BRAIN RESEARCH 1410 (2011) 89–100

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BRAIN RESEARCH

Research Report

Multiple constraints on semantic integration in a hierarchical structure: ERP evidence from German

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ARTICLE INFO

Article history:
Accepted 27 June 2011
Available online 4 July 2011

Keywords:
Semantic process
Syntactic hierarchy
Multiple constraints
Sentence comprehension
N400
P600
ERP

ABSTRACT

A recent ERP study on Chinese demonstrated dissociable neural responses to semantic integration processes at different levels of syntactic hierarchy (Zhou et al., 2010). However, it is unclear whether such findings are restricted to a non-case marked language that relies heavily on word order and semantic information for the construction of sentence representation. This study aimed to further investigate, in a case-marked language, how semantic processes in a hierarchical structure take place during sentence reading. We used German sentences with the structure "subject noun + verb + article/determiner + adjective + object noun + prepositional phrase", in which the object noun was constrained either at the lower level by the adjective or at the higher level by the verb, and manipulated the semantic congruency between the adjective and the object noun and/or between the verb and the object noun. EEGs were recorded while participants read sentences and judged for their semantic acceptability. Compared with correct sentences, a biphasic pattern of an N400 effect followed by a late positivity effect was observed on the object noun for sentences with either lower- or higher-level mismatch or with double mismatches. Both the N400 effect and the late positivity (P600) effect were larger for the double mismatch condition than for either of the single mismatch conditions. These findings demonstrate cross-language mechanisms for processing multiple semantic constraints at different levels of syntactic hierarchy during sentence comprehension.

1. Introduction

During sentence comprehension, the reader or listener needs to integrate various sources of information in real time to construct a coherent sentence representation. The extraction of semantic relations between words relies on how these words are organized into a certain type of syntactic structure (Jackendoff and Pinker, 2005). In a recursive and hierarchical structure, constraints at different levels of syntactic hierarchy act in concert (Bahlmann et al., 2006; Friederici, 2004; Friederici et al., 2006; Jiang and Zhou, 2009; Makuuchi et al., 2009; Opitz and Friederici, 2007) in determining how a sentence representation could be formed (Makuuchi et al., 2009; Zhou et al., 2010). The mental representation of a sentence with a hierarchical structure (e.g. *Nele schneidet das dünne Papier…/Nele cuts the thin paper…*) must be formed simultaneously by

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doi:10.1016/j.brainres.2011.06.061

combining the meanings of sentence constituents in local, lower-level hierarchy (e.g., *das dünne Papier*) and by combining the meanings of sentence constituents in a higher level of hierarchy (e.g., *schneidet das Papier*).

As shown in Fig. 1, verbs and adjectives can be differentiated in terms of their positions in the syntactic hierarchy, with verbs at a higher level and adjectives at a lower level. The same noun phrase (NP) can be constrained simultaneously by an adjective at the lower level and by the verb at the higher level. The local combination of the adjective with the object noun forms a complex argument of the verb. Traditionally linguistic theories assign a mandatory and pivotal role to verbs in sentence interpretation (Chomsky, 1981; Dowty, 1991). Verbs are important in determining thematic roles (Altmann and Kamide, 1999). Incongruent verbs disrupt the entire argument structure of the sentence, posing great integrative challenge. In contrast, adjectives are optional in a sentence and are limited to phrases with a single thematic role, be it an agent or patient (Prior and Bentin, 2006). Incongruent adjectives only create interruptions in local phrases which they modify in the processing of sentence meaning. Furthermore, as Syntactic Prediction Locality Theory (SPLT, Gibson, 1998) suggested, locality could influence the cost of integration; the cost for linking the noun to the verb would be larger than that for linking the noun to the adjective, as the distance become longer (see Patel, 2003 for a review). Although it seems clear that verb and adjective play roles of different importance in sentence comprehension, it is still an unanswered question how these constraints at different levels of syntactic hierarchy (verb–noun and adjective–noun) would act in concert and affect online semantic integration processes (Zhou et al., 2010).

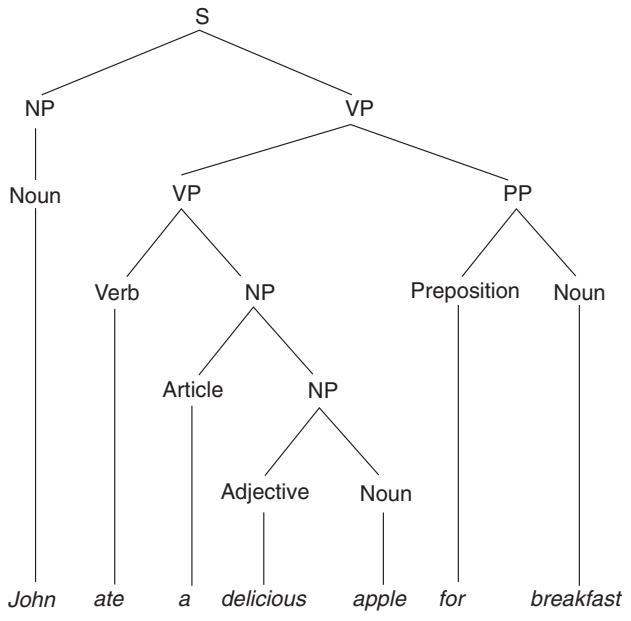

Fig. 1 – The hierarchical structure of an exemplar sentence in the form of "subject noun + verb + article + adjective + object noun + prepositional phrase". S = sentence; NP = noun phrase; VP = verb phrase; PP = prepositional phrase. The adjective and the object noun form a local, lower-level phrase while the verb and the object noun form a higher-level structure.

Most previous ERP studies on semantic processes have focused on the impact of a single or local constraint upon the integration of a sentence constituent and could not answer this question. The N400 effect was widely observed in experiments where a single source of constraint was violated (e.g., in adjective–noun mismatch, Hagoort, 2003; Prior and Bentin, 2006; in verb–noun mismatch, Friederici and Frisch, 2000; Hahne and Friederici, 2002; Jiang et al., 2009; Li et al., 2006; Ye et al., 2007) or where the contextual constraint was violated (e.g., in the incongruence between word and sentential/discourse context, Kutas and Hillyard, 1980; Van Berkum et al., 1999). The N400 effect was assumed to reflect difficulty in integrating the local lexical semantics into the prior sentence/discourse representation (Van Berkum et al., 1999, 2003) or difficulty in lexical access (Lau et al., 2008; Wlotko and Federmeier, 2007; see Kutas and Federmeier, 2000, 2011; Kutas and Van Petten, 1994; Lau et al., 2009 for reviews).

Studies that indeed manipulated multiple constraints simultaneously have focused on the interplay between the constraint at local phrase level and the constraint at some global representation level (e.g., sentential- or discourse-level). But these studies could not answer our question either because these studies did not consider the syntactic structure of sentence. One study by Hald et al. (2007) examined the interaction between discourse context congruency and world knowledge compatibility. They found that the N400 effect was comparable on words in mere discourse incongruent condition and in mere world knowledge incompatible condition, but was enhanced in the condition in which both constraints were violated, suggesting that neither discourse context nor world knowledge can override each other completely in online semantic integration. Other studies, however, showed that the N400 effect engendered by semantic mismatch between words in a local phrase could be blocked by the presence of a thematic role attraction (Hoeks et al., 2004; Kim and Osterhout, 2005; Kuperberg et al., 2003, 2006, 2007), world knowledge heuristics (Kolk et al., 2003; Van Herten et al., 2005, 2006; Vissers et al., 2007), or supportive discourse context (Filik and Leuthold, 2008; Nieuwland and Van Berkum, 2005, 2006). In these studies, a P600 effect was observed on the mismatching words instead. Although the P600 effect is commonly viewed as a reflection of syntactic anomaly, complexity and ambiguity (Friederici et al., 1996; Hagoort et al., 1993; Neville et al., 1991; Osterhout and Holcomb, 1992; see Gouvea et al., 2010 for a review), the P600 here was responsive to semantic manipulations. This semantic P600 effect is assumed to reflect a continued processing after the detection of mismatch/conflict between the combinatorial rule-based and the heuristic-based semantic analysis (Kuperberg, 2007), a monitoring process which checks for potential errors on the difficulty/failure to form a congruent sentence interpretation (Kolk et al., 2003; Kolk and Chwilla, 2007; Van Herten et al., 2005, 2006; Vissers et al., 2007), or a process of suppressing a strong prediction (Federmeier et al., 2007). Either way, the difficulty in semantic integration at a local level is assumed to trigger continued processes to coordinate the semantic integrations at local and other levels.

Studies that are particularly relevant to our question are those showing that the semantic integration processes could

be affected by syntactic complexity (Kolk et al., 2003) or by the individual cognitive control ability in interaction with syntactic complexity (Ye and Zhou, 2008). In German, studies employing relatively complex syntactic structures (e.g., with verb and noun separated by a adverbial phrase structure, see Gunter et al., 1997; or with verb and noun embedded in an object complement clause, see Experiment 1 in Friederici and Frisch, 2000) have found a biphasic pattern of N400 plus late positivity (P600) effect for semantically incongruent target words, while other studies with similar but simpler syntactic structures observed only a N400 effect (Hahne and Friederici, 2002; Experiment 2 in Friederici and Frisch, 2000). However, these studies either did not manipulate syntactic complexity directly or used between-item designs and hence could not give a direct answer to the question of how semantic processes at different syntactic levels might act in concert.

As a first attempt to investigate directly how multiple constraints at different levels of syntactic hierarchy impact upon semantic processes during sentence comprehension, Zhou et al. (2010) asked participants to read Chinese sentences with an unambiguous hierarchical structure of "subject noun + verb + numerical + classifier + object noun", in which the sentence-final object noun was either constrained by the classifier at the lower level or by the verb at the higher level. The semantic constraints between classifier and noun, between verb and noun and between verb and classifier were manipulated, resulting in sentences with single, double, or triple mismatches. ERP results showed that semantic mismatch in the lower-level structure (the classifier-noun mismatch condition) elicited an N400 effect whereas semantic mismatch in the higher-level structure (the verb–noun mismatch and the double-mismatch conditions) elicited a dissociable pattern: an N400 effect followed by a left-posterior positivity effect. Moreover, all the mismatches engendered a late anterior negativity effect. The N400 effect revealed an interaction between lower- and higher-level semantic congruency, with the effect in the double mismatch smaller than the sum of two single mismatches. The late positivity effect was larger in the double-mismatch than in the verb–noun mismatch condition. The authors hypothesized that 1) the lower- and the higher-level semantic processes take place simultaneously (and possibly interactively) in integrating a target word into a sentential context and 2) difficulty in semantic integration at the higher level might trigger a process of coordinating semantic processes across levels in the construction of final representation.

These hypotheses were derived from a single study on a particular language; it is not clear whether they can be extended to other languages with different syntactic properties. As a non-inflectional language, Chinese lacks morpho-syntactic markers (such as case markers) that assign directly a syntactic role to a sentence constituent. The construction of Chinese sentence representation relies heavily on word order and semantic properties encoded in lexical items (Bornkessel-Schlesewsky and Schlesewsky, 2009; Phillip et al., 2008; Wang et al., 2009; Ye et al., 2006; Zhou et al., 2010). For example, in Chinese, the verb-medial form "subject noun–verb–object noun" is the most frequent word order with relatively fixed positions for nouns and verbs. On the other hand, the lack of case marking renders Chinese more flexible regarding thematic role assignment. This is coupled with the fact that Chinese allows for prenominal relative clauses (which is not allowed in German), making it possible for an NP to be assigned with different thematic roles via biclausal analyses of the input. For example, the local classifier-noun mismatch "Xiaoming mai le na ben Laoshi [Xiaoming bought$_{\text{perfective}}$ that ben$_{\text{book classsifier}}$ teacher]" could be easily edited out by expanding the sentence to "Xiaoming mai le na ben laoshi tuijian de shu [Xiaoming bought$_{\text{perfective}}$ that ben$_{\text{book classsifier}}$ teacher recommend DE book]/*Xiaoming bought the book that the teacher recommended*". Since the prenominal clauses are commonly used, native speakers of Chinese are accustomed to this temporary ambiguity during the unfolding of sentence input, and they even use the incongruent classifier as a cue for upcoming relative clause (Wu et al., 2009). This temporary ambiguity may have contributed to the ERP patterns we observed in the Chinese study.

In contrast, case-marked languages, such as German, have few restrictions on word order and the construction of syntactic structure relies heavily on case marking (Bornkessel et al., 2002). For example, the German sentence can either take the verb-medial form "subject noun–verb–object noun" (e.g., *Ich wasche das Auto jeden Sonntag*) or the verb-final form "subject noun–object noun–verb" (e.g., in the subordinate clause: *Er weiß, dass ich jeden Sonntag das Auto wasche*). In either form, if the case is unambiguous, both the case marking and the verb's selectional restrictions play a role in constructing a structural hierarchy (Friederici and Frisch, 2000); If the case is ambiguous, hierarchy for thematic arguments (e.g., animacy) may come into play (Schlesewsky and Bornkessel, 2004). The occurrence of the verb-final sentences in German may render the role of word order in sentence meaning construction, even for subject–verb–object (SVO) sentences, less important in German than in Chinese.

To make the data more comparable and the cross-language comparison possible, here we employed German sentences with the structure similar to the Chinese we have examined. The hierarchical structure, "subject noun + verb + article/determiner + adjective + object noun + prepositional phrase", is widely used for German sentences without clauses. In this structure, the object noun is constrained either by adjective at the lower level or by the verb at the higher level and the local combination of article/determiner, adjective and object noun formed a complex argument of the verb (see Fig. 1). We manipulated the semantic congruency between the verb and the object noun and the semantic congruency between the adjective and the noun, creating four types of sentences: correct sentences, sentences with verb–noun mismatch, sentences with adjective–noun mismatch, and sentences with mismatch of both verb–noun and adjective–noun (see Table 1). We measured brain responses to the object nouns using event-related potentials while native speakers of German read the sentences. Note, unlike the Chinese study (Zhou et al., 2010), the object nouns here were in the middle of sentences, rather than at the sentence-final position. This excludes the potential contribution of a more general wrap-up process to the semantic integration processes for sentence constituents per se. The wrap-up process, taking place mainly at clause- or sentence-final constituents, is a process of reinterpreting all the arguments of the sentence in order to check if they have been

Table 1 – Experimental conditions and exemplar sentences with English translation. The semantic constraints between verb and adjective, between adjective and noun and between verb and noun were either matched or mismatched in each critical condition.

Conditions	Example	Verb–adjective congruency	Adjective–noun congruency	Verb–noun congruency
Correct	Nele schneidet das dünne Papier am Tisch. *Nele cuts the thin paper at the table.*	√	√	√
Adjective–noun mismatch	Claudius schneidet das köstliche Papier mit einer Schere. *Claudius cuts the delicious paper with scissors.*	√	×	√
Verb–noun mismatch	Heinrich erntet das dünne Papier mit Geduld. *Heinrich harvests the thin paper with patience.*	√	√	×
Double mismatch	Lotte erntet das köstliche Papier mit Sorgfalt. *Lotte harvests the delicious paper with diligence.*	√	×	×

represented correctly for obtaining the whole meaning of the utterance (Hagoort, 2003; Molinaro et al., 2008).

Based on previous studies involving the local semantic violation (Friederici and Frisch, 2000; Hagoort, 2003; Hahne and Friederici, 2002; Jiang et al., 2009; Li et al., 2006; Martín-Loeches et al., 2006; Zhou et al., 2010), we predicted a N400 effect on the object noun for the local, adjective–noun mismatch, as compared with the baseline condition. We also predicted an N400 effect plus a late positivity on the noun for the higher-level, verb–noun mismatch condition based on Zhou et al. (2010) and studies on German which manipulated compatibility between verb and noun separated by a prepositional phrase structure (Gunter et al., 1997) or between verb and noun within a object complement clauses (Friederici and Frisch, 2000).

Crucially, we predicted an N400 effect plus a late positivity on the noun for the condition with combined violations involving both adjective–noun mismatch and verb–noun mismatch. According to Hald et al. (2007) and Zhou et al. (2010), we expected the combined violations to engender an equally large or larger N400 effect as compared with adjective–noun mismatch or verb–noun mismatch. If semantic processes at different levels of syntactic hierarchy interact or act in concert, the N400 effect for the combined condition would be smaller or larger than the sum of the two single mismatches. Moreover, according to Zhou et al. (2010), we expected a larger late positivity for the combined violations than for the verb–noun mismatch condition. This result could indicate that the semantic integration process at the higher level (i.e., between verb and noun), which dominates in sentence comprehension, could be modulated by the difficulty of semantic integration at the lower level (Zhou et al., 2010).

2. Results

2.1. Behavioral results

On average, the accuracy rate for sentence semantic acceptability judgment was 91% for the baseline condition, 91% for the adjective–noun mismatch condition, 94% for the verb–noun mismatch condition and 95% for the double mismatch condition. An ANOVA with adjective–noun congruency and verb–noun congruency as two within-participant factors revealed a main effect of verb–noun congruency, $F(1, 17) = 18.42$, $p < 0.01$. Sentences involving verb–noun mismatch were judged more accurately than sentences with the matched verb–noun combinations. Neither the main effect of adjective–noun congruency nor the interaction between adjective–noun congruency and verb–noun congruency reached significance, both $F(1, 17) < 1$.

2.2. ERP results

As shown in Fig. 2 on the object noun, all the mismatching conditions elicited an N400 effect followed by a late positivity effect as compared with the baseline. These effects appear to be larger for the double mismatch condition than for the two single mismatch conditions.

2.2.1. N400 effect in the 350–450 ms time window

The omnibus ANOVA involving adjective–noun congruency at the lower level, verb–noun congruency at the higher level and topographical variables revealed a main effect of adjective–noun congruency on midline, $F(1, 17) = 15.74$, $p < 0.01$, and on lateral, $F(1, 17) = 18.45$, $p < 0.01$, suggesting that larger N400 responses were elicited on the object noun by sentences with adjective–noun mismatches [−1.07 μV for midline, −0.78 μV for lateral] than by sentences with matching ones [0.23 μV for midline, 0.34 μV for lateral]. ANOVA also revealed a main effect of verb–noun congruency on midline, $F(1, 17) = 15.37$, $p < 0.01$, and on lateral, $F(1, 17) = 20.15$, $p < 0.01$, suggesting that larger N400 responses were elicited on the object noun by sentences with verb–noun mismatches [−1.07 μV for midline, −0.84 μV for lateral] than by sentence with matching ones [0.23 μV for midline, 0.39 μV for lateral]. Moreover, adjective–noun congruency and verb–noun congruency interacted on midline, $F(1, 17) = 5.08$, $p < 0.05$, and on lateral, $F(1, 17) = 4.28$, $p = 0.05$.

Further analysis was conducted to investigate the interaction. The effect of adjective–noun congruency was significant when the object noun was congruent with the verb (adjective–noun mismatch vs. baseline), $F(1, 17) = 18.12$, $p < 0.01$, on midline, $F(1, 17) = 17.35$, $p < 0.01$, on lateral, suggesting that sentences with single adjective–noun mismatch [−0.65 μV for midline, −0.40 μV for lateral] elicited larger N400 responses as compared with sentences in the baseline condition [1.11 μV for midline, 1.17 μV for lateral]. The effect of adjective–noun congruency was marginally significant when the object noun was incongruent with the verb (double mismatch vs. verb–noun mismatch), $F(1, 17) = 3.22$, $0.05 < p < 0.1$, on midline, $F(1, 17) =$

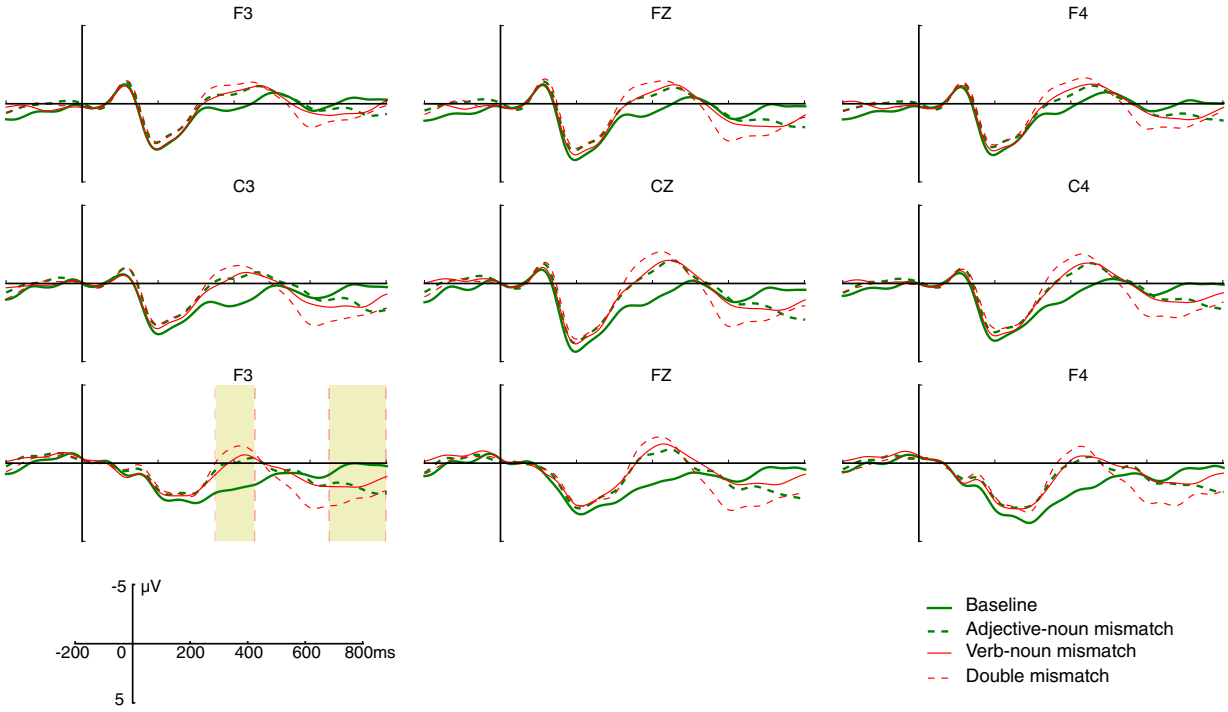

Fig. 2 – The ERP grand-average waveforms from −200 pre-onset to 800 ms post-onset of the critical object noun (with 0–100 ms post-stimulus waveform for baseline correction) on 9 representative electrodes.

3.78, $0.05<p<0.1$, on lateral, suggesting that sentences with double mismatch [−1.40 μV for midline, −1.17 μV for lateral] elicited a larger N400 responses as compared with sentences with verb–noun mismatch [−0.74 μV for midline, −0.50 μV for lateral], although the N400 effect [−0.66 μV for midline, −0.67 μV for lateral] was much smaller than the effect in verb–noun congruent condition [−1.76 μV for midline, −1.57 μV for lateral]. These findings suggested that the lower-level congruency still has impact upon brain responses to the object nouns when the higher-level integration process for the verb and the noun is in difficulty.

On the other hand, the effect of verb–noun congruency was significant when the object noun was congruent with adjective (verb–noun mismatch vs. baseline), $F(1, 17)=17.66$, $p<0.01$, on midline, $F(1, 17)=18.42$, $p<0.01$, on lateral, suggesting that sentences with the mere verb–noun mismatch elicited larger N400 responses as compared with sentences in the baseline condition. The effect of verb–noun congruency was also significant when the object noun was incongruent with the local adjective (double mismatch vs. adjective–noun mismatch), $F(1, 17)=5.09$, $p<0.05$, on midline, $F(1, 17)=6.45$, $p<0.05$, on lateral, suggesting that sentences with double mismatch elicited a larger N400 responses as compared with sentences with adjective–noun mismatch. Similarly, the N400 effect for verb–noun congruency was more pronounced when the adjective was congruent with the noun [−1.85 μV for midline, −1.67 μV for lateral] than when they are incongruent [−0.75 μV for midline, −0.77 μV for lateral]. These findings may be taken to suggest that the higher-level congruency affects the processing of the object noun even when the lower-level process is in difficulty.

Direct comparison between adjective–noun mismatch and verb–noun mismatch conditions, involving sentence type and topographic factors, showed no effect of sentence type, $F(1, 17)<1$, for both midline and lateral, suggesting that the two types of mismatches elicited equal N400 responses. Moreover, when we added the N400 effects in the two single mismatch conditions together [−3.61 μV for midline, −3.24 μV for lateral] and compared the summed effects with the N400 effect [−2.51 μV for midline, −2.34 μV for lateral] in the double mismatch condition, we found that the latter was significantly smaller than the former, $F(1, 17)=5.08$, $p<0.05$ on midline and $F(1, 17)=4.28$, $p=0.05$ on lateral.

2.2.2. *Late positivity effect in the 650–800 ms time window*

The omnibus ANOVA revealed a significant main effect of adjective–noun congruency on midline, $F(1, 17)=8.93$, $p<0.01$, and on lateral, $F(1, 17)=7.72$, $p<0.05$, suggesting that sentences with local adjective–noun mismatch [1.76 μV for midline, 1.51 μV for lateral] elicited larger positive responses than the match sentences [0.88 μV for midline, 0.71 μV for lateral]. This adjective–noun congruency effect interacted with scalp region on lateral, $F(2, 34)=4.14$, $p<0.05$, with the congruency effect being significant in the central and posterior regions, $F(1, 17)=5.37$, $p<0.05$, and $F(1, 17)=5.77$, $p<0.05$, respectively, but not in the anterior regions, $F(1, 17)=2.97$, $p>0.1$.

The main effect of verb–noun congruency was also significant on midline, $F(1, 17)=8.16$, $p<0.01$, and on lateral, $F(1, 17)=7.92$, $p<0.01$, suggesting that sentences with verb–noun mismatch [1.72 μV for midline, 1.48 μV for lateral] at the higher-level elicited larger positive responses than the match sentences [0.91 μV for midline, 0.73 μV for lateral]. There was no interaction between

verb–noun congruency and topographic variables, $F(2, 34)<1$, suggesting that this positivity effect was broadly distributed.

There was no significant interaction between lower-level adjective–noun congruency and higher-level verb–noun congruency in this window either, $F(1, 17)<1$, suggesting that two congruency effects were additive in the double mismatch condition. It appeared also on Fig. 2 that the onset of the late positivity effect for the double mismatch condition was about 50 ms earlier and was larger in magnitude than the effect for either of the two single mismatch conditions. Moreover, it appeared that the late positivity effect lasted longer for the adjective–noun mismatch and double mismatch than for the verb–noun mismatch. However, given that words after the critical object-noun were not matched across conditions, we did not carry out further analysis.

3. Discussion

The main purpose of this study was to investigate neural responses to multiple constraints in semantic integration processes at different levels of a hierarchical structure during German sentence comprehension. In sentences with the structure "subject noun + verb + article/determiner + adjective + object noun + prepositional phrase", the object noun was constrained simultaneously by adjective at the lower level or by verb at the higher level. The semantic congruency between adjective and object noun and between verb and object noun were manipulated. Results demonstrated that, as compared with the baseline condition, all mismatch conditions elicited an N400 effect followed by a late positivity effect. The N400 effect for the double mismatch condition was larger than the effect for either the adjective–noun or the verb–noun mismatch condition but was smaller than the sum of the effects for two single mismatch conditions. The late positivity effect was also larger in the double mismatch than in either of the single mismatch conditions. These findings, partially replicating the previous study on Chinese (Zhou et al., 2010), may be taken as evidence for a general mechanism for semantic integration of target words constrained simultaneously by sentence constituents at different levels of syntactic hierarchy. In the following paragraphs, we will focus on two issues: 1) the N400 effect and semantic integration at different hierarchical levels; and 2) the late positivity effect and the coordination process across syntactic levels.

3.1. *The N400 effect and semantic integration at different hierarchical levels*

Consistent with the previous finding of an N400 effect for the violation of a lower-level constraint between adjective and the object noun (Hagoort, 2003; Martín-Loeches et al., 2006), a significant N400 was found in the comparison between the adjective–noun mismatch and the baseline conditions. Although previous studies (e.g. Filik and Leuthold, 2008; Nieuwland and Van Berkum, 2006) on semantic constraints at different representation levels demonstrated that the N400 effect for the local semantic incongruence could disappear when the discourse (global) context is strongly supportive, this study, by manipulating semantic constraints at different levels of syntactic hierarchy, demonstrated that semantic mismatch at the lower level still elicited an N400 effect even when the verb and the object noun at the higher level was congruent, replicating our previous study on Chinese (Zhou et al., 2010) where the lower level incongruence between classifier and noun led to a N400 effect irrespective of the congruency at the higher level. Similarly, consistent with our previous study (Zhou et al., 2010), the incongruence between verb and noun at the higher level also engendered an N400 effect, despite the fact that the object noun was embedded in a local, coherent phrase. This finding suggests that the effect of semantic mismatch at either level cannot be overridden by the process at the other level. In other words, the disruption of one semantic process at a level of syntactic hierarchy cannot block completely the process at another level. Importantly, the N400 effect (and sentence acceptability rating) showed a statistical interaction between the adjective–noun congruency at the lower level and the verb–noun congruency at the higher level, with the effect for the double mismatch condition being larger than the effect for either of the single mismatch condition. This finding was consistent with Hald et al. (2007), in which a larger N400 effect was observed when both discourse congruence and world knowledge were violated, than when only one constraint was violated.

There could be three possible accounts for this pattern of effects. The first account assumes that this pattern might simply reflect the overall semantic plausibility/acceptability of the sentence (Van de Meerendonk et al., 2010). In Van de Meerendonk et al. (2010), sentences continued with words that resulted in either mild (3 on a 5-point Likert scale, compared with the baseline of 5) or strong (1 on a 5-point Likert scale) implausibility of the whole sentence engendered increased N400 responses, as compared with the correct sentences. The N400 effect was larger for sentences with strong implausibility than for those with mild implausibility. It seems that this account can explain here the larger N400 in the double mismatch condition than in either of the single mismatch conditions and the larger N400 in the single mismatch conditions, as compared with the baseline condition. However, this account cannot explain why the N400 effect did not differ between the verb–noun mismatch and the adjective–noun mismatch conditions, given that the verb–noun mismatch condition (2.26 on the 5-point Likert scale) was rated as being significantly less plausible than the adjective–noun mismatch condition (2.97). Further analysis comparing 40 most acceptable sentences [3.03 for their mean acceptability] with 40 least acceptable sentences [2.08 for their mean acceptability] from the two single mismatch conditions yielded no significant differences in the N400 amplitudes, confirming that the N400 amplitude does not necessarily reflect the overall acceptability rating.

The second account might link the N400 effects here with the lexical access hypothesis of the N400 (Kutas and Federmeier, 2000, 2011; Lau et al., 2008, 2009). This hypothesis claims that semantic information of words can be pre-activated by predictive sentence context and semantically associated prime words, and the magnitude of the N400 may reflect the difficulty of lexical access. Studies supporting this hypothesis (Federmeier et al., 2007; Lau et al., 2008; Wlotko and Federmeier, 2007) generally observed a larger N400 on words that were less expected by the preceding sentence context (defined by the cloze probability of a

word as a potential continuation of the sentence fragment) than on the expected ones. However, results were less consistent for semantically associated individual words. A group of works revealed reduced N400 for lexical associates embedded in sentence-like but meaningless word strings (*After fixing the movie she found they should have killed left instead of right at the pot.* Schwartz, et al., 2003; Van Petten, 1993; Van Petten, et al., 1997), but such a reduction in N400 could be absent when the lexical associates were presented in a sentence context (Van Petten et al., 1999). Moreover, one study reported that words unexpected in a sentence context could elicit a reduced N400 effect when they are semantically associated to the expected words than when they are not (Federmeier and Kutas, 1999). In the present study, the target nouns were unexpected in the sentence context for all mismatch conditions as suggested by the roughly zero cloze probabilities (see Table 2). We also tested a group of eight participants on the lexical association between the target noun and the previous individual words in sentence context (see also Camblin et al., 2007). The participants were asked to generate a word which first came to their mind after reading the prime words (i.e. verb or adjective). The result showed only a small chance for the target noun to be successfully produced after reading the adjective prime (4.8% for the congruent condition, 0 for the incongruent condition) or the verb prime (8.4% for the congruent condition, 0 for the incongruent condition). Given the non-predictive sentence context and the rather weak semantic association between verb/adjective and noun, the lexical access hypothesis seems unattractive since it is hard to account for the reduced N400 effect in the single mismatch condition as compared with the double mismatch condition.

The third account assumes that the N400 reflects the process of integrating the current word with the previous context to construct a coherent representation. An enlarged N400 indicates a more difficult or more effortful integration process. In the double mismatch condition, the object noun was semantically incongruent with either the preceding adjective or the more distant verb, and hence both the local semantic process and the higher level semantic process were interrupted, eliciting the enlarged N400. Here the two semantic processes could be parallel and independent from each other, but the N400 responses resulted from the interruption of the two semantic processes were combined or merged in an interactive manner. Alternatively, the two semantic processes themselves were conducted interactively. In this way, the semantic process at either level was not completely blocked by the process at the other level, which can be reflected by a larger N400 for the double than for either single mismatch (see also Hald et al., 2007). It seems that the present data do not allow us to choose between these two alternatives although the latter hypothesis would be preferred if we take into account the findings in Zhou et al. (2010). Stronger evidence could come from studies that take advantage of the characteristics (e.g., case-marking) of the German language (see below).

Table 2 – Mean scores of semantic acceptability ratings and cloze probabilities of the object noun for each critical condition.

Sentence type	Mean acceptability (SD)	Cloze probability (%)
Correct	4.86 (0.08)	27
Adjective–noun mismatch	2.97 (0.76)	2
Verb–noun mismatch	2.26 (0.73)	0
Double mismatch	1.66 (0.55)	0

3.2. *The late positivity and the coordination process across syntactic levels*

The present study observed the increase of the late positivity in all the three mismatch conditions, with the effect in the double mismatch being larger than the effect in either of the two single mismatch conditions. Moreover, it seems that the P600 effect appeared earlier in time course than the effect in a single mismatch condition (see Fig. 2). These findings partially replicated Zhou et al. (2010).

We interpret this late positivity as reflecting an effort to coordinate parallel semantic processes across different levels of syntactic hierarchy (Sitnikova et al., 2008; Zhou et al., 2010). This positivity has also been observed for semantic manipulations in sentences with complex composite as object complement clause (Friederici and Frisch, 2000) or in sentences in which an adverbial clause (Gunter et al., 1997) or a preposition phrase (Hoeks et al., 2004) was inserted between the mismatching noun and the verb, but not in sentences in which the verb and the noun forms a local, simple phrase (Hahne and Friederici, 2002; Jiang et al., 2009; Li et al., 2006; Ye et al., 2007). Adjectives, which violated the hierarchical order in adjective sequences (e.g. *Jennifer rode a grey huge elephant*; Kemmerer et al. 2007), also engendered such positivity. All the critical words mismatching semantic constraints were embedded in hierarchical constructions in these studies. But before elaborating how the coordination process takes place in online sentence comprehension, we need to rule out several alternative accounts for the positivity effect.

Considering the temporal dynamics and the topographic distribution, one might relate the positivity observed here to the P600 effect typically observed in previous studies with syntactic or semantic manipulations (see Gouvea et al., 2010; Kaan et al., 2000; Kolk and Chwilla, 2007; Kuperberg, 2007 for reviews). In the present study, all the sentences were syntactically intact and unambiguous. For sentences with masculine singular nouns, the syntactic structure was determined by the case marker. For sentences with feminine or neuter nouns, despite the ambiguity in the case marking (accusative vs. nominative), the thematic requirement of the verb preceding the noun ensured the morph-syntactic role of the noun (see Friederici and Frisch, 2000). Clearly, the positivity effect in this study was not syntactic but semantic in nature.

Semantic P600s have usually been found on words violating the verb selectional restrictions on the animacy (e.g. with stronger verb–noun association, *For the breakfast, the eggs would eat…*, Kuperberg et al., 2003, 2006; with less stronger verb–noun association, *For the breakfast, the eggs would plant…*, Kuperberg et al., 2007) or on words which violated the constraints of thematic order (e.g. *The poacher that the fox hunted…*, Kolk et al., 2003; Van Herten et al., 2005, 2006; Vissers

et al., 2007). Three accounts have been offered to explain the semantic P600. The first account argued that the semantic P600 reflected continued processing after detecting a conflict between competing semantic representations derived from the rule-based and the heuristics-based (or thematic-based) analyses (see Kuperberg, 2007 for a review). It is suggested that the violation of animacy or thematic order constraints triggered a continued process to reanalyze the morphosyntactic structure of verb (e.g. to change active voice into passive voice) or to reassign thematic roles (Kim and Osterhout, 2005; Kuperberg et al., 2003, 2006, 2007). In this study, although mismatch at the higher level between object noun and verb elicited a late positivity effect, the object noun did not violate the animacy constraint of the verb. Moreover, the lower level mismatch between adjective and object noun also elicited a late positivity effect. Therefore, this thematic view of semantic P600 cannot easily account for the late positivity effects in this study.

The second account of the semantic P600 assumes that it reflects a monitoring process for potential errors in the face of processing failure (Kolk and Chwilla, 2007; Van de Meerendonk et al., 2010; Vissers et al., 2007, 2008). In this way, the P600 effect might be consequential of a general executive control mechanism (see Ye and Zhou, 2009 for review), which is involved in resolving conflicts or in-determinacy in language perception. Supporting evidence came from the P600 effect on words violating the plausibility of an event (e.g. in semantically reversible sentences with competing sentence representations; *The cat that fled from the mice ran across the room*, Kolk et al., 2003; Hoeks et al., 2004; Van Herten et al., 2006; Vissers et al., 2007) and on words violating the expectancy built upon a preceding sentence context (e.g., conflicts between prediction-based word representation and the actual word input; Nieuwland and Van Berkum, 2005; Van de Meerendonk et al., 2010). It is suggested that the strength of the un-expectedness determines the presence of a P600 effect. Highly unexpected words, that are highly implausible in the context, trigger a monitoring process for potential error and elicits a biphasic N400-P600 effect; slightly unexpected words do not produce strong conflict, eliciting only the N400 effect (Van de Meerendonk et al., 2010; see also Federmeier et al., 2007). In the present manipulation, however, the positivity was clearly shown in the single mismatch condition, despite the fact that the single mismatch here can be viewed, in terms of acceptability rating, as similar to the mild implausibility in Van de Meerendonk et al. (2010) who did not observed a P600 effect for this condition.

The third account of the semantic P600 (preceded by an N400 effect) takes it as reflecting a categorization of the sentence well (ill)-formedness in a certain experimental environment (Bornkessel-Schlesewsky et al., 2011; Bornkessel-Schlesewsky and Schlesewsky, 2008; Frenzel et al., 2011). This P600 effect usually appears in an "error-detection" task in which the well-formedness of a sentence needs to be verified. Indeed, in our task the semantic well-formedness of each sentence had to be verified in order to make the acceptability judgment. However, this account does not predict this positivity effect to be modulated by the number of mismatches, since detection of mismatch at one level is sufficient for a correct categorization response.

We propose that the late positivity effect here reflects an effort to coordinate parallel semantic integration processes at lower- and higher-levels and to build up an integrated sentence representation (Zhou et al., 2010). On encountering difficulty of semantic integration at one level in a hierarchical structure, the system may redeploy the attentional or processing focus from the level encountering difficulty to another level in search for additional information or constraints that might mitigate the difficulty and help to construct a coherent representation. More such attempts may take place when semantic processes at both the higher- and lower-level meet difficulty, resulting in a more positive P600. This coordination process may take place largely in an automatic fashion, although in the present experiment we did emphasize reading for comprehension. Thus the increased effect may reflect the increased effort to coordinate the semantic integration processes at different hierarchical levels.

Clearly, this account is in line with the present findings. Here the coordination procedure was initiated by the semantic integration difficulty at either the higher- or lower-level, an argument different from the suggestion that the coordination process is dominated by the difficulty in the higher-level semantic integration process in reading Chinese sentences (Zhou et al., 2010).

There could be different explanations for why we obtained the P600 effect for mismatch at either the higher- or lower-level whereas Zhou et al. (2010) did not find this effect for the lower-level classifier–noun mismatch in Chinese. The first possibility is that due to the availability of prenominal relative clauses in Chinese, the thematic role of the critical noun might be temporarily ambiguous, as it could be assigned a subject role for a possible relative clause, thus providing a "way out" for the incongruence between the classifier and the object noun (Bornkessel-Schlesewsky et al., 2011; Wu et al., 2009). This potential biclausal analysis might have attenuated or delayed the P600 response elicited by the lower-level classifier–noun mismatch. The second possibility is that a sentence-final wrap-up process, which elicits a negativity effect (Hagoort, 2003; Molinaro et al., 2008), may have overshadowed the potential positivity effect on the object noun since this target word was at the sentence-final position. In this study, however, the target words were always at a sentence-medial position.

The present study may be subject to a few limitations. In particular, to make the data comparable and the cross-language comparison possible, we have deliberately used German sentences with the structure similar to the Chinese we examined before. In this way, we did not take the advantage of the characteristics of case-marking and flexible word order in German. It is for further investigation whether the present pattern of effects for multiple semantic constraints can be observed when word order is the more typical subject–object–verb (SOV) or non-canonical object–subject–verb (OSV) in German and the brain potentials are measured on the verb rather on the object noun. As suggested by Bornkessel-Schlesewsky et al. (2011), Philipp et al. (2008), Schlesewsky and Bornkessel (2004) and Wang et al. (2009), cross-language differences such as case marking may play important roles in argument hierarchizing.

Another limitation is that we focused on a particular type of semantic processes in sentence comprehension: selectional restrictions between sentence constituents. However, there

are other types of semantic processes that may have different neuro-cognitive mechanisms (e.g., the semantic compositional operations; Pylkkänen et al., 2004; 2009). Further studies are needed to investigate how other types of semantic process would manifest in multiple constraints during sentence comprehension.

4. Conclusion

By using German sentences with a hierarchical structure "subject noun + verb + article/determiner + adjective + object noun + prepositional phrase" and by recording ERP responses to the object noun which matched or mismatched the preceding adjective and/or the verb, a biphasic pattern of an N400 effect followed by a late positivity effect was observed for sentences with either lower- or higher-level mismatch or with double mismatches compared with correct sentences. Both the N400 effect and the late positivity effect were larger for the double mismatch condition than for either of the single mismatch conditions. Together with our earlier study on Chinese (Zhou et al., 2010), these findings demonstrate cross-language mechanisms underlying processing multiple semantic constraints in a hierarchical structure during sentence comprehension.

5. Experimental procedures

5.1. *Participants*

Twenty right-handed native speakers of German (10 female, mean age = 23.4 years), who were visiting students at Peking University, were paid to participate in the ERP experiment. All of them had normal or corrected-to-normal vision. Data from one participant was excluded due to lower accuracy in the acceptability judgment task and data from another participant was missing due to equipment malfunction. This study was approved by the Academic Committee of the Department of Psychology, Peking University.

5.2. *Materials*

Fifty-two concrete nouns were selected as object nouns, with each used in a quartet of experimental sentences, resulting in a total of 208 sentences (see Table 1). Each sentence took the structure of "subject noun + verb + article/determiner + adjective + object noun + prepositional phrase", which is commonly used in German, with the object noun as the crucial target. Semantic congruency of adjective–noun, verb–noun and verb–adjective were all intact in the baseline condition. The mismatch conditions were created by replacing a new adjective at lower-level (the adjective–noun mismatch), a new verb at higher-level (the verb–noun mismatch), or both (the double mismatch). Each sentence began with a different person name. All the verbs were transitive and required an animate noun as agent and 92% of them required an inanimate as patient. None of the verbs were object-experiencer verbs and none of them can select a second indirect, dative object. All the subject nouns were common names of a person and 92% of the object nouns were inanimate, manipulable singular-formed entities. Only a small portion of object nouns (19 of 52) were masculine, with their cases unambiguously marked as accusative. The others were feminine or neuter, with cases that can indicate the role of the noun as either nominative subject or accusative object. However, as evaluated by two native German speakers who did not participate in the ERP study, all the sentences had one syntactic structure with no structural ambiguity, as indicated above. In such way, we made the entire set of critical material largely comparable to the material used in our previous Chinese study. The object nouns were always followed by a prepositional phrase. The mismatching object nouns did not violate the animacy constraints of the preceding verbs or adjectives. No agreement mismatch in gender or case occurred between verb, article, adjective and object noun. We also included 104 filler items to balance the number of correct and incorrect sentences and to create a greater variety of sentence structures. One third of them had the same structure as the critical sentences except that the adjectives were omitted (e.g. "subject noun + verb + object noun + prepositional phrase", *Laura kritisiert ihren Mann nur im Privaten/Laura criticizes her husband only in private*). Another third of the filler sentences used an intransitive structure, in which both the adjective and the object were dropped (e.g., "subject noun + verb + prepositional phrase", *Janus arbeitet lieber in der Bibliothek als Zuhause/Janus prefers to work in the libary rather than at home*). In the remaining third, a subordinate clause was appended to the main intransitive structure (e.g. "subject noun + verb [+ subordinating conjunction + subject noun + object noun + verb]$_{clause}$", *Felix weiß, wie man im Hintergrund Strippen zieht/Felix knows how to pull the strings in the background*).

5.3. *Pretests*

A sentence acceptability rating and a sentence completion test were conducted for the critical stimuli (see Table 2). The sentence acceptability rating was to examine whether the mismatching sentences were indeed unacceptable. Eighteen subjects, who did not take part in the ERP experiment, were asked to rate each sentence on a 5-point Likert scale (with 1-point indicating extremely unacceptable and 5-point indicating extremely acceptable). The repeated measures ANOVA involving adjective–noun congruency and verb–noun congruency as two within-participant factors revealed a main effect of adjective–noun congruency, $F(1, 17) = 453{,}84$, $p < 0.001$, a main effect of verb–noun congruency, $F(1, 17) = 517.69$, $p < 0.001$, and also an interaction between the two, $F(1, 17) = 33.86$, $p < 0.001$. Pair-wise comparison between each two of the four conditions revealed lower acceptability scores for mismatching conditions than for the baseline, $ps < 0.001$, lower score for double mismatch than for single mismatches, $ps < 0.001$, and lower score for single verb–noun mismatch than for single adjective–noun mismatch, $ps < 0.001$ (see Table 2).

The sentence completion study was to examine the cloze probability of the target word in each type of sentences. A group of nineteen participants were asked to complete sentence fragments of "subject noun + verb + article/determiner + adjective" with a most appropriate word. The average probability of the target word was 27% in the baseline condition and was zero or approaching zero in the other three mismatch condition (Table 2). The average probability of the most expected word was 38.6% for

sentence fragments in the baseline condition, 24.9% in the adjective–noun mismatch condition, 30.4% in the verb–noun mismatch condition, and 28.1% in the double mismatch condition.

5.4. *Procedure*

Participants were seated comfortably in a dimly-lit and sound-attenuating booth. They were about 100 cm from a computer screen. The sentence trial began with a fixation point which was presented for 500 ms, followed by a 200 ms blank interval. The sentence stimuli were presented word-by-word in serial visual presentation mode at the center of the screen. Each word remained for 400 ms on the screen and was followed by a 400 ms blank screen interval (Zhou et al., 2010). Participants were instructed to read each sentence attentively. At the end of each sentence, a response cue of "?" appeared on the screen for 2000 ms. Participants were asked to judge the semantic plausibility of the preceding sentence by pressing "yes" or "no" button on a joystick with their left or right hand. The assignment of button press was counter-balanced across participants. They were informed prior to the experimental session that half of the sentences were well-formed while the other half was not.

The experimental and filler sentences were pseudo-randomized for each participant, with the restriction that no more than three sentences from the same condition were presented consecutively and each two sentences within the same quadrant were separated by 30 sentences from other quadrants (Hahne and Friederici, 2002). Each participant was given a different sequence of the test sentences. Sentences were divided into six blocks and participants had a break between blocks. Before the experimental session, 12 sentences were given as practice trials. The practice went through the same procedures as the formal experiment, except that the accuracy feedback was given after each response.

5.5. *EEG recording*

EEGs were recorded from 62 electrodes mounted on an elastic cap (NeuroScan Inc., Herndon, Virginia, USA) according to the positions specified by the International 10/20 system. The vertical electrooculogram (VEOG) was recorded from electrodes located above and below the left eye and the horizontal EOG (HEOG) from electrodes placed 1.5 cm lateral to the left and right external canthi. All electrode recordings were referenced online to the left mastoid, and re-referenced offline to the linked mastoids. Electrode impedance was kept below 5 kΩ. The EEG and EOG were amplified using a 0.05–100 Hz band pass and digitized at 500 Hz.

5.6. *Data analysis*

Trials contaminated by excessive movement artifacts (mean voltage exceeding ±70 μV) or incorrectly judged were excluded before averaging. On average, above 85% trials were accepted for statistical analysis [44 trials for the baseline, 44 for the adjective–noun mismatch, 44 for the verb–noun mismatch and 45 for the double mismatch].

ERPs for each participant and for each experimental condition were epoched from 200 ms pre-onset to 800 ms post-onset of the object noun. The first 100 ms interval post-onset of the object noun was chosen for baseline correction. The lexical difference preceding the critical object noun across experimental conditions (adjective–object noun mismatching vs. adjective–object noun matching) made it undesirable to use pre-stimulus EEG activity for the baseline correction (see similar reasoning and operation in Friederici et al., 1996; Hahne and Friederici, 1999; 2002; Neville, et al., 1991). The early exogenous component (e.g. N1) generally would not be affected by effects spilled over from the preceding word (see Baggio et al., 2008; Jiang et al., 2009). In fact when the average EEG in the 100 ms interval pre-onset of the object noun was used for baseline correction, the same pattern of ERP responses was obtained. Here only ERP results with 100 ms interval post-onset baseline correction were reported. A 30 Hz low-pass filter was applied to remove artifacts due to power line noise.

Repeated measures ANOVAs were conducted on average ERP amplitudes time locked to the object noun. Two time windows were selected based on visual inspection and the previous study (Zhou et al., 2010): 350–450 ms for the N400 effect, and 650–800 ms for the late positivity effect. Statistics were performed on midline and lateral sites separately. For the midline analysis, ANOVAs were performed with three within-participant factors: adjective–noun congruency at the lower level (congruent vs. incongruent), verb–noun congruency at the higher-level (congruent vs. incongruent) and electrode (FZ, FCZ, CZ, CPZ, PZ, POZ and OZ). For the lateral analysis, the topographic factors were hemisphere (left vs. right) and region (anterior vs. central vs. posterior). Thus there were six regions of interest (ROI), each with six representative electrodes: left anterior (F1,F3, F5,FC1, FC3, FC5), left central (C1,C3, C5,CP1, CP3, CP5), left posterior (P1,P3, P5,O1, PO3, PO5), right anterior (F2,F4, F6,FC2, FC4, FC6), right central (C2,C4, C6, CP2, CP4, CP6), right posterior (P2,P4, P6, O2,PO4, PO6). When there was interaction between adjective–noun congruency and verb–noun congruency, planned comparisons were performed. Additional ANOVAs involving sentence type and topographic factor(s) were performed to examine the difference between the single adjective–noun mismatch and the single verb–noun mismatch conditions. The Greenhouse–Geisser correction was applied when appropriate (Greenhouse and Geisser, 1959).

Acknowledgment

This study was supported by grants from the Natural Science Foundation of China (30970889) and from National Basic Research Program of China (973 Program: 2010CB833904) to Xiaolin Zhou, and grants from China Postdoctoral Science Foundation (20100480150) to Xiaoming Jiang. Yang Zhang, Xiaoming Jiang and Henrik Saalbach equally contributed to this work. We thank three anonymous reviewers for their constructive comments and suggestions concerning the earlier versions of the manuscript.

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