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Involvement of cognitive control in sentence comprehension: Evidence from ERPs

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ABSTRACT

This study investigates the reanalysis processes as a consequence of conflict between incompatible sentential representations in sentence comprehension. Using the event-related potential (ERP) technique, we examined the situation in which the sentential representation built upon world knowledge (i.e., the plausibility heuristic) conflicts with the one built upon syntactic rules (i.e., the syntactic analysis). We found that sentence processing is constrained both by the complexity of syntactic structure and by the reader's cognitive control ability. For readers with higher control abilities, as measured by the Stroop task, a sustained positivity was observed between 350 and 850 ms when conflicts occurred in complex (i.e., passive) sentences, whereas an anterior negativity was observed between 300 and 600 ms when conflicts occurred in simple (i.e., active) sentences. For readers with lower control abilities, however, brain potentials were not affected by the complexity of syntactic structure, with a sustained positivity obtained between 350 and 750 ms for conflicts occurring in both active and passive sentences. These results suggest that the mechanisms of cognitive control are involved in the reanalysis processes to resolve conflict between incompatible sentential representations. The sustained positivity is possibly associated with detection and resolution of representational conflict, while the anterior negativity is associated with suppression of inappropriate representation or response tendency.

1. Introduction

During sentence comprehension, syntactic and semantic processes take place at least partially in parallel and operate according to syntactic or semantic rules respectively (Friederici and Weissenborn, 2007; Jackendoff, 2002, 2007; Kuperberg, 2007; Piñango, 2006). Syntactic processes assign thematic roles on the basis of morpho-syntactic constraints, concerning the subject-verb agreement and the case marking (i.e., the syntactic analysis, see Friederici, 2002; Friederici and Kotz, 2003; Friederici and Weissenborn, 2007; Kuperberg, 2007). Semantic processes prime a likely meaning on the basis of semantic relationships between content words. One dominant semantic strategy, the plausibility heuristic, treats sentences as unordered lists of words and combines lexical items according to world knowledge (Bever, 1970; Caramazza and Zurif, 1976; Ferreira, 2003; Sanford and Sturt, 2002; Townsend and Bever, 2001). In many cases, the syntactic analysis and the plausibility heuristic conspire toward a coherent sentential representation, leading to an appropriate response. Occasionally, however, they point toward competing and incompatible representations, giving rise to the activation of mutually exclusive action representations (Kuperberg, 2007;

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Novick et al., 2005). For implausible sentences such as "the man bit the dog", the conflict appears between the propositional meaning deriving from the plausible heuristic (i.e., the words man-bite-dog lead to the interpretation that the dog bit the man) and the one resulting from the syntactic analysis (i.e., the man bit the dog).

The conflict between incompatible sentential representations may lead to longer reading times for critical words (e.g., "the dog", see Braze et al., 2002; Murray and Rowan, 1998), accompanied by an increase in eye movement regression (Braze et al., 2002; Ni et al., 1998; Rayner et al., 2004) and more errors in answering content questions (Ferreira, 2003). Event-related potential (ERP) studies observed a P600 component with (e.g., Kuperberg et al., 2003, 2006a, 2006b) or without (Kim and Osterhout, 2005; Kolk et al., 2003; Kuperberg et al., 2007; Van Herten et al., 2005, 2006) a preceding N400 effect for implausible sentences as compared with plausible sentences. Although recent neurocognitive models of language processing (e.g., Kim and Osterhout, 2005; Kuperberg, 2007; Kolk and Chwilla, 2007) agree that the P600 here reflects the reanalysis processes as a consequence of conflict between incompatible sentential representations, they diverge in their views concerning the functional characterizations of the reanalysis processes and therefore, the functional significance of the P600.

One assumption is that the reanalysis employs the mechanisms of cognitive control (Kolk and Chwilla, 2007; Novick et al., 2005), which help not only to detect the occurrence of conflict (i.e., conflict monitoring), but also to resolve the conflict by biasing towards the sentential representation that respects the most reliable source of linguistic information (e.g., the syntactic information) (i.e., conflict resolution) (for cognitive control in bilingual language processing, see Rodriguez-Fornells et al., 2002, 2005, 2006). When the conflict appears between incompatible sentential representations, the reanalysis is triggered to check whether the conflict is due to processing error (Kolk and Chwilla, 2007; Van Herten et al., 2006; Vissers et al., 2007) and/or to select one representation among competing alternatives according to the task requirement (Novick et al., 2005; Thompson-Schill, 2005; Zhou et al., submitted for publication). Thus, the P600 may be linked to the reanalysis stage in which the cognitive control system interacts with the language system (Kolk and Chwilla, 2007; Zhou et al., submitted for publication). Moreover, this view assumes that the mechanisms of cognitive control involved in sentence comprehension may be fundamentally similar to those employed in non-parsing conflict tasks (e.g., the Stroop task, see MacLeod, 1991; Stroop, 1935) in that both are responsible for resolving representational conflicts (Novick et al., 2005; Thompson-Schill, 2005; Zhou et al., submitted for publication). Consequently, individual differences in cognitive control ability as measured by non-parsing conflict tasks will predict similar variations in sentence parsing ability, i.e., the ability to adhere to one representation and override competing alternatives (e.g., Novick et al., 2004).

An alternative assumption is that the P600 reflects the reassignment of thematic roles on the basis of morpho-syntactic constraints and therefore, is syntactic in nature (Kuperberg, 2007; Kuperberg et al., 2003, 2006a, 2007). This view assumes that animacy plays an important role in the plausibility heuristic. When encountering implausible sentences (e.g., *at the breakfast, the egg would eat*…), the morpho-syntactic information (e.g., "would eat" rather than "would be eaten") suggests "egg" to be the agent of the action "eat". An alternative assignment, based on the plausibility heuristic and conducted in parallel to the syntactic assignment, determines the thematic role of "egg" (e.g., as the patient of the action "eat") according to the animacy rule (i.e., inanimate entities are mostly patients). When the two processes lead to conflicting results, the syntactic process is continued to construct the thematic relationship according to morpho-syntactic constraints. It is this further syntactic processing that gives rise to the P600, although it is not clear in this view whether the comparison between the outputs of the two parallel processes would manifest in ERP waveforms. Nevertheless, this syntactic view is consistent with previous views that the P600 is the index of syntactic processes (Hagoort et al., 1993, 2003), syntactic repair and reanalysis (Friederici, 1995, 2002; Kaan and Swaab, 2003; Osterhout et al., 1994), or syntactic integration processes in general (e.g., the integration of the moved filler into the phrase structure at the gap point in WH-questions, Fiebach et al., 2002; Kaan et al., 2000).

Apart from the difference in theoretic interpretations of the P600 effect, there is discrepancy between previous ERP findings concerning whether the P600 is preceded by an N400 effect. Studies using active sentences tended to obtain a right lateralized N400 effect (Kuperberg et al., 2006a) or N400 effects over the medial and the lateral sites (Kuperberg et al., 2003, 2006b) preceding the P600 (but see Kim and Osterhout, 2005; Kuperberg et al., 2007), whereas studies using relative clause sentences tended to found no such N400 effect preceding the P600 (Kolk et al., 2003; Van Herten et al., 2005, 2006; Visser et al., 2007). The syntactic view suggests that the processes indexed by the N400 and the P600 are functionally linked (Kuperberg et al., 2003, 2007). Semantic integration, as reflected by the N400, may be attenuated by the cost in processing reflected by the P600. Kolk and colleagues, on the other hand, assume that the absence of the N400 effects in their studies is due to the suspension of the effort to semantic/pragmatically integrate the incoming word into its preceding context once the system detects the existence of conflict between two possible representations (Kolk and Chwilla, 2007; Van Herten et al., 2006; Vissers et al., 2007). However, they did not provide account for the presence of the N400 effect, followed by the P600 effects in some of the studies on pragmatic anomaly sentences (Kuperberg et al., 2003, 2006a, 2006b, 2007) or sentences with strong contextual expectancy (Federmeier et al., 2007; Zhou et al., submitted for publication). There are two possible reasons for the discrepancy concerning the N400 effect. Firstly, differences in ERP observations may result from differences in complexity of syntactic structure, as relative clause sentences are more complex than active sentences in syntax. Previous studies demonstrated that complex sentences (e.g., passive sentences, relative clause sentences) lead to more misrepresentations than simple, active sentences (e.g., Barton and Sanford, 1993; Erickson and Mattson, 1981; Ferreira et al., 2002; Ferreira, 2003; Fillenbaum, 1971; Garnham and Oakhill, 1987; Nieuwland and Van Berkum, 2005; Sanford and Sturt, 2002). Complex structures may decrease the possibility that pragmatic anomalies could be detected, as reflected by the absent N400 effect in relative clause sentences. Secondly, differences in ERP observations may result from individual differences in cognitive control ability. Previous ERP studies found that individuals with high working memory capacities showed a biphasic pattern of P345 and P600 while individuals with low working memory capacities showed no such effect in response to conflict between the preferred sentential representation and the sentential representation supported by the new information in reading garden-path sentences (Friederici et al., 1998, 2001; Mecklinger et al., 1995). By analogy, individuals with different cognitive control abilities may show different ERP patterns in response to conflict between incompatible sentential representations in reading implausible sentences. It is possible that the N400–P600 pattern in the implausible vs. plausible contrast may be due to a mix of individuals who mostly show the N400 effect with individuals who mostly show the P600 effect (Osterhout et al., 2004).

As no consensus has been reached concerning the functional characterizations of the reanalysis processes or the functional significance of the P600 in response to conflict between incompatible sentential representations, this study further investigates this issue from the perspective of syntactic complexity and individual differences. We focus on the situation in which the sentential representation built upon the plausibility heuristic clashes with the one built upon the syntactic analysis. We used implausible sentences with two animate arguments (see Table 1). For the implausible vs. plausible contrast, the cognitive control views (Kolk and Chwilla, 2007; Van Herten et al., 2006; Zhou et al., submitted for publication) predict a P600 which reflects the processes of conflict monitoring and/or conflict resolution. The syntactic view (Kuperberg, 2007; Kuperberg et al., 2003, 2006a) predicts no P600 since there is no violation of animacy in the sentences.

Differing from previous studies, this study explores whether the complexity of syntactic structure and/or the individual differences in cognitive control abilities contribute to the discrepancy in ERP findings. To investigate the effect of syntactic complexity, we employ both active (i.e., simple) and passive (i.e., complex) sentences, resulting in four types of sentences, namely, the active plausible, the active implausible, the passive plausible, and the passive implausible sentences (see Table 1). Given that the N400 effect was observed in previous studies with simple sentences (e.g., Kuperberg et al., 2003, 2006a,b) but not in those with complex ones (e.g., Kolk et al., 2003; Van Herten et al., 2005, 2006), it could be predicted that an N400 effect is more likely to be observed in the active stimuli than in the passive stimuli for the implausible vs. plausible contrast.

Moreover, to investigate the effect of individual differences in cognitive control abilities, we use the color-word Stroop task (MacLeod, 1991; Stroop, 1935) to measure individual's general cognitive control ability and to relate participants' scores in this task to their ERP patterns in the sentence comprehension task. Thus, we group participants according to their sizes of Stroop interference effects, i.e., a high control group with individuals showing smaller interferences, and a low control group with individual showing larger interferences. According to the cognitive control view (Novick et al., 2005; Thompson-Schill, 2005; Zhou et al., submitted for publication), individual differences in cognitive control ability may predict similar variations in sentence parsing abilities. However, it is unclear what kind of variation will show up in ERPs for our critical contrasts, because no study, as we know, has examined the relationship between individual differences in cognitive control abilities and ERP patterns in sentence comprehension. Here we have no *priori* prediction from the syntactic view for the two groups of participants because it doesn't explicitly assume individual differences in syntactic parsing abilities.

Table 1 – Experimental conditions and example sentences with approximate literal translations

Conditions	Examples					
(1)	民警把小偷<u>拘留</u>在派出所。					
	minjing	ba	xiaotou	<u>juliu</u>	zai	paichusuo
Active	the policeman	BA	the thief	<u>kept</u>	in	the police station
Plausible	The policeman kept the thief in the police station.					
(2)	小偷把民警<u>拘留</u>在派出所。					
	xiaotou	ba	minjing	<u>juliu</u>	zai	paichusuo
Active	the thief	BA	the policeman	<u>kept</u>	in	the police station
Implausible	The thief kept the policeman in the police station.					
(3)	小偷被民警<u>拘留</u>在派出所。					
	xiaotou	bei	minjing	<u>juliu</u>	zai	paichusuo
Passive	the thief	BEI	the policeman	<u>was kept</u>	in	the police station
Plausible	The thief was kept in the policeman station by the police.					
(4)	民警被小偷<u>拘留</u>在派出所。					
	minjing	bei	xiaotou	<u>juliu</u>	zai	paichusuo
Passive	the policeman	BEI	the thief	<u>was kept</u>	in	the police station
Implausible	The policeman was kept in the police station by the thief.					

The critical word is underlined.

2. Results

2.1. *Performance in the sentence comprehension task*

The participants were asked to read the testing sentences and to judge whether the probe sentences are semantically consistent with the testing sentences. The accuracy rates in this task were 93% in the active plausible condition, 91% in the active implausible condition, 89% in the passive plausible condition, and 87% in the passive implausible condition. There were significant effects of Syntactic Complexity (active vs. passive), $F\,(1, 24) = 6.62$, $p < 0.05$, and Plausibility (plausible vs. implausible), $F\,(1, 24) = 7.19$, $p < 0.05$, but no interaction of Syntactic Complexity * Plausibility, $F < 1$. Thus, participants were less accurate with the passive sentences (88%) than the active sentences (92%), and they were more accurate with the plausible stimuli (91%) than the implausible stimuli (89%).

2.2. *Event-related potentials*

Figs. 1 and 2 show the grand average ERPs time-locked to the onsets of the critical verbs for the active and the passive stimuli respectively. For the passive stimuli (Fig. 2), a positivity was observed between 350 and 850 ms in response to the implausible sentences as compared with the plausible sentences. For the active stimuli (Fig. 1), however, no ERP effect was visible in response to the implausible sentences as compared with the plausible sentences. These observations were confirmed by statistical analyses.

For the active stimuli, no effect was found in the mean amplitudes for either the 350–600-ms or the 650–850-ms time window. For the passive stimuli, statistical analyses in the 350–850-ms time window revealed significant main effects of Plausibility for the midline, $F\ (1, 24) = 12.34$, $p < 0.01$, and the medial sites, $F\,(1, 24) = 6.15$, $p < 0.05$, but not for the lateral sites, $F < 1$. Thus, a sustained positive effect was observed for the passive implausible condition (0.81 μV) as compared with the passive plausible condition (−0.40 μV).

These ERP patterns were unexpected for two reasons. First, for the passive stimuli, the positivity in terms of timing was different from the P600 observed in previous studies with implausible sentences, which was usually between 600 and 850 ms (e.g., Kim and Osterhout, 2005; Kolk et al., 2003; Kuperberg et al., 2007; Van Herten et al., 2005, 2006). Second, for the active stimuli, the finding of no main effect of Plausibility was inconsistent with previous findings that the implausible condition usually gave rise to a N400 effect and a following P600 as compared with the plausible condition (e.g., Kuperberg et al., 2003, 2006a,b). These unusual patterns of ERP effects led us to more detailed analyses of data, from the perspective of individual differences.

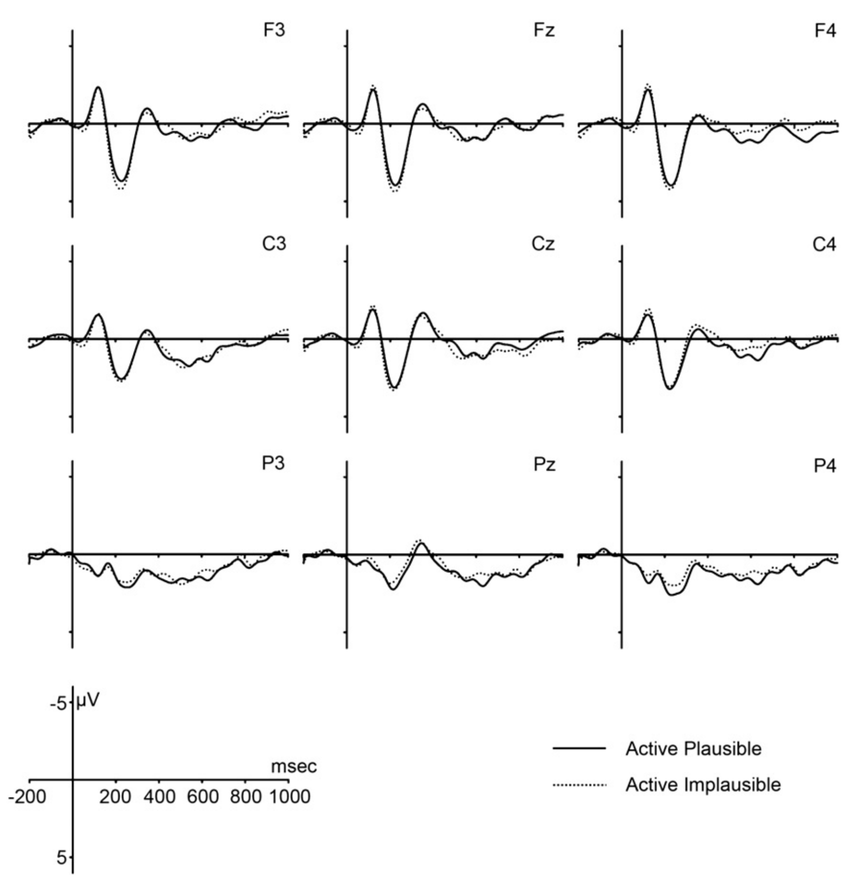

Fig. 1 – Grand average ERPs in response to the active plausible (solid line) and the active implausible conditions (dotted line). Averages are time-locked to the onset of the critical verb.

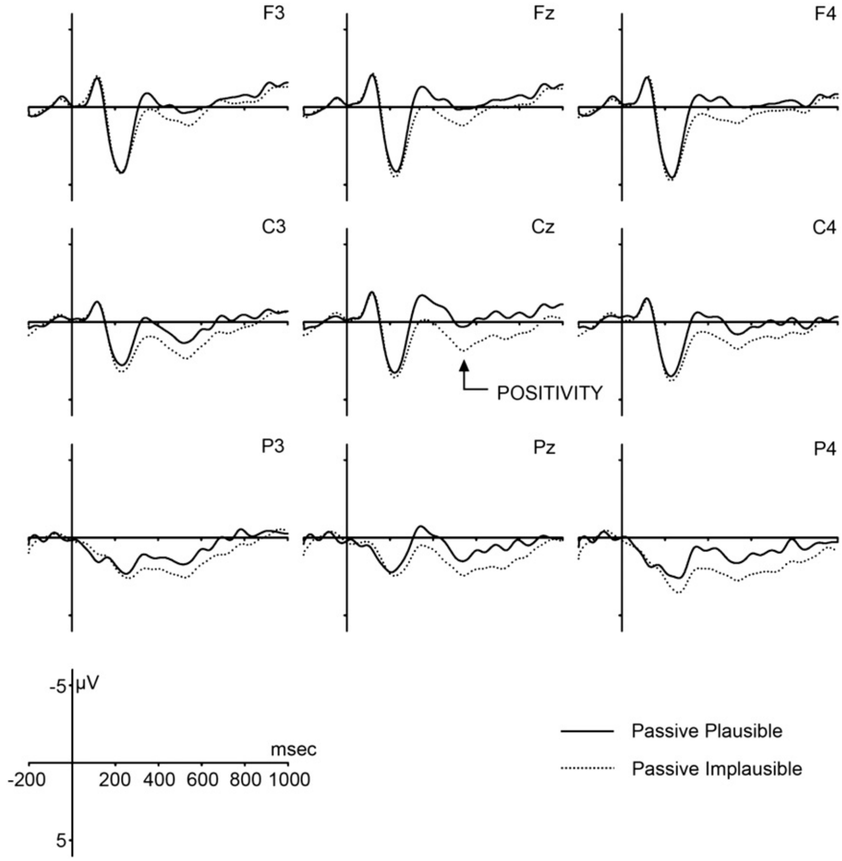

Fig. 2 – Grand average ERPs in response to the passive plausible (solid line) and the passive implausible conditions (dotted line). Averages are time-locked to the onset of the critical verb.

2.3. *Individual differences*

Inspections of ERPs of each participant suggested that individual differences in ERP effects contributed to the observed pattern for the active stimuli: 13 participants showed negative effects for the implausible vs. plausible contrast, whereas other 12 participants showed positive effects. We hypothesized that, these individual differences in ERP effects might arise from individual differences in general cognitive control ability. To examine to what extent individual differences in cognitive control ability measured by non-parsing conflict tasks had contributed to the individual differences in ERP effects, we grouped participants according to their performance in the Stroop task.

2.3.1. *Performance in the manual color-word Stroop task*

The overall accuracy rates were 95% in both the congruent and the incongruent conditions. The overall reaction times were 421 ms (SD=62 ms) in the congruent condition and 429 ms (SD=69 ms) in the incongruent condition. The interference effect was small (8 ms) but significant, F (1, 24)=5.31, $p<0.05$. This small Stroop effect may be due to the restricted range of stimuli (only two) and the manual response (see also Chen et al., 2006; Egner and Hirsch, 2005). Previous Stroop tasks producing stronger interferences effects usually employed stimuli with more tokens and required verbal responses (MacLeod, 1991).

Participants were then grouped according to the sizes of interference effect in RTs. Thirteen participants (i.e., the high control group) showed interference effects (mean=−3 ms, SD=6 ms) smaller than the grand mean (8 ms), whereas 12 participants (i.e., the low control group) showed interference effects (mean=20 ms, SD=19 ms) larger than the grand mean. The low control group (i.e., the group showing stronger Stroop interference) was slower in response to the incongruent stimuli (mean=459 ms, SD=66 ms) than the congruent stimuli (mean=439 ms, SD=58 ms), F (1, 11)=13.60, $p<0.01$. In contrast, the high control group (i.e., the group showing little Stroop interference) was as fast in response to the incongruent stimuli (mean=401 ms, SD=61 ms) as to the congruent stimuli (mean=404 ms, SD=63 ms), $F<2.4$. The reaction time analysis for the two groups also revealed a marginal main effect of Group, F (1, 23)=3.55, $p=0.07$, indicating that the low control group (449 ms) was in general slower than the high control group (403 ms). The accuracy analysis did not find anything significant.

2.3.2. *Correspondence between ERP patterns and Stroop effects*

There was a great correspondence between this grouping and participants' ERP responses to active sentences: 10 participants (77%) in the high control group showed negative effects for the implausible vs. plausible contrast; 9 participants (75%) in the low control group showed positive effects for the same contrast. We also grouped participants according to their patterns of ERP effects in the implausible vs. plausible contrast in active sentences. Twelve participants who showed positive effects had a marginally significant Stroop interference effect: 427 ms vs. 417 ms, F (1, 11) = 4.37, p = 0.06. Thirteen participants who showed negative effects had no significant Stroop effect: 431 ms vs. 425 ms, F (1, 12) = 1.43, p = 0.26. Thus, individual differences in cognitive control ability could predict variations in ERP patterns, and vice versa. The great correspondence between the patterns of ERP effects and the groupings of participants according to their performance in the Stroop task, either *a priori* or *post hoc*, demonstrated that the group classification was reliable even though the interference effect was rather small due to the restricted response set.

2.4. *Individual differences in the sentence comprehension task*

For the low control group, the accuracy rates in this task were 93% in the active plausible condition, 90% in the active implausible condition, 87% in the passive plausible condition, and 84% in the passive implausible condition. For the high control group, the accuracy rates were 93% in the active plausible condition, 92% in the active implausible condition, 91% in the passive plausible condition, and 90% in the passive implausible condition. There were significant effects of Syntactic Complexity, F (1, 23) = 6.93, p < 0.05, and Plausibility, F (1, 23) = 7.93, p < 0.05, but no interaction of Syntactic Complexity * Plausibility, F < 1. Moreover, there was neither significant effect of Group, F < 1, nor the interaction of Syntactic Complexity * Group, or Plausibility * Group, Fs < 2.4. Thus, both groups were more accurate with the active stimuli than with the passive stimuli, and both were more accurate with the plausible stimuli than with the implausible stimuli.

2.5. *Individual differences in ERPs*

Figs. 3–5 present the ERPs for the low and the high control groups. For the low control group (Fig. 3, ERPs for active and the passive sentences were not presented separately because of the similarity between two patterns, see the following statistical results), implausible sentences elicited a sustained positivity between 350 and 750 ms as compared with plausible sentences. For the high control group, however, the ERP effects of the implausible vs. plausible contrast varied between the active and the passive stimuli, as shown in Figs. 4 and 5. The active implausible condition gave rise to an anterior negativity between 350 and 600 ms as compared with the active plausible condition (Fig. 4), while the passive implausible condition gave rise to a sustained positivity between 350 and 850 ms as compared with the passive plausible condition (Fig. 5). These observations were confirmed by statistical analyses.

In the 350–600-ms time window, interactions of Syntactic Complexity * Plausibility * Group were obtained over the midline, F (1, 23) = 6.01, p < 0.05, the medial, F (1, 23) = 5.97, p < 0.05, and the lateral sites, F (1, 23) = 4.14, p = 0.06. In the 650–850-ms time window, interactions of Syntactic Complexity * Plausibility * Group were obtained over the midline, F (1, 23) = 5.87, p < 0.05, and the medial sites, F (1, 23) = 3.63, p = 0.07, but not over the lateral sites, F < 1. These interactions suggested that the two groups of participants showed different ERP patterns in response to the critical stimuli. Separate analyses were then conducted for the two groups of participants.

2.5.1. *Low control group*

In the 350–750-ms time window, the midline analysis revealed a significant effect of Plausibility, F (1, 11) = 6.58, p < 0.05, indicating that a positive effect was obtained for the implausible sentences (0.61 μV) as compared with the plausible sentences (−0.48 μV).

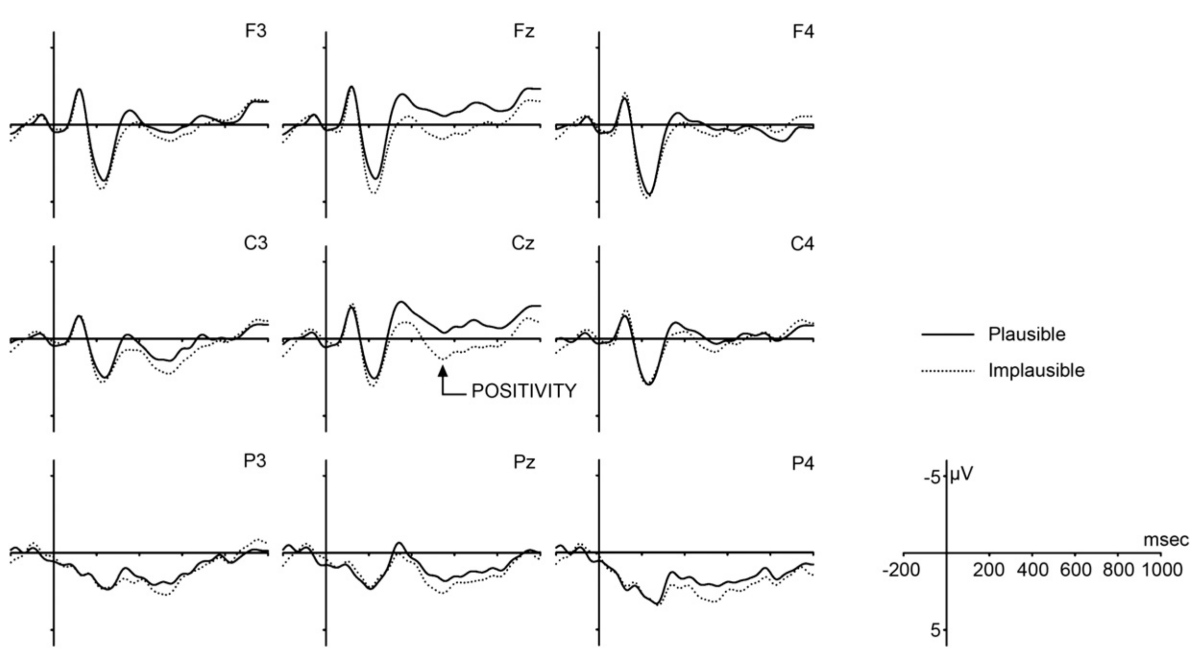

Fig. 3 – Grand average ERPs in response to the plausible (solid line) and the implausible stimuli (dotted line) in the low control group. Averages are time-locked to the onset of the critical verb.

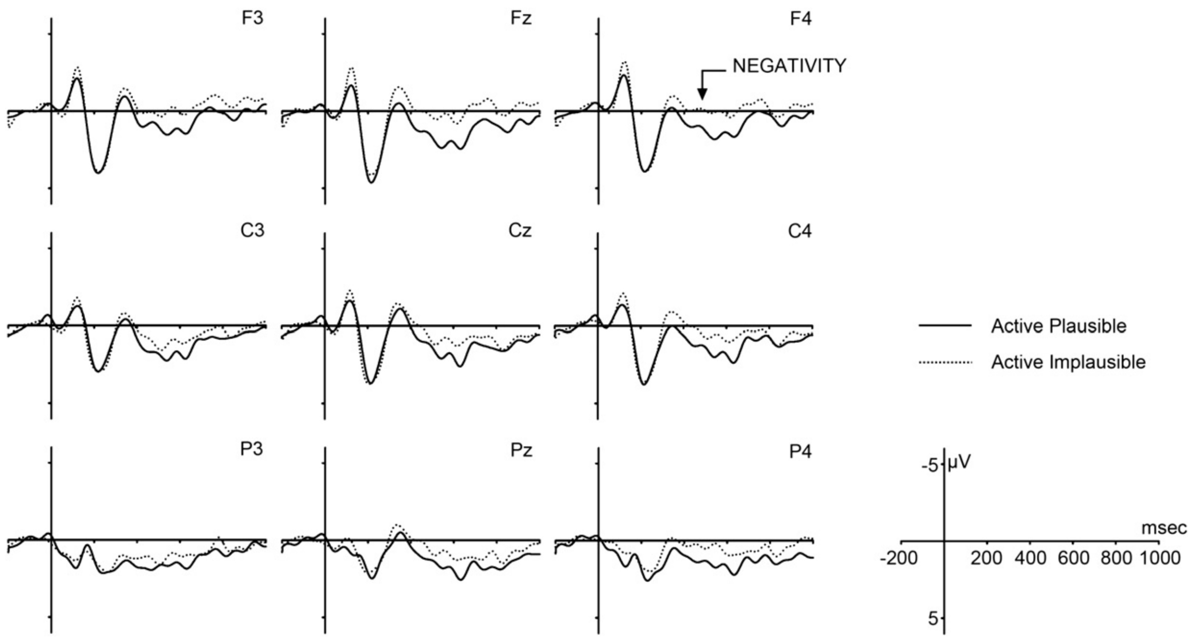

Fig. 4 – Grand average ERPs in response to the active plausible (solid line) and the active implausible conditions (dotted line) in the high control group. Averages are time-locked to the onset of the critical verb.

There was no effect of Syntactic Complexity, nor interaction of Syntactic Complexity * Plausibility, *Fs*<1. The medial and the lateral analyses did not find anything significant.

2.5.2. *High control group*

For the active stimuli, statistical analyses in the 350–600-ms time window revealed a significant main effect of Plausibility for the right medial sites, F (1, 12)=5.65, p<0.05, indicating that a negative effect was obtained for the implausible sentences (0.15 μV) as compared with the plausible sentences (1.52 μV). This negative effect maximized over the anterior sites (for F4 and FC4, *Fs* > 5.6). There were also marginal effects of Plausibility for the midline, F (1, 12)=3.06, p=0.10, the right lateral, F (1, 12)=3.56, p=0.09, and the left medial sites, F (1, 12)=3.19, p=0.10.

For the passive stimuli, statistical analyses in the 350–850-ms time window revealed a significant main effect of Plausibility for the midline, F (1, 12)=12.54, p<0.01, the left medial, F (1, 12)=14.04, p<0.01, the right medial, F (1, 12)=11.55, p<0.01, and the right lateral sites, F (1, 12)=7.16, p<0.05, indicating that

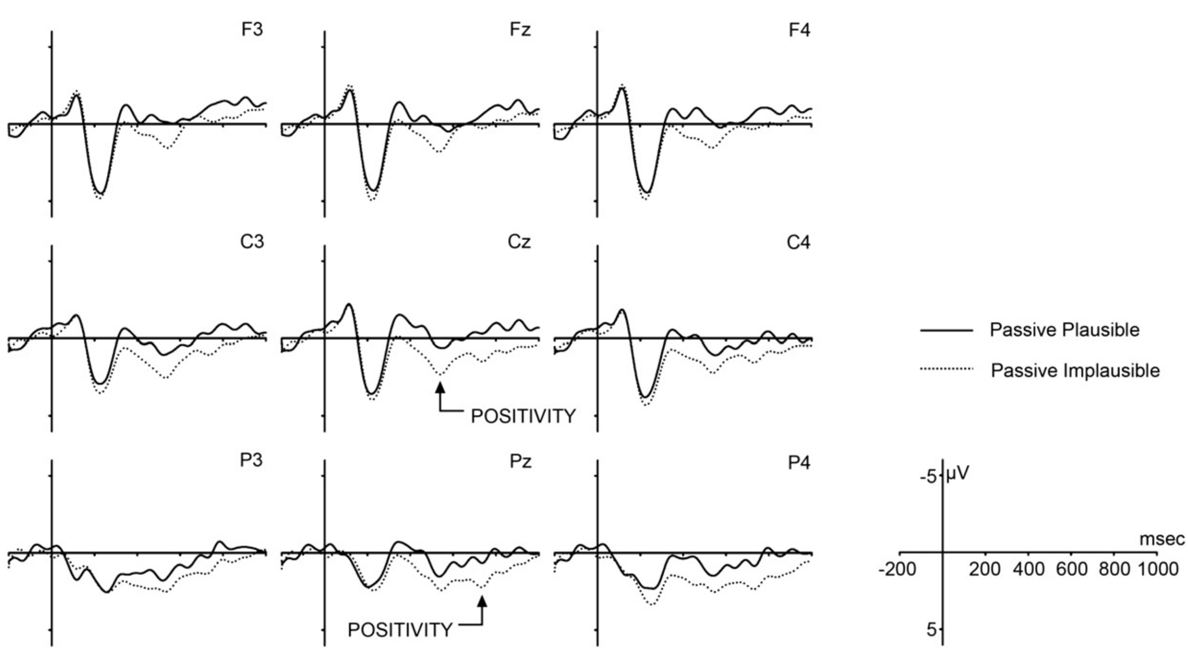

Fig. 5 – Grand average ERPs in response to the passive plausible (solid line) and the passive implausible conditions (dotted line) in the high control group. Averages are time-locked to the onset of the critical verb.

a positive effect was obtained for the implausible sentences (1.00 μV) as compared with the plausible sentences (−0.50 μV). Statistical analyses over the consecutive 50-ms time windows showed that the sustained positive effect may be composed of two parts, i.e., an early part and a late part. Over the midline electrodes, the early part started from 350–400 ms, F (1, 12) = 8.28, $p < 0.05$, maximized between 500–550 ms, F (1, 12) = 9.83, $p < 0.01$, and fall down to the baseline during 550–600 ms, F (1, 12) = 2.86, $p = .12$. The late part started from 700 to 750 ms, F (1, 12) = 10.74, $p < 0.01$, maximized between 750 and 800 ms, F (1, 12) = 11.79, $p < 0.01$, and fall down to the baseline during 850–900 ms, $F = 2.77$, $p = 0.12$.

2.5.3. *General processing speed, reading span and the ERP patterns*

The high and low control groups differed not only on the magnitude of the Stroop effects, but also on the general processing speed of the Stroop stimuli. To rule out the possibility that it was the processing speed, rather than the amount of Stroop interference that contributed to the variations in ERP patterns, we conducted ANCOVAs over the ERP effects (i.e., the mean amplitude in the active implausible condition minus the mean amplitude in the active plausible condition) on the exemplar electrodes in the 350–600 time window for the active stimuli. Statistical analyses, with Group as between-participant factor and Processing Speed (i.e., RT in the congruent condition in the Stroop task) as covariate, revealed no significant main effect of Processing Speed, $Fs < 1.4$, or interaction of Group * Processing Speed, $Fs < 1$, for the right anterior (i.e., F4) or the frontal midline (i.e., FCz) sites. There were main effects of Group over the F4, F (1, 21) = 3.60, $p = 0.07$, and the FCz electrodes, F (1, 21) = 6.10, $p < 0.05$. Thus, variations in the ERP effect for the active stimuli could not be attributed to individual differences in processing speed in the Stroop task. The low control group showed positive effects (F4: 0.30 μV; FCz: 1.89 μV, evaluated at processing speed = 421 ms), while the high control group showed negative effects (F4: −1.49 μV; FCz: −1.10 μV, evaluated at processing speed = 421 ms) between the time window of 350 and 600 ms for the active stimuli.

Moreover, we examined whether individual difference in working memory capacity contributes to variations in ERP pattern for the active stimuli, as previous studies observed that individuals with high and low reading spans (Daneman and Carpenter, 1980) showed different ERP patterns when reading garden-path sentences (Friederici et al., 1998, 2001; Vos and Friederici, 2003). However, ANOVAs with Reading Span as covariate revealed no significant main effect of Reading Span or interactions with Reading Span, $Fs < 2.0$, indicating that variations in ERP effect for the active stimuli could not be attributed to individual differences in working memory capacity. Furthermore, we also grouped participants according to their reading spans, but found no correspondence between participants' reading spans and their ERP responses to active sentences either.

3. Discussion

This study investigated the reanalysis processes as a consequence of conflict between incompatible sentential representations (i.e., representations based on the plausibility heuristic clashes and those based on the syntactic analysis). In line with the cognitive control view (Kolk and Chwilla, 2007; Novick et al., 2005; Zhou et al., submitted for publication), we found that ERP effects in sentence processing were related to reader's cognitive control ability in the non-parsing conflict task (i.e., the color-word Stroop task). For readers with lower control abilities, a positivity was obtained between 350 and 750 ms for implausible sentences as compared with plausible sentences regardless of the syntactic complexity. For readers with higher control abilities, however, ERP effects in sentence processing were affected by the complexity of syntactic structure. An anterior negativity was observed between 350 and 600 ms for active implausible sentences as compared with active plausible sentences. In contrast, a positivity was observed between 350 and 850 ms for passive implausible sentences as compared with passive plausible sentences. This sustained positive effect may be composed of two parts, an early part between 350 and 600 ms and a late part between 700 and 900 ms. Considered the time window of the anterior negativity (i.e., 350–600 ms) in the high control group and that of the positivity (i.e., 350–750 ms) in the low control group, it is not surprising that these effects canceled out when the average for the active stimuli was made over all participants (Fig. 1). In addition, variations in EPR patterns could not be attributed to individual differences in processing speed or working memory capacity. These findings appear to be incompatible with the syntactic view, which predicts no P600 without animacy violation in such pragmatically anomaly sentences. Finally, we didn't obtain any N400 effect in the present study. This absence of N400 is consistent with the hypothesis of Kolk and colleagues (Kolk et al., 2003; Van Herten et al., 2005, 2006) that the N400 reflects semantic processes in which the plausibility heuristic primes likely interpretations. No N400 showed up in the present study because there is no difference for the plausibility heuristic to produce likely interpretations for either plausible or implausible sentences. In the following paragraphs, we discuss how existing theories concerning the general cognitive control can account for the present results and how the conflicting findings in some previous studies can be reconciled and integrated.

For readers with higher control abilities, conflicts occurring in passive sentences gave rise to a sustained positivity which was possibly composed of an early positive effect between 350 and 600 ms and a late positive effect between 700 and 900 ms. The early positive effect may reflect the detection of conflict between incompatible sentential representations (Kolk and Chwilla, 2007; Van Herten et al., 2006; for similar findings in ambiguous sentences, see Mecklinger et al., 1995; Friederici et al., 1998, 2001). The late positive effect, which was similar to the P600 reported in previous studies with similar materials (e.g., Kim and Osterhout, 2005; Kolk et al., 2003; Kuperberg et al., 2003, 2006a; Van Herten et al., 2005, 2006), may reflect the resolution of representational conflict by biasing toward the representation which respects the most reliable source of linguistic information (i.e., syntactic rules) (Novick et al., 2005; Thompson-Schill, 2005; West et al., 2005; Zhou et al., submitted for publication). For readers with lower control abilities, a similar sustained positivity showed up in response to conflicts occurring in both the passive and the active sentences. Although without clear dissociation between an early part and a late part, this sustained positivity is possibly a manifestation of multiple neural events, including both the monitoring and the resolution processes. These sustained positivities are clearly inconsistent with the syntactic assumption that the P600 effect reflects the reassignment of thematic roles in response to animacy violations (Kuperberg, 2007; Kuperberg et al., 2003, 2006a).Thus, the mechanisms of cognitive control may be involved in the reanalysis processes to resolve conflict between incompatible sentential representations, leading to the correct final interpretations (e.g., participants were accurate 89% of times for implausible sentences).

For readers with higher control abilities, conflicts occurring in active sentences elicited an anterior negativity between 350 and 600 ms. This anterior negativity in terms of distribution is different from the lexical-semantic N400 effect which has a more posterior distribution. On the other hand, similar anterior negativity was observed when participants name an ink color which is inconsistent with the word meaning in the Stroop task (the so-called N450, see Liotti et al., 2000; Markela-Lerenc et al., 2004; Qiu et al., 2006; West et al., 2005), or when they change from one task to another in the switching task (Brass et al., 2005), or when they read a sentence mismatched with the content of the preceding picture in the sentence-picture matching task (Vissers et al., in press; Wassennar and Hagoort, 2007). Dipole source analyses revealed prefrontal sources for the anterior negativity, including the left inferior frontal junction and the right inferior frontal gyrus (Brass et al., 2005), and the left lateral prefrontal cortex (Markela-Lerenc et al., 2004). Since previous studies suggested that the bilateral inferior frontal cortexes serve to suppress inappropriate responses (e.g., Garavan et al., 1999, 2002; Konishi et al., 1998, 1999; Rubia et al., 2003), incorrect task sets (e.g., Brass et al., 2003; Dreher and Berman, 2002; Sohn et al., 2000), or interfering memories (e.g., Anderson et al., 2004; D'Esposito et al., 1999; Jonides et al., 1998; for a reviews, see Aron et al., 2004), it is possible that the anterior negativity observed in this study reflects the inhibitory processes, which suppress the interfering representation based on the plausibility heuristic and/or the inappropriate response tendency guided by world knowledge.

With respect to the different ERP patterns between active and passive sentences for readers with higher control abilities, there could be two possible accounts. One possibility is that the syntax-based representations of complex sentences may be weaker than those of simple sentences. Consequently, they need more strengthening than the simple sentences from the mechanisms of cognitive control to be selected over competing heuristic-based representations (Novick et al., 2005; Thompson-Schill, 2005; Zhou et al., submitted for publication), giving rise to the P600 effect only in complex sentences. Another possibility is that complex sentences employ additional operations such as syntactic transformations to construct sentential representations. As a result, they require extra efforts to be checked for possible error in the processing of syntactic information (Kolk et al., 2003; Van Herten et al., 2006; Vissers et al., in press). These extra efforts are reflected by the P600 effect. However, readers with lower control abilities are weaker in their ability to suppress alternative representations and/or to monitor possible processing errors. Consequently, both active and passive sentences put great demand on the control system, leading to the P600 effects for both types of sentences.

Based on the above arguments, we can re-interpret the N400 effects observed in response to pragmatic anomalies over the right hemisphere (Kuperberg et al., 2006a) or the medial and the lateral sites (Kuperberg et al., 2003, 2006b) in some previous studies during the processing of active sentence. It is possible that this right lateralized N400 effect is due to a mix of the high control readers, who show a right lateralized negativity, and the low control readers, who show a midline positivity. Moreover, such a mix may lead to the absence of an early positive effect in previous studies because the early positivity and the anterior negativity have the same time window (both between 350 and 600 ms).

In conclusion, this study provided ERP evidence for the involvement of cognitive control in sentence comprehension. When conflicts appear between incompatible sentential representations, the mechanisms of cognitive control are employed in the reanalysis processes to monitor and resolve representational conflicts, as reflected by the sustained positivity. In addition, sentence processing is constrained by the reader's cognitive control ability as well as by the complexity of syntactic structure. Readers with different cognitive control abilities show different processing patterns when encountering conflicts during sentence comprehension.

4. Experimental procedures

4.1. *Participants*

Twenty-nine students from Peking University (17 females) participated in the experiment. Their mean age was 21 years (range 19–27 years). All were native speakers of Mandarin Chinese and had normal or corrected-to-normal vision. They were right-handed according to Chinese Handedness Questionnaire (Li, 1983). Four participants could not be tested, due to their graduating from the university, for the Stroop task and their ERP data were then excluded from analysis. Among them, two showed positive effects and two negative effects for the implausible vs. plausible contrast in active sentences.

4.2. *Materials*

4.2.1. *Sentence comprehension task*

There were four conditions, each containing 50 sentences: the active plausible sentences, the active implausible sentences, the passive plausible sentences, and the passive implausible sentences (see Table 1). All active sentences took the form of "Subject-*ba*-Object-VP" (i.e., the *ba* construction) in which the subject was followed by the prepositional *ba* and the object, and the final VP consisted of the critical verb and a prepositional phrase (for an introduction to the *ba* construction, also see Ye et al., 2006, 2007). All passive sentences took the form of "Object-*bei*-Subject-VP" (i.e., the *bei* construction) in which the object was followed by the prepositional *bei* and the subject, and the final VP consisted of the critical verb and a prepositional phrase (see Table 1). The active plausible condition described a plausible and familiar real-world event, such as the policeman keeping the thief in the police station, in the active voice. The same event was expressed in the passive voice in the passive plausible condition. The active implausible condition resulted from reversing the subject and the object NP of the active plausible condition, describing a very unlikely and even impossible event, such as the thief keeping the policeman in the police station. This implausible event was expressed in the passive voice in the passive implausible condition. For each sentence, both the subject and the object were animate. In all sentences, the pragmatic anomalies were not evident before the critical verbs. Another 120 sentences were used as fillers. All these sentences were presented in a pseudo-randomized order, which was employed to make sure: (a) sentences from the same condition were not presented in more than 3 consecutive trials; and (b) at least 30 trials intervened between repetitions of the same critical verb.

The plausibility of events was assessed in a pre-test involving 30 participants, who did not participate in the ERP experiment. All events were presented in their active forms and were distributed, in a counter-balanced manner, into two lists so that the plausible versions and their counterparts would not appear in the same list. One participant responded to only one of these lists. They were asked to rate each sentence on a scale from 1 to 7, where "1" meant that the event was so implausible as to be anomalous and "7" meant the sentence described an extremely likely real-world event. The implausible events (mean=2.09, SD=.82) were rated as far less plausible than the plausible events (mean=6.36, SD=.56), t (98)= 30.37, $p<.01$.

4.2.2. *Color-word Stroop task*

There were two conditions, i.e., the congruent and the incongruent conditions. In the congruent condition, the words "red" and "green" were randomly presented in the congruent color (e.g., the word "red" in red ink). In the incongruent color, the same words were presented in the incongruent color (e.g., the word "red" in green ink).

4.3. *Procedure*

4.3.1. *Sentence comprehension task*

In the sentence comprehension task, sentences were presented word-by-word at the center of a 17 inch computer screen. Each sentence was preceded by a 500-ms fixation asterisk and followed by a 500-ms blank screen, after which the probe sentence appeared. Words were displayed in white on a black background at a viewing distance of approximately 1 m. Each word was presented for 600 ms with a 400-ms inter-stimulus interval (ISI). Participants were seated in a sound-proof, electrically-shielded chamber and instructed to read the stimulus sentences silently. They were asked to judge whether the probe sentence was semantically consistent with the testing sentence and response by pressing buttons. The assignment of the "Yes" and "No" to the left and right buttons was balanced between participants. A new trial started 500 ms after the button press response. The experiment began with a practice block. The formal experiment was divided into five blocks of 64 sentences each and short breaks were given between blocks. This ERP experiment lasted about 2.5 h.

4.3.2. *Color-word Stroop task*

Words were displayed at the screen center on a black background at a viewing distance of approximately 60 cm. Each word was preceded by a 500-ms fixation asterisk and was followed by a 2000-ms blank screen. The word duration was 200 ms and the stimulus size was 1.4° (horizontal)*1.4° (vertical). Participants were instructed to identify the color in which the word was presented as fast and as accurately as possible and to respond by pressing buttons. The assignment of the "Red" and "Green" to the left and the right buttons was counterbalanced between participants. The experiment began with a practice block. The formal experiment was divided into two blocks of 60 trials each (30 congruent and 30 incongruent trials for each block) and a short break was given between blocks.

4.4. *EEG recording*

EEG were recorded by the SynAmp amplifier from 30 electrodes attached to an elastic cap. The electrodes were located in the standard International 10–20 System (Jasper 1958) over prefrontal (FP1, FP2), frontal (F7, F3, Fz, F4, F8), frontal–temporal (FT7, FT8), frontal–central (FC3, FCz, FC4), temporal (T7, T8), central (C3, Cz, C4), temporal–parietal (TP7, TP8), central–parietal (CP3, CPz, CP4), parietal (P7, P3, Pz, P4, P8), and occipital areas (O1, Oz, and O2) for the left and the right hemispheres. The vertical electrooculogram (VEOG) was monitored from electrodes located above and below the left eye and the horizontal EOG (HEOG) from electrodes located at the outer canthus of each eye. The AFz electrode on the cap served as ground. Recordings were referenced to the linked bilateral mastoids. Electrode impedances were kept below 5 kΩ. The biosignals were amplified with a band pass from .05 to 70 Hz and digitized at 500 Hz.

4.5. *Data analyses*

For behavioral data of the sentence comprehension task and the color-word Stroop task, accuracies and reaction times were calculated for each condition. Incorrectly answered trials were excluded from the reaction time analysis. For the sentence comprehension task, the reaction time analysis had repeated measure ANOVAs with two factors: Syntactic Complexity (active vs. passive), and Plausibility (plausible vs. implausible). For the color-word Stroop task, the reaction time analysis had repeated measure ANOVAs with the Congruency factor (congruent vs. incongruent).

ERPs were computed for each participant over an epoch from 200 ms before to 1000 ms after the onset of critical verbs, with 200-ms pre-verb as the baseline. Epochs contaminated by blinks and other eye movement artifacts were excluded from averaging by the criteria of 60 μV. Trials with incorrect responses were also excluded from averaging. On average, 32% (SD=11%) trials in the active plausible condition, 32% (SD=14%) trials in the active implausible condition, 33% (SD=12%) trials in the passive plausible condition, and 36% (SD=13%) trials in the passive implausible condition were rejected because of artifacts or incorrect responses. The number of rejected trials did not differ for the four conditions, $F<1$. Averages of artifact-free correct ERP trials were computed for each condition. Each data points had at least 32 trials.

Statistical analyses were firstly carried out for each consecutive 50-ms interval between 0 and 1000 ms to ensure that no possible effect may be overlooked (see the Results section; Liotti et al., 2000; Markela-Lerenc et al., 2004; Qiu et al., 2006; Ye et al., 2006). Based on these results, three time windows, i.e., 350–600 ms, 650–850 ms and 350–850 ms, were chosen to provide the coverage for critical effects. Mean amplitudes were then calculated in these two time windows respectively for each condition. In order to examine hemisphere differences, statistical analyses were performed separately for the midline, the medial, and the lateral sites. In order to examine region differences, the Electrode factor (5 levels) was employed, containing five electrodes from anterior to posterior sites. Such division of electrodes should have provided more details for distributions of ERP effects than the anterior–posterior division (2 levels). The midline analysis had repeated measure ANOVAs with three factors: Syntactic Complexity, Plausibility, and Electrodes (Fz, FCz, Cz, CPz, and Pz). The medial analysis had the ANOVAs with four factors: Syntactic Complexity, Plausibility, Hemisphere (left vs. right), and Electrodes (F3/F4, FC3/FC4, C3/C4, CP3/CP4, and P3/P4). The lateral analysis had the ANOVAs with four factors: Syntactic Complexity, Plausibility, Hemisphere, and Electrodes (F7/F8, FT7/F T8, T7/T8, TP7/TP8, and P7/P8). Further comparisons were planned if interactions reached significance. The Greenhouse–Geisser correction was applied when evaluating effects with more than one degree of freedom in the numerator.

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