Research Report

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

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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

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).

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

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$_{perfective}$ that ben$_{book\ classsifier}$ teacher]" could be easily edited out by expanding the sentence to "Xiaoming mai le na ben laoshi tuijian de shu [Xiaoming bought$_{perfective}$ that ben$_{book\ classsifier}$ 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

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 $F(1, 17) < 1$.

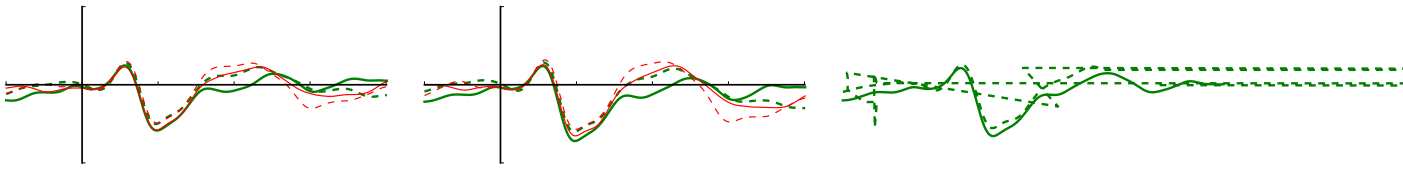
2.2. ERP results

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, $F(1, 17) =$



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

et al., 2007). It seems that the present data do not
o choose between these two alternatives although
hypothesis would be preferred if we take into
e findings in Zhou et al. (2010). Stronger evidence
e from studies that take advantage of the charac-
.g., case-marking) of the German language (see

e late positivity and the coordination process across evels

nt study observed the increase of the late positivity
three mismatch conditions, with the effect in the
smatch being larger than the effect in either of the
mismatch conditions. Moreover, it seems that the
appeared earlier in time course than the effect in a
match condition (see Fig. 2). These findings partially
Zhou et al. (2010).

erpret this late positivity as reflecting an effort to
parallel semantic processes across different levels
c hierarchy (Sitnikova et al., 2008; Zhou et al., 2010).
vity has also been observed for semantic manipu-
sentences with complex composite as object
nt clause (Friederici and Frisch, 2000) or in sen-
which an adverbial clause (Gunter et al., 1997) or a
n phrase (Hoeks et al., 2004) was inserted between
tching noun and the verb, but not in sentences in
verb and the noun forms a local, simple phrase
d Friederici, 2002; Jiang et al., 2009; Li et al., 2006; Ye
). Adjectives, which violated the hierarchical order
e sequences (e.g. *Jennifer rode a grey huge elephant*;
et al. 2007), also engendered such positivity. All the
rds mismatching semantic constraints were em-
hierarchical constructions in these studies. But
orating how the coordination process takes place in
tence comprehension, we need to rule out several
accounts for the positivity effect.

ering the temporal dynamics and the topographic
n, one might relate the positivity observed here to
effect typically observed in previous studies with
r semantic manipulations (see Gouvea et al., 2010;
, 2000; Kolk and Chwilla, 2007; Kuperberg, 2007 for
In the present study, all the sentences were
ly intact and unambiguous. For sentences with
singular nouns, the syntactic structure was deter-
the case marker. For sentences with feminine or
uns, despite the ambiguity in the case marking
e vs. nominative), the thematic requirement of the
ding the noun ensured the morph-syntactic role of
evious)gvs.8.272160TD.013Tc[Fererie a-85.5(n5.1(d)-659.7Fm)
but semantic
antic

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

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).

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