 REL (*de*)	孙子 grandson	安慰 comforted	爷爷。 grandfather.	孙子了解奶奶。 The grandson understood the grandmother.
	The grandson who understood the grandmother comforted the grandfather.						
SO	奶奶 grandmother	了解 understood	的 REL (*de*)	孙子 grandson	安慰 comforted	爷爷。 grandfather.	孙子安慰爷爷。 The grandson comforted the grandfather.
	The grandson who the grandmother understood comforted the grandfather.						
OS	爷爷 grandfather	安慰 comforted	了解 understood	奶奶 the grandmother	的 REL (*de*)	孙子。 grandson	奶奶了解孙子。 The grandmother understood the grandson.
	The grandfather comforted the grandson who understood the grandmother.						
OO	爷爷 grandfather	安慰 comforted	奶奶 grandmother	了解 understood	的 REL (*de*)	孙子。 grandson	爷爷安慰奶奶。 The grandfather comforted the grandmother.
	The grandfather comforted the grandson who the grandmother understood.						

effect due to reanalysis is supposed to occur later than both the relativization and embeddedness effects, and be observed only for the contrast between object-modifying RCs because there is no similiar structural abmibuity for the contrast between subject-modifying RCs.

5. Methods

5.1. Participants

Twenty-five Native speakers of Mandarin Chinese were recruited at Indiana University with a length of residence no more than 5 years in the U. S. and gave written informed consent which was approved by the Indiana University Institutional Review Board before participation (20 females, 5 males; age 19–30 years, mean = 21.4, SD = ± 2.46 years). All subjects were right-handed, had normal or corrected-to-normal vision and did not have any neurological disorders. They were paid for their participation in the experiment.

5.2. Materials

The 192 critical sentences were grouped into 48 quadruples including subject-modifying subject-relativization (SS), subject-modifying object-relativization (SO), object-modifying subject-relativization (OS) and object-modifying object-relativization (OO) relative clauses. Table 3 listed an exemplar quadruple used in the present study. The test sentences were adapted from Hsiao and Gibson (2003) in view of frequencies in the Chinese National Corpus (http://www.cncorpus.org/). The average word frequency of verbs was 1.19 (SD = ± 0.43) per hundred. Each sentence was 6 words in length with only animate noun phrases because the animacy of subjects and objects of Chinese RCs has been found to be asymmetric in facilitating sentence comprehension between subject- and object-relativization (Wu, Kaiser, & Andersen, 2012). All the verbs were reversible in argument structure, i.e. agent and patient could be switched without significant difference in plausibility across conditions (see the following plausibility judgment task). The critical regions of interest included the relative marker *de* and the head noun: C3 - C4 in subject-modifying RCs and C5 – C6 in object-modifying RCs (Table 3). In addition, there were 200 filler sentences of different structures to minimize the priming effect, including simple declaratives, declaratives with embedded *wh*-questions and declaratives with embedded noun complement clauses. The sentence length varied from 6 to 7 words.

5.3. Procedure

5.3.1. Plausibility judgment task

Fourteen Chinese native speakers who did not participate in the ERP study were recruited to complete a task of rating the sentence stimuli for plausibility on a 7-point Likert scale with 1 indicating very implausible and 7 indicating highly plausible. The 192 critical sentences were split into the same four lists used in the ERP experiment to ensure that no sentence in the same quadruple appeared in the same list. The two lists with no sentences belonging to the same modification condition were responded by half the participants to counterbalance the ratings between subjects and diminish the similarity effect. The mean rating of the plausibility of each relative clause type was calculated by averaging across trials and then across subjects. The raw mean ratings of SS and SO were 4.87 (SD = ± 1.88) and 4.96 (SD = ± 1.82). OS and OO had the average ratings of 5.30 (SD = ± 1.82) and 5.29 (SD = ± 1.66) respectively. The transformed Z-scores of subjects' ratings were fit into a linear mixed-effect model using the *lmer4Test* package in R (R Development

(*footnote continued*)
only two sentences were the embedded verbs consistently interpreted as a noun in a possessive relationship with the subjects of the relative clauses by all five respondents. The average rate of this type of interpretation was 5.6%. The rest of the items were completed with the embedded verbs as the predicates of either the matrix subjects or the subjects within the relative clause.

Core Team, 2016). The relative clause type was entered into the model as a fixed effect, and subjects and items were entered as crossed random factors. We also compared this random intercept model to a second model with subject and item random slopes. The results showed that the more parsimonious random intercept model fit the data better than the maximum random effect full model (AIC = 3827.3 < 3830.6). The parameters and p values were estimated with t-tests for each sentence type and the results showed that there were no significant differences in the plausibility ratings by subjects across relative clause types. Pairwise comparisons of all four sentence types were carried out based on the Tukey method to adjust p values for multiple comparisons. None of the comparisons were significantly different (OO-OS: $t = -0.28$, $p = 1.0$; OO-SO: $t = 1.899$, $p = .23$; OO-SS: $t = 1.954$, $p = .21$; OS-SO: $t = 2.12$, $p = .15$; OS-SS: $t = 2.24$, $p = .12$; SO-SS: $t = 0.07$, $p = 1.0$). Hence the plausibility of each sentence in a quadruple of experimental stimuli was not significantly affected by the reversal of the noun phrases.

5.3.2. The ERP experiment

Participants were seated in a comfortable chair in a moderately humidified soundproof room, 90 cm away from the computer monitor. The E-prime software was used to present the experimental stimuli. The experimental instructions were first displayed on the computer and participants could ask questions to clarify task instructions. Then a practice session was implemented to familiarize the subjects with the experimental procedure and they also had the option to repeat the practice session if necessary.

The test sentences were presented using the Rapid Serial Visual Presentation (RSVP) paradigm (Fig. 1). Before each sentence, a 55-point-font fixation cross was displayed in the center of the computer monitor for 250 ms followed by a 500 ms blank screen. Then each 50-point-Song-font simplified Chinese word in one sentence was presented serially with 300 ms duration and 400 ms ISI. The sixth word was followed by a 1200 ms blank screen. A follow-up comprehension probe was then displayed all at once for 6000 ms after each experimental sentence. The 6 s limitation was imposed because our pilot study showed that the normal range of response time to the probes was between 2 and 5 s. We assume that if subjects fail to respond in 6 s, sentence comprehension may be disrupted by other external factors such as lack of attention or fatigue. The correspondent test sentences will be discarded in data analysis. Participants were asked to press the right (Yes) or left arrow (No) on a keyboard to indicate whether the probe was semantically congruent with the preceding test sentence. Fifty percent of comprehension probes are congruent and 50% are incongruent. Reaction time was collected along with the electrophysiological data using E-prime.

The total of 392 sentences was divided into four blocks with 98 sentences in each one, which included 12 sentences for each experimental condition and 50 fillers. All these sentences were randomized within each block and pseudo-randomized between blocks to ensure that no sentences in the same quadruple appeared in the same block. Since there were three noun phrases in each sentence, such as *nainai* 'grandmother', *sunzi* 'grandson' and *yeye* 'grandfather' in Table 3, forming three kinds of possible relations, the probes were designed in a way that each quadruple addressed the three relations with counter-balanced true or false responses. Meanwhile, the relations were asked for different conditions across quadruples (see Table 3 for examples).

The total data acquisition time was approximately 75 min. Participants were asked to be relaxed and refrain from making body movements to reduce artifacts. After the experiment, a 10 min follow-up survey was administered for each subject. The questions aimed at investigating processing difficulty and possible strategies the participants developed during the experiment.

The continuous EEG signals were recorded from a 64-channel Geodesic Sensor Cap (Fig. 2), sampled at the frequency of 1000Hz, amplified by an EGI NetAmps 300 amplifier and filtered with a bandpass from 0.1 to 100 Hz. The impedance of all electrodes was kept under 5 kΩ before each recording session. Recordings were referenced to vertex online.

5.4. Data analysis

5.4.1. Statistical analysis of the behavioral data

Our study investigated two experimental factors: 1) relativization with two levels, i.e. subject-relativization and object-relativization; and 2) embeddedness, i.e. subject-modification and object-modification. Two-by-two repeated measures ANOVAs in R (R Development Core Team, 2016) were used to analyze the accuracy and response time of the probe questions. Items with null responses were excluded (SS: 1%; SO: 0.82%; OS: 0.82%; OO: 1.4%).

5.4.2. EEG data preprocessing

Using EEGLAB toolbox (Matlab version R2016), the continuous EEG data of the four blocks were first merged and the 192 epochs of interest were extracted for each subject. Each epoch was 5750 ms long including a 750 ms fixation and 5000 ms sentence duration. The last time point was when the blank screen following the last word ended. The 60 Hz line noise was removed based on visual inspection of channel spectra. The channels with amplitude over 75 μV for more than 10% of total epochs were removed from the next preprocessing steps. Meanwhile, manual channel scroll was also performed to reject the epochs with muscle movements. Four subjects were excluded for suboptimal data quality because the rejection rate of epochs for either one or more sentence types exceeded 15%. The raw data of 21 subjects were used for further analysis. The average rejection rate of epochs across all subjects for four conditions was 12.802%. There was no significant difference in rejection rates among them (Tukey correction: $F(3,80) = 1.148$, $p = .335$). An independent component analysis was used to correct eye movements and cardiac artifacts. Lastly, channels removed in the previous pre-processing steps were interpolated and all the electrodes were re-referenced offline to the average of left/right mastoids (E29 and E47 for the EGI-64 channel system).

The sentence epochs were then separated into four conditions (SS, SO, OS and OO) and corrected with the 750 ms fixation period as the baseline. In order to perform the analysis at the individual word level, the sentence epoch of each condition was re-epoched into six words and time-locked to the onset of each word. Each epoch of the first five words was 900 ms, including 200 ms baseline,

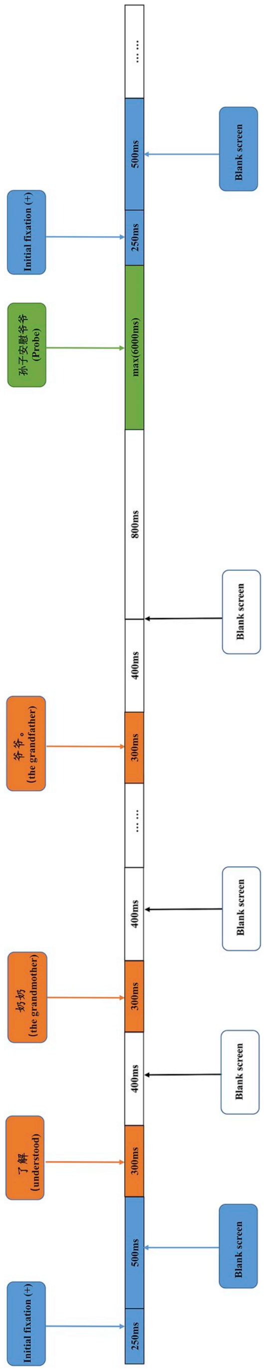


Fig. 1. Time course of the stimulus. Each sentence consisted of 750 ms pre-stimulus period, 300 ms for displaying each word and 400 ms ISI except the last word followed by a 1200 ms blank screen.

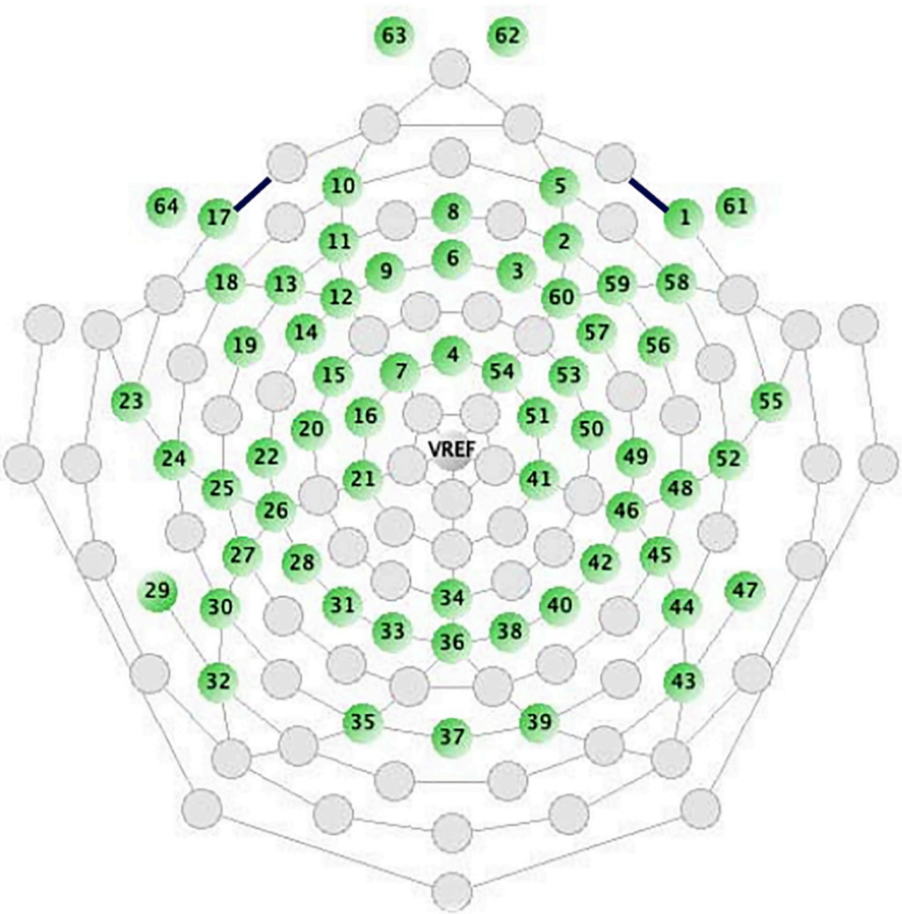


Fig. 2. Schematic map of the 64-EGI electrode net used in the experiment.

300 ms word duration and 400 ms inter-stimulus interval (ISI). We also extracted 1600 ms epoch for the last word (C6) to investigate possible sentence wrap-up effect.

5.4.3. Statistical analysis of EEG data

Instead of following the typical ERP analytic method of pre-defining ROIs and time windows, our study used cluster-based nonparametric permutation tests which derive significant time windows and electrode clusters on each critical word to deal with the issue of multiple comparisons across a large number of spatio-temporal pairs (Maris & Oostenveld, 2007). Indeed, the traditional analytic approach to time window and ROI selection suffers from two main drawbacks. The time windows and ROIs of ERP signatures relevant to sentence processing vary across tasks and subject populations. Researchers generally do not have prior knowledge of the exact time or spatial range for each component, hence, the decisions have to be made based on previous studies rather than the features of collected data. However, the selection of time windows may have an effect on the interpretations of the results. For example, the same ERP component in the previous literature was observed in non-overlapping time windows. Sun et al (2016) found a P600 effect within 550–700 ms on the head noun of object-modifying Chinese RCs, whereas Packard et al. (2010) only observed the positivity between 500 and 550 ms. Some effects are likely artifacts of pre-defined window length.

ROI selection also involves subjective choices. Packard et al. (2010) chose six ROIs with five electrodes in each region to get extensive coverage of the scalp, while Sun et al (2016) and Bulut et al. (2018) only used five to eight pairs of lateral electrodes plus midline electrodes. If only a small number of electrodes are selected for analysis, especially with one electrode representing one subregion of the scalp, spurious effects that may not reflect the true experimental manipulations are likely to be captured. On the other hand, averaging too many electrodes in one ROI may result in biases introduced by outlier electrodes.

The second drawback of preselection is that the choice of time windows and ROIs -is constrained by the need to control the family-wise error rate, which will decrease the statistical sensitivity to experimental effects. Since EEG data are usually collected at multiple electrodes across different time points, multiple comparisons in statistical analysis, therefore, might inflate false alarm rates. In contrast, the non-parametric permutation approach can help circumvent these difficulties in analytical decisions by reducing subjective interventions from experimenters and controlling the false alarm rate under the permutation distribution of the sample (Maris & Oostenveld, 2007).

The cluster-based random permutation statistical method (Maris & Oostenveld, 2007) was implemented using the FieldTrip toolbox (Oostenveld, Fries, Maris, & Schoffelen, 2011). The test statistic was computed as follows: first, the dependent sample *t*-test was performed to compare the mean difference between two conditions for each subject. Then the *t*-values greater than the threshold (5%) of the sensor-time pair samples were added based on their spatio-temporal adjacency. This was the test statistic at the cluster level. The Monte Carlo estimate of the permutation distribution was computed by randomly partitioning trials of the two conditions for 1,000 times within each subject. We tested the null hypothesis that the marginal probability of each experimental condition was equal. Significant clusters were obtained by comparing the absolute values of observed cluster-level test statistics with the permutation distribution of the largest cluster-level statistics at the significance level $\alpha = 0.025$. The cluster neighbors were defined by the triangulation parameter in the Fieldtrip toolbox with the average 7 neighbor electrodes for each electrode. Significant clusters and time windows were then used in the repeated measures ANOVAs, implemented in R to examine main effects and interactions.

6. Results

6.1. Behavioral results

The average accuracy of the probe questions of the four conditions was SS 71.12%, SO 81.74%, OS 74.09%, and OO 73.34%, as shown in Fig. 3. There was a significant main effect of relativization ($F(1, 20) = 11.201$, $p = .003$). Subjects were more accurate in answering probes of object-relativization than subject-relativization RCs (77.54% vs. 72.60%). There was also a significant interaction between relativization and embeddedness ($F(1, 20) = 7.906$, $p = .011$). A Tukey-corrected post hoc test indicated that SO has a significantly higher accuracy than SS ($p < .001$), while no significant difference was found between OS and OO ($p = .877$).

The average response time of the probes was SS 2.55s, SO 2.28s, OS 2.39s and OO 2.50s, as shown in Fig. 4. There was a significant main effect of relativization ($F(1, 20) = 6.899$, $p = .016$) and a significant interaction between relativization and embeddedness ($F(1, 20) = 36.336$, $p < .001$). The Tukey-corrected post hoc tests revealed that the probe response to SS was significantly slower than SO ($p < .001$), but OS was significantly faster than OO ($p < .05$). Meanwhile, OO was significantly slower than SO ($p < .001$).

6.2. Results of EEG data

At the relative marker *de*, the factorial analysis based on our cluster-based permutation tests showed one negative cluster for a significant main effect of relativization in the time window of 110–220 ms after the onset of *de* with object-relativization (mean = -0.381, SD = ± 0.313) showing more negative ERP responses than subject-relativization RCs (mean = 0.180, SD = ± 0.315) (Table 4). Fig. 5a displayed the negative clusters in a stepwise time interval of 10 ms ($t = -6104.1$, $p < .001$, $\alpha = 0.025$). The anterior electrodes on the left scalp were more consistently involved than the electrodes on the right side. The left anterior E17 and E18 were two electrodes with a significant difference between object-relativization and subject-relativization RCs across the entire time window (Fig. 5b).

A significant main effect of embeddedness ($t = -950.22$, $p < .001$, $\alpha = 0.025$) was observed in the time window of 410–440 ms. Fig. 6a displayed the results at a stepwise time interval of 10 ms. The anterior cluster was more left-lateralized with E12,

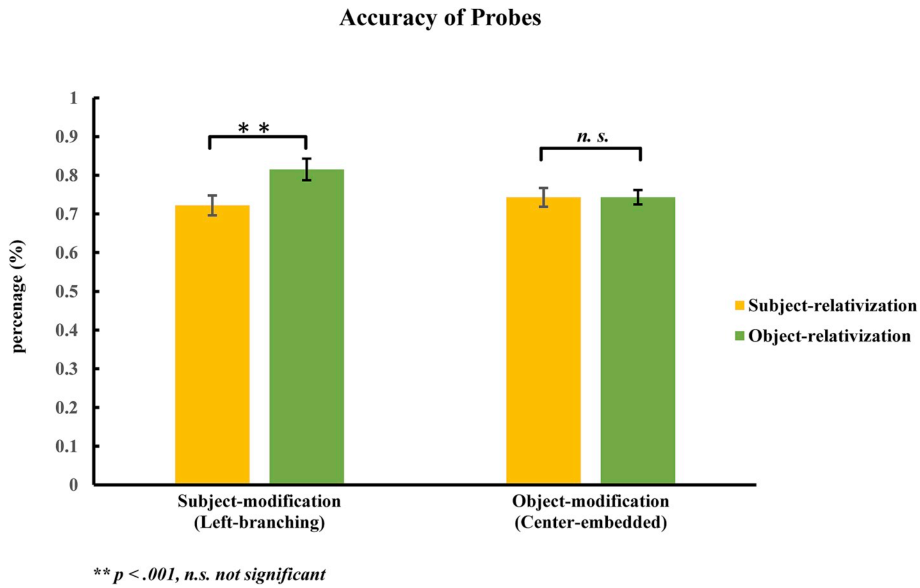


Fig. 3. Bar graph of accuracy of probe questions (mean ± SEM). *$P < .05$, **$P < .01$, *n.s.* = not significant.

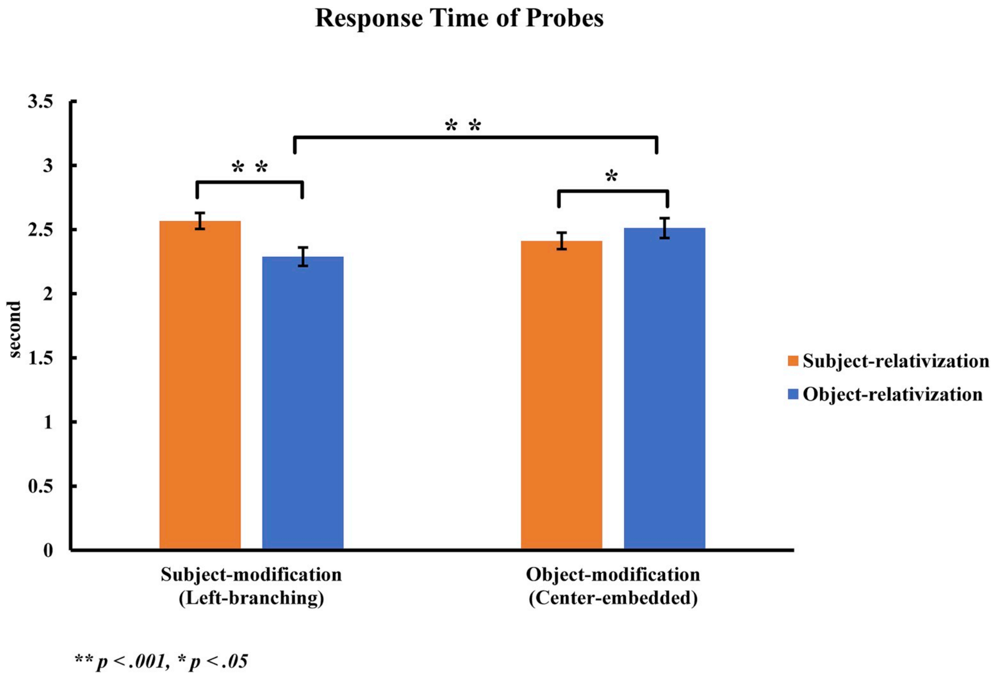


Fig. 4. Bar graph of response time of probe questions (mean ± SEM). $*P < .05$, $**P < .01$, *n.s.* = not significant.

E13 and E14 consistently involved across the entire time window (Fig. 6b). Average ERPs of the three electrodes in this time window showed that center-embedded RCs (mean = −1.767, SD = ± 0.546) elicited more negative ERPs than left-branching RCs (mean = −0.711, SD = ± 0.383) (Table 4 and Fig. 6b).

A significant interaction between relativization and embeddedness was found in the time window 540–620 ms after the word onset of *de*. A positive cluster encompassed the centro-posterior/parietal regions ($t = 3993.0$, $p < .001$, $\alpha = 0.025$) (Table 4). Fig. 7a displayed the positive cluster in a stepwise time interval of 10 ms. The centro-posterior electrode E33 and E35 were consistently involved across the entire time window (Fig. 7b). Although some centro-posterior cluster electrodes were also involved in the relativization main effect, the time windows of the two effects did not overlap.

Post-hoc tests of the average ERPs in the time window of 540–620 ms indicated that the interaction was mainly driven by center-embedded RCs (Fig. 7b). OO RCs were significantly more positive than OS RCs (Bonferroni correction: $p < .001$), while there was no significant difference between SO and SS RCs ($p = .270$) (Table 4).

At the head noun, a significant main effect of embeddedness was found at left lateralized negative clusters in the time window of 73–123 ms ($t = -3709.8$, $p < .001$, $\alpha = 0.025$) (Table 4). Fig. 8a displayed the results at the stepwise time interval of 10 ms. E20, E21, E25, E26, E27 and E28 were consistently involved across the entire time window (Fig. 8b). Average ERPs of the electrodes in this time window indicated that center-embedded relative clauses (mean = −0.526, SD = ± 0.136) elicited more negative electrical

Table 4
Experimental effects.

Time window	Effect				Mean (Mean difference)	p-value	Clusterstat (t value)
de (relative marker)							
110–220 ms	Relativization	Object- relativization			-.381	.000**	−6104.1
		Subject- relativization			.180		
410–440 ms	Embeddedness	Object-modifying			−1.767	.000**	−950.2213
		Subject-modifying			-.711		
540–620 ms	Embeddedness * Relativization	Object-modifying	Object-relativization	Subject-relativization	1.359*	.000**	3993.0
		Subject-modifying	Object-relativization	Subject-relativization	-.425	.270	
Head Noun							
73–123 ms	Embeddedness	Object-modifying			-.526	.000**	−3709.8
		Subject-modifying			.082		

Note: there were no significant differences between OO and SO RCs (p = .64), and OS and SS RCs (p = .68) for the interaction effect.

a)

b)

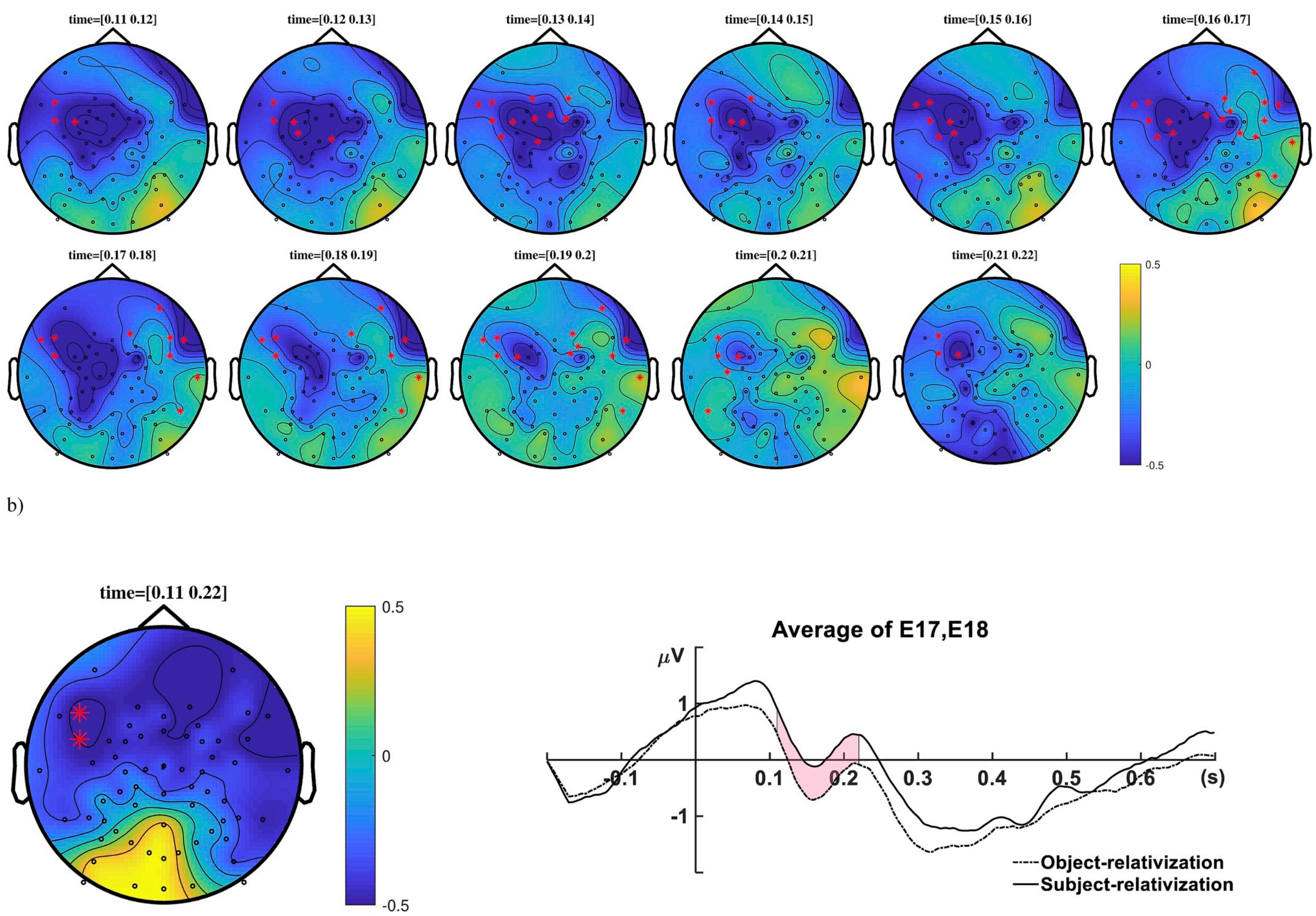


Fig. 5. Electrode clusters with a significant main effect of relativization in the time window of 110–220 ms at *de*. (a) Significant clusters displayed at the stepwise time interval of 10 ms; (b) Left panel: a topographical map of E17 and E18 consistently involved across the time window; right panel: a plot of the average ERP waveforms of the object-relativization and subject-relativization RCs at the two electrodes.

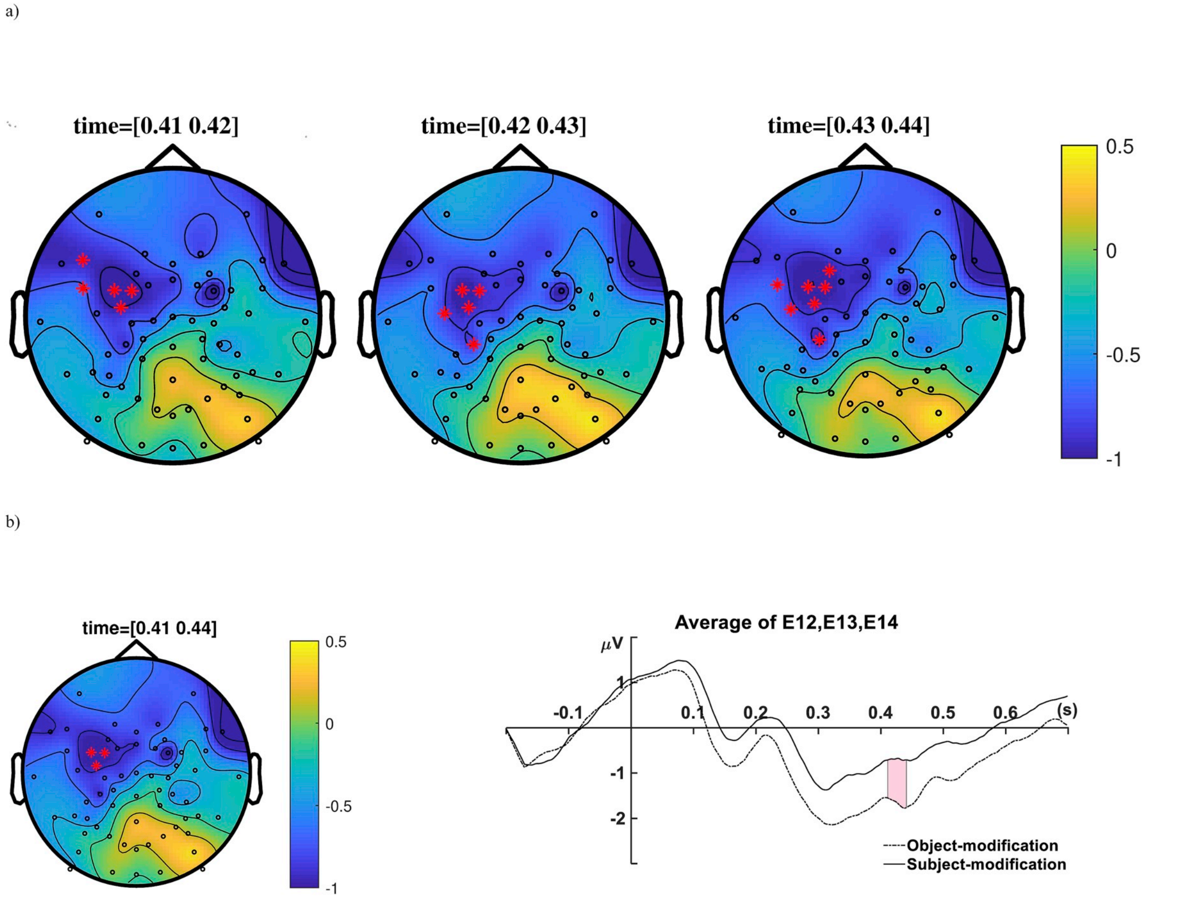


Fig. 6. Electrode clusters with a significant main effect of embeddedness in the time window of 410–440 ms at *de*. (a) Significant clusters displayed at the stepwise time interval of 10 ms; (b) Left panel: a topographical map of E12, E13 and E14 consistently involved across the time window; right panel: a plot of the average ERP waveforms of the object-modifying (center-embedding) and subject-modifying (left-branching) RCs at the three electrodes.

potentials than left-branching relative clauses (mean = 0.082, SD = ± 0.166) (Table 4 and Fig. 8b).

7. Discussion

Our study of the temporal interaction of the sentence context (embeddedness) with relativization found an early relativization effect (110–220 ms) that was followed by an embeddedness effect (411–441 ms) with a late interaction effect between 540 and 620 ms at the relative marker (RQ1). The main effect of relativization as a left anterior negativity suggests that there is a processing advantage of subject-relativization independent of sentence context (RQ2), but the effect is rather transitory and followed by a left-lateralized anterior negativity for the center-embedded RCs, which implies increased working memory load introduced by preceding sentence context (RQ3). In addition, the interaction between embeddedness and relativization as a late centro-posterior positivity of OO compared to OS RCs showed that embeddedness impacts the processing costs of Chinese object-relativization RCs in terms of structural reanalysis (RQ4). Only the embeddedness effect was observed at the head noun, further indicating that *de* is critical in disambiguating the subcategories of verb arguments and the head noun instantiates semantic contents of these arguments.

7.1. The relativization effect and subject-relativization processing advantage

The early left anterior negativity for the main effect of relativization in the 110 ms-220 ms time window of *de* (Fig. 5) supports our prediction that the relativizer should be attached to the local relative clause structure via gap-filler dependencies, deriving an RC before the RC can be incorporated into the main sentence.

The main effect of relativization preceded both the main effect of embeddedness and the interaction windows, but crucially it did not overlap with them. This finding suggests to us that the parser follows the economical parsing principles (Minimal Attachment and Late Closure) at the initial stage of parsing by constructing a local gap-filler dependency. This process is independent of sentence context constraint (Frazier, 1979, 1999).

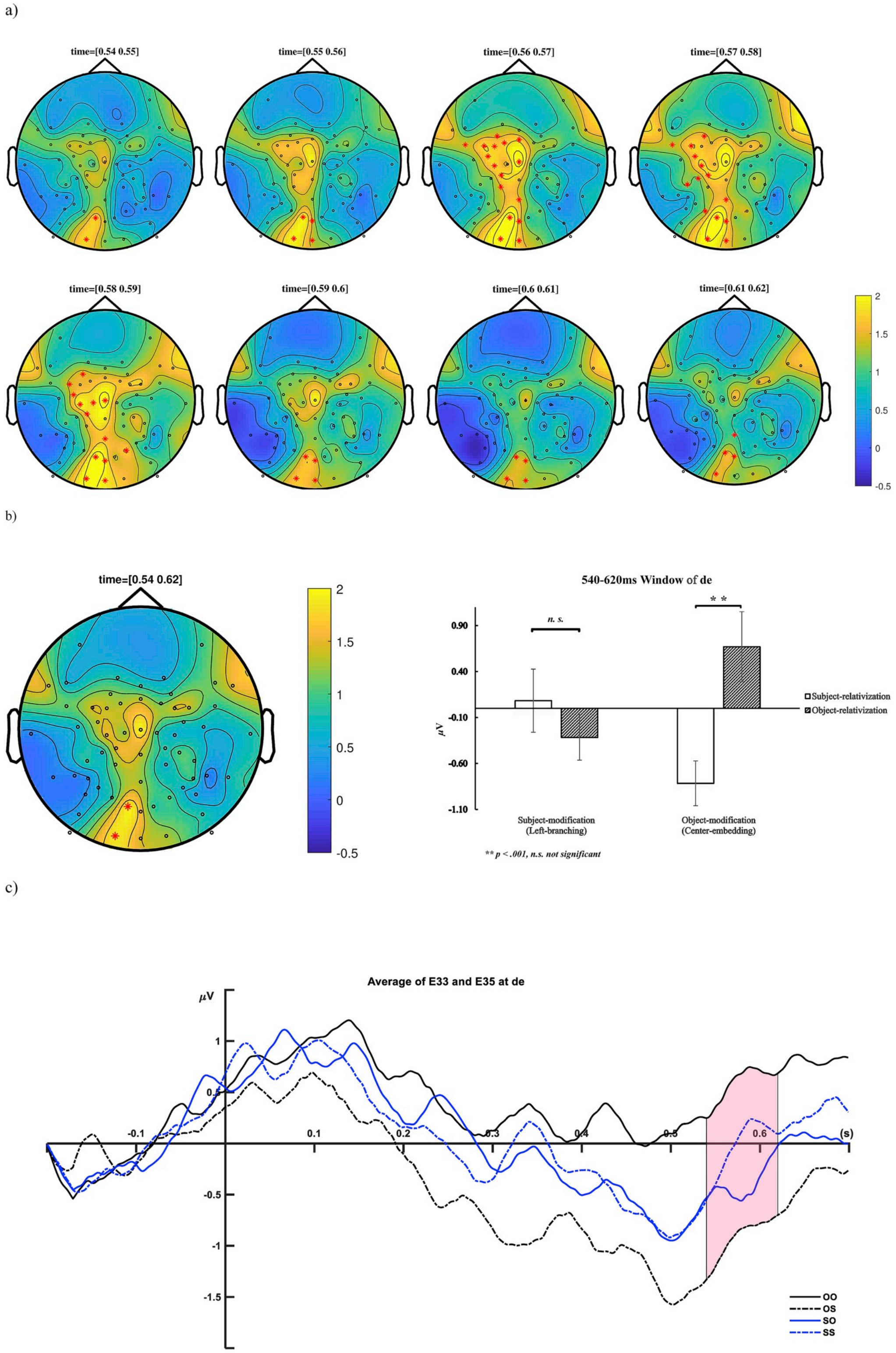


Fig. 7. Electrode clusters with a significant interaction between embeddedness and relativization in the time window of 540–620 ms at *de.* (a) Significant clusters displayed at the stepwise time interval of 10 ms; (b) Left panel: a topographic map of E33 and E35 consistently involved across the time window; right panel: a graph of the interaction effect at the three electrodes; (c) Average ERP waveforms of the four types of relative clauses (OO/OS/SO/SS) at the posterior electrodes E33 and E35.

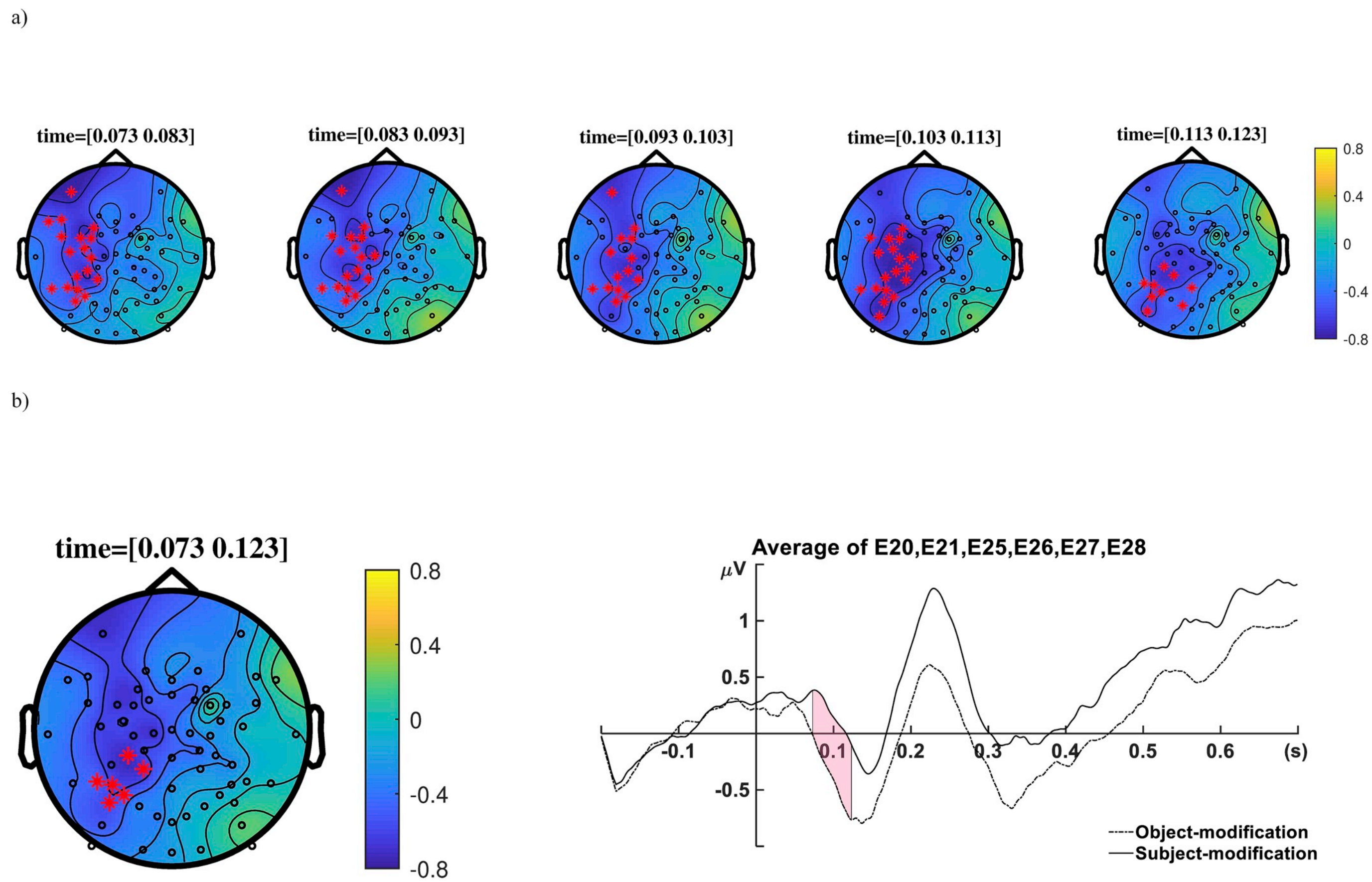


Fig. 8. Electrode clusters with a main effect of embeddedness in the time window of 73–123 ms at the head noun. (a) Significant clusters displayed at the stepwise time interval of 10m; (b) Left panel: a topographic map of E20, E21, E25, E26, E27 and E28 consistently involved across the time window; right panel: a plot of the average ERP waveforms of the object-modifying (center-embedding) and subject-modifying (left-branching) pairs at the six electrodes.

The greater left anterior negativity of object-relativization RCs irrespective of embeddedness indicated the higher working memory load in object-relativization RC processing (King & Kutas, 1995, Kwon et al., 2013; Ueno & Garnsey, 2008).[4] Our results, therefore, are consonant with the findings of Zhang and Jiang (2010), Lin and Bever (2006) and Jäger et al. (2015) who also observed left lateralized negativity and longer reading time at *de* for the object-relativization RCs., The results also support the Phrase Structural Distance Hypothesis (SDH) of O'Grady (2007) as relativization over the structurally less embedded subject position should engage fewer resources than relativization over more deeply embedded object position.

However, the subject-relativization processing preference induced by a closer phrase-structure distance between gap and filler is not held throughout the entire comprehension process as previous behavioral studies have suggested. Instead, at the relative marker *de*, relativization began to quickly interact with embeddedness at just about 410 ms after the onset of the relative marker. It is reasonable to infer that the subject-relativization processing preference observed in the previous behavioral studies of center-embedded Chinese RCs might be a product of the interaction between local gap-filler integration and cross-clausal domain integration due to the low time resolution. This scenario is different from English RCs, because the syntactic features of post-modification and left-edged relative markers (*who/that*) do not induce any thematic assignment ambiguity in the object-modifying context, and immediately trigger an active search lasting throughout the clause. The heavier processing load of English object-relativization RCs directly reflects the processing difficulty evoked by filler-gap integration. In contrast, the preceding sentence constraint of center-embedded Chinese RCs has a more immediate impact on the online parsing and modulates the processing costs dynamically.

7.2. The embeddedness effect

A significant main effect of embeddedness as a left-lateralized negativity was observed in the time window of 410–440 ms after the onset of *de*. The results support our hypothesis that working memory modulates the ease of integration of RCs with sentence context (Traxler, 2007) given that object-modifying RCs showed greater integration costs than subject-modifying RCs without preceding sentence context.

The closed-class *de* is classified as a clitic in Chinese (Wu, 2004). In our experiment, *de*, as a crucial disambiguating word in the sentence, announces category information for the following head noun (Packard et al., 2010). When the parser encounters *de*, there is as yet no referential information about the head noun. Consistent with the processing loads inherent in the structural computations in Table 2, the greater left anterior negativity of center-embedded RCs indicated that increased working memory was needed to maintain the selectional information of the main verb *anwei* 'comforted' in addition to that of the RC verb *liaojie* 'understood'. The higher processing load of these two sentences comes with the need to sort out the arguments of both the main clause and RC verbs. Our results gain support from the self-paced reading study by Lin and Bever (2006), who reported that participants responded significantly faster to *de* in Chinese subject-modifying relative clauses than object-modifying relative clauses.

The object-modifying RCs also elicited a left-lateralized negative ERP relative to the subject-modifying RCs at the head noun. As Fig. 8a illustrates, an extensive electrode cluster from the frontal to posterior region on the left hemisphere showed a significant main effect of embeddedness in an early time window of 73–123 ms post-word onset. In order to investigate whether the observed effect was a carryover effect from the previous relative marker, we compared the difference in electrical amplitudes between the object- and subject-modifying RCs in the 200 ms time window before the onset of the head noun. The results showed that there was no significant difference between them ($t = 0.641$, $p = .523$), suggesting that the early left-lateralized negativity constitutes an independent ERP component elicited by the head noun itself. Since the head noun is consistent across conditions, the effect is not likely to be the N100 effect either, which is assumed to be related to perceptual processing and discrimination between words of different grammatical classes (Brandeis & Lehmann, 1994; Leikin, 2008).

As Fig. 8b shows, the early negative deflection of electrical potential was sustained across the entire time window of the head noun. A possible explanation is that the component represents anticipatory sentence comprehension modulated by working memory in object-modifying RCs (Kutas, DeLong, & Smith, 2011, pp. 190–207; Delong, Troyer & Kutas, 2014). Sentence comprehension is performed in both predictive and integrative manner, which influences parsing prior to as well as after receipt of the word. As the phrase markers in Table 2 show, with object-modifying RCs, the head noun integration finalizes a representation for a full sentence, requiring the unification of the contents of two clauses in discourse. In subject-modifying RCs, however, the matrix clause predicate information is still pending at the head noun, so that no such full clausal unification can be performed yet. The left-lateralized negativity effect for object-modifying RCs might reflect the complexity of the information encoded in the phrase marker at the time of integration. Yang et al. (2010) also reported a sustained negativity at the head noun and interpreted it as related to increased cognitive demands for memory resources as a function of the two transitive verbs in referential processing. As Table 2 shows, by the time that *de* is encountered, a predicate has been derived through binding across contexts, so that the referent of the anticipated head

[4] As noted by an anonymous reviewer that the time window of the left anterior negativity of the relativization effect was earlier than the typical time range between 200 and 500 ms, we propose that the latency variability might arise from the specific experimental effects such as the probability of occurrence of stimulus, the ISI and other subject-specific factors such as cognitive capabilities. Iturrate, Chavarriaga, Montesano, Minguez, and Millán (2014) found that latency of ERP components later than 200 ms are more prone to these effects. Moreover, Kwon et al. (2013) argue that the distinction between left anterior negativity and sustained negativity, both indexing higher working memory load, is not clear-cut. The waveforms illustrated in Fig. 5b showed that the time window of the left anterior negativity of object-relativization RCs was sustained until approximately 400 ms. Since both ERP components are assumed to be driven by similar cognitive processes, we used the name left anterior negativity more based on its typological distribution and the total time window.

noun will also participate in two events described by the RC and matrix-clause verbs. Although in the object-modifying case only, the matrix-clause verb is already specified, the computation still already anticipates a verb phrase in the subject-modifying case, with predicate-level place holders in the semantic representation. The head nouns of any RC will therefore automatically engage a dependency within and without the RC. In view of this, it seems to us that the amount of activation in the partially specified phrase marker constitutes the central distinction in processing.

7.3. Structural reanalysis makes object[HYPHEN]relativization harder

An interaction between embeddedness and relativization was found in a late time window 540–620 ms at *de*. Post hoc tests revealed a more positive central parieto-occipital electrical potential for OO than OS RCs. Fig. 7c shows that the positivity is sustained across the entire time window of *de*. The topographic distribution and time window of this ERP component matches the Syntactic Positive Shift (SPS) reported by Hagoort et al. (1993, 2000, 2003). This component is treated as a generalized form of the P600, a neural signature of both syntactic violations and structural reanalysis (Hagoort et al., 1993). Since the parsing system does not keep all possible structures at the same activation level. The more frequent and computationally economical structures are preferred (Frazier & Rayner, 1982; Garnsey, Tanenhaus, & Chapman, 1989; Rayner, Carlson, & Frazier, 1983). Revision of the preferred structure with unexpected incoming words elicits an SPS (Hagoort et al., 1993).

The parsing processes of OO and OS RCs before *de* differ in the way that the N + V + N + V sequence of OO RCs creates a garden path effect, while the N + V + V + N structure of OS RCs only requires gap-filler integration. Thus *nainai* 'grandmother' in the OO condition is initially interpreted as the object of the main verb *anwei* 'comforted' until the parser encounters the verb of the embedded relative clause *liaojie* 'understood', resulting in temporary ambiguity. As Table 2 shows for the OO condition, an RC analysis is not expected until *de* is encountered. Economy considerations (Minimal Attachment) will favor root clause analysis, but not allow predicate formation until the disambiguating *de* requires it, triggering reanalysis in which *nainai* 'grandmother' is assigned as the subject of the embedded relative clause. Our sentence completion task speaks to the plausibility of this argument since 86.7% of the incomplete N + V + N + V structure of OO RCs were interpreted as conjoined clauses with *yeye* 'grandfather' as the subject of both verbs due to the frequent subject-dropping in Chinese (Kwon et al., 2013).[5] In contrast, in the OS condition, the main verb *anwei* 'comforted' is followed by another verb *liaojie* 'understood', which prompts the parser to anticipate a null object for *anwei* and a null subject for *liaojie* simultaneously. The double gaps need to be maintained in working memory until the relative marker *de* reconciles the categorical information of the two null arguments in a hierarchical manner. It is still a process of gap-filler integration with no revision of the thematic role of the embedded object *nainai* 'grandmother'. The late SPS effect at *de* suggests that the higher processing costs of OO RCs arise from the reanalysis procedure, which comes online as soon as the relativization is required by *de*.

Osterhout, Holcomb, and Swinney (1994) have found that garden paths elicit positive-going electrical potentials at disambiguating words when ambiguous sentences without an overt complementizer are compared with unambiguous sentences with a complementizer. Although the researchers only reported 500–800 ms as a significant time window of the posterior positivity, the waveforms in Fig. 2 displayed a sustained positivity starting from the critical disambiguating auxiliary verb onward with maximum posterior distribution. Gouvea et al. (2010) also reported that the onset latency of the positivity for grammatical garden path sentences was much earlier than in ungrammatical sentences, indicating that onset latency is a function of time spent on recognition and retrieval. We propose that the sustained positivity of OO relative to OS RCs at *de* in our experiment might be a composite component consisting of early positive ERP components with a late SPS effect (Fig. 7c). A previous study (Sun et al., 2016) has found an early P200 component at *de* in OO RCs. We refrain from interpreting the observed early positivity as a specific component because the onset of the maximum peak before 300 ms is quite early (110 ms) and another peak, smaller in amplitude occurred around 200 ms. Different from Sun et al (2016) who identified the later component as an N400 effect for OS RCs, we propose that the component is a late SPS effect, because the processing of the functional word *de* should be that of syntactic/sentence-level semantic integration rather than the integration of lexical information with the current semantic memory manifested as an N400 (Kutas & Federmeier, 2011). Additionally, the topographic distribution and time window of the ERP component agree with the SPS effect observed in previous studies (Hagoort et al., 1993, 2000, 2003).

An important finding of the present study is that the subject-relativization processing advantage in Chinese RCs is driven by different underlying linguistic processes at different stages of parsing. An early relativization effect (110–220 ms) at *de* irrespective of embeddedness indicates that higher processing costs of object-relativization are heavily influenced by gap-filler integration difficulty. The longer phrase structure distance between gap and filler in object-relativization may require more processing resources. However, at the later 540–620 ms time window, no across-the-board processing advantage of subject-relativization was observed, which suggests that the processing advantage solely driven by gap-filler integration is transitory. Instead, the greater processing difficulty resides with the structural reanalysis in OO RCs. This becomes a more dominant trigger of increased processing load in the later time window at *de*. Therefore, the processing load of Chinese RCs is significantly modulated by sentence context because it interacts with relativization in a highly dynamic manner. A 'universal processing advantage' for subject-relativization clauses needs to be updated

[5] There was also another possibility that the second N + V structure in the N + V + N + V sequence of OO RCs was interpreted as an embedded complement clause. For example, *huangzhe denghou yisheng tuijian* 'The patient waited for the doctor recommended' in 4b was completed as *huangzhe denghou yisheng tuijian xinyao*'The patient waited for the doctor recommended new medicine'. The average rate of this interpretation is 13.3%. Although our present experiment could not completely exclude this alternative interpretation, it is proposed that the relativization structural reanalysis should still occur when the relative marker *de* is encountered regardless of the previous interpretations.

by more fine-grained elucidations of the computational and neural mechanisms driving the formation of RC interaction with the sentence context.

8. Conclusions

The present study found that the sentence context was processed after 410ms at the relative marker *de*. Center-embedding dramatically increased processing load of OO RCs because an ambiguity resolution mechanism was mobilized. Both syntactic gap-filler integration and context-incurred structural reanalysis increased processing load in Chinese object-relativization RCs at distinct time points, showing the necessity to adjust the account of RC processing beyond a 'processing advantage for subject-relativization' to accommodate the effects of sentence context cross-linguistically. Nevertheless, our results still need to be confirmed by the manipulations which include both subject-modifying and object-modifying RCs in a single experimental paradigm and treat them as the two levels of one factor in the analysis. We note that the problem of comparing different word categories within the relative clause region could not be solved, so that no direct observations of the difference between object- and subject-relativization RCs at the first and second words in the relative clause regions could be made. Further research could introduce a higher baseline to tackle the issue.

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