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Semantic integration processes at different levels of syntactic hierarchy during sentence comprehension: An ERP study

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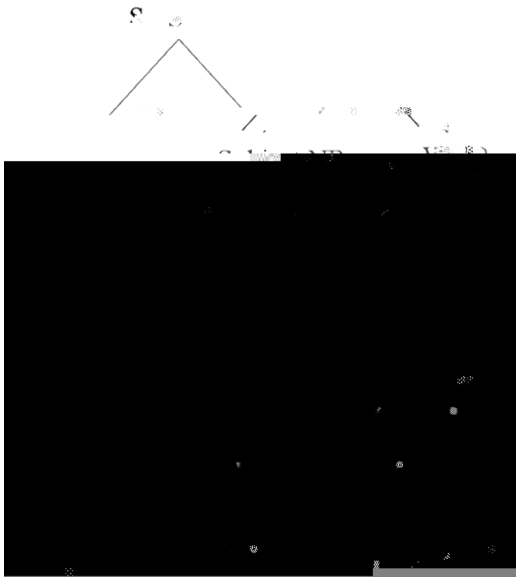

. **1.** The hierarchical structure of the sentence in the form of "subject noun + verb + numeral + classifier + object noun". S = sentence; NP = noun phrase, VP = verb phrase; DP = determiner phrase. The classifier (DP) and the object noun form a local, lower-level phrase while the verb and the object noun form a higher-level structure.

representation during sentence comprehension have different neural manifestations when a target word is semantically constrained by constituents at different levels of syntactic hierarchy and (ii) to what extent the semantic process at the higher-level is influenced by the process at the lower-level or vice versa.

Previous event-related potential (ERP) studies have focused mainly on the process of semantic integration between constituents within a local phrase structure or on the process of integrating a target word into the sentence/discourse representation. An N400 effect (see Brown, Hagoort, & Kutas, 2000; Kutas & Federmeier, 2000; Kutas & Van Petten, 1994 for reviews) is commonly obtained in response to a target word violating the semantic constraints (selectional restrictions) from a constituent in the local structure (e.g. the adjective-noun mismatch, Hagoort, 2003; Prior & Bentin, 2006; the verb–noun mismatch, Friederici, Steinhauer, & Frisch, 1999; Friederici & Frisch, 2000; Hahne & Friederici, 2002; Jiang, Tan, & Zhou, 2009; Li, Shu, Liu, & Li, 2006; Osterhout & Nicol, 1999; Wicha, Moreno, & Kutas, 2004; Ye, Zhan, & Zhou, 2007). This N400 effect has also been observed on a target word mismatching a given sentence/discourse context (Kutas & Hillyard, 1980; Van Berkum, Brown, & Hagoort, 1999), a word incongruent with the real-world knowledge (Hagoort, Hald, Bastiaansen, & Peterson, 2004; Hald, Steenbeek-Planting, & Hagoort, 2007), or an unexpected but semantically congruent word (Camblin, Gordon, & Swaab, 2007; Coulson, Federmeier, Van Petten, & Kutas, 2005; Federmeier & Kutas, 1999a,b; Van Petten, Coulson, Weckerly, Federmeier, Folstein, & Kutas, 1999; Wlotko & Federmeier, 2007). It is assumed that the N400 effect reflects the difficulty in integrating the local lexical semantics into the sentence/discourse representation (Van Berkum et al., 1999; Van Berkum, Brown, Hagoort, & Zwitserlood, 2003) or the difficulty in lexical access (Kutas & Federmeier, 2000).

A few other studies manipulated multiple semantic constraints simultaneously and examined the possible interaction between the semantic integration processes taking place in parallel at different representation levels. It is demonstrated that the semantic congruency effect for a local structure can be overridden by the discourse congruency (Filik & Leuthold, 2008; Nieuwland & Van Berkum, 2006). Although an N400 effect was found on a word that mismatched the local semantic constraints in the absence of discourse context or when the context is not supportive (e.g. Terry was very annoyed at the traffic jam on his way to work. He picked up the lorry and carried on down the road), this effect was absent when the context was supportive, in terms of readers' background knowledge, of the processing of the locally mismatching word (e.g. The Incredible Hulk was annoyed that there was a lot of traffic in his way. He picked up the lorry and carried on down the road). When the discourse congruency and lexical association between two words embedded in a local structure were crossed, consistent findings were found (Camblin et al., 2007; Coulson et al., 2005; Van Petten et al., 1999). The local association effect was only observed on a target word which was not congruent with the discourse. Moreover, the N400 effect on the target noun mismatching the lower-level restrictions can be blocked or replaced by P600 when an alternative interpretation is viable and easily accessible by means of discourse priming (Nieuwland & Van Berkum, 2005), thematic role attraction (Kim & Osterhout, 2005; Kuperberg, Caplan, Sitnikova, Eddy, & Holcomb, 2006a; Kuperberg, Sitnikova, Goff, & Holcomb, 2006b; Kuperberg, Kreher, Sitnikova, Caplan, & Holcomb, 2007; Kuperberg, Sitnikova, Caplan, & Holcomb, 2003, or world knowledge heuristic (Hoeks,

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Experimental conditions and exemplar sentences with the structure of "subject + verb + numeral + classifier + noun". The selectional restrictions of the classifiers are noted in the brackets. The match or mismatch of semantic constraints in the lower or higher-level of syntactic hierarchy are marked in the right columns, with "√" indicating a semantic match and "×" indicating a semantic mismatch.

[illegible]

for the correct and the verb–noun mismatch conditions, 8.2 for the classifier-noun and double-mismatch conditions, and 8.8 for the triple-mismatch condition. The numeral preceding the classifiers was always "—" (one). All the subject nouns were two- or three-character animate nouns denoting human names and/or their occupations and all the object nouns were inanimate.

One hundred and fifty filler sentences were constructed with the same sentence frame as the critical ones. Among them, 125 were correct sentences and another 25 were incorrect sentences with double-mismatches on the verb-classifier and the classifier–noun combinations.

2.3. Pretests

Four pretests, including two acceptability ratings, one cloze probability test and one sentence completion test, were carried out to select the final set of the critical stimuli. The sentence acceptability rating test was to ensure that sentences with various types of mismatches were indeed not acceptable. The local phrase acceptability rating test was to ensure that the local classifier–noun congruency was maintained (or violated) to the same extent across conditions. The five-point Likert scale was used for both ratings, with twenty participants each for the potential stimuli. The rating test of sentence acceptability had 960 sentences. The local phrase acceptability rating was obtained for each of the 400 phrases having the structure of "numeral + classifier + noun". Mean scores for the finally selected critical stimuli are shown in Table 2 as a function of experimental conditions.

Clearly, relative to the correct sentences, sentences containing the classifier–noun mismatch, the verb–noun mismatch, and/or the verb-classifier mismatch had much lower acceptability in the sentence acceptability rating, $ps < 0.001$. Moreover, sentences with double mismatches or triple mismatches were rated less acceptable than sentences with a single mismatch, $ps < 0.001$. Furthermore, the classifier–noun combinations were rated equally unacceptable in conditions involving the classifier–noun mismatch.

To determine the cloze probability of a word at the object noun position, forty participants were instructed to complete the sentence fragments (i.e., without the final object nouns) of sentences in the correct and the classifier–noun mismatch conditions. Results showed that the average cloze probability for the target nouns used in the correct sentences was 12.1%. The average cloze probability for the mostly produced words (but were generally not used in the actual stimuli) was 40.1% for sentence fragments in the correct condition and 42.4% for sentence fragments in the classifier–noun mismatch condition.

To make sure that the classifier was congruent or incongruent with the verb in each sentence, another 16 participants were instructed to complete the sentence fragments of "subject + verb + numeral + classifier" with any word or phrase that made sense and to skip fragments which were hard to continue. It is clear from Table 2 that the sentence fragments containing the verb-classifier mismatch in the triple-mismatch condition had a very low possibility of completion, compared with fragments in which the classifiers were congruent with the preceding verbs in the other four conditions, $ps < 0.001$.

2.4. Procedure

Participants were seated in a comfortable chair in a sound attenuated and electrically shielded chamber. They were instructed to move as little as possible and to keep their eyes fixated on a sign at the center of the computer screen. This fixation sign was at eye-level and was approximately 1 m away. After the presentation of the fixation sign for 700 ms, sentences were presented segment-by-segment in serial visual presentation mode at the center of the screen. Each sentence consisted of 6 segments (i.e., "Grandma | bought | one | bag of | starch | ."). Segments were presented in white against black background, with a visual angle of less than 1°. Each segment was presented for 400 ms, followed by a blank screen for 400 ms. After the separately presented full stop, a question mark appeared on the screen for 1000 ms and participants were asked to judge whether the sentence was semantically acceptable by pressing buttons with their first fingers of the right and the left hand. The assignment of response buttons was counter-balanced across participants. Twenty-eight different test sequences were generated according to a pseudo-randomization procedure. In randomization, sentences from the same critical set were separated by at least 30 other sentences and no more than three sentences from the same condition were presented consecutively (see also Hahne & Jescheniak, 2001). Different sequences were randomly assigned to each participant. In this way, any effects due to the repeated use of verbs, object nouns or classifiers in different conditions were minimized. Each participant read 400 sentences in total, with 50 sentences from each experimental condition. The critical and filler sentences were divided into eight test blocks after randomization. There were 21 practice trials prior to the formal test.

2.5. EEG recording

The EEGs were recorded from 30 electrodes in a secured elastic cap (Electrocap International) localized at the following positions: FP1, FP2, F7, F3, FZ, F4, F8, FT7, FC3, FCZ, FC4, FT8, T7, C3, CZ, C4, T8, TP7, CP3, CPZ, CP4, TP8, P7, P3, PZ, P4, P8, O1, OZ and O2. The vertical electro-oculogram (VEOG) was recorded from electrodes placed above and below the left eye. The horizontal EOG (HEOG) was recorded from

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Mean scores and standard deviations in the four pretests. The local phrase acceptability and the sentence acceptability rating used five-point Likert scales, with 5 representing “totally acceptable” and 1 representing “totally unacceptable”. The listed scores for the cloze probability test are for the target nouns used in the correct sentences.

Experimental condition	Local phrase acceptability		Sentence acceptability		Cloze probability of the target noun		Sentence completion possibility	
	Mean	SD	Mean	SD	Mean	SD	Mean (%)	SD
Correct	4.71	0.10	4.70	0.20	12.1%	0.19	95.1	0.11
classifier–noun mismatch	1.51	0.27	2.08	0.43	0.0%	0.00	95.0	0.07
verb–noun mismatch	4.74	0.11	1.92	0.31	0.0%	0.00	95.1	0.11
Double-mismatch	1.39	0.22	1.36	0.18	0.0%	0.00	95.0	0.07
Triple-mismatch	1.39	0.23	1.25	0.18	–	–	22.8	0.18

electrodes placed at the outer cantus of each eye. The linked bilateral mastoids served as reference and the GND electrode on the cap served as ground. Electrode impedance was kept below 5 k . The biosignals were amplified with a band pass between 0.05 and 70 Hz. The EEG and EOG were digitized on-line with a sampling frequency of 500 Hz.

2.6. Data analyses

Incorrectly judged sentences and sentences contaminated by EEG artifacts (with potentials greater than ±70 μV) were rejected before the EEG averaging procedure, resulting in on average 90.9% of the artifact-free trials for the experiment (92.1% in the correct condition, 90.4% in the classifier–noun mismatch condition, 92.5% in the verb–noun mismatch condition, 89.2% in the double-mismatch condition, 90.3% in the triple-mismatch condition). ERPs were computed separately for each participant and each experimental condition, from −200 ms before to 800 ms after the onset of the critical classifiers or the object nouns. For classifiers, ERPs in the first 200 ms pre-stimulus onset were used for baseline correction; for object nouns, ERPs in the first 100 ms post-stimulus onset were used for baseline correction, given that the nouns in the triple-mismatch condition immediately followed classifiers which mismatched the preceding verbs. The patterns of effects did not change according to the way the baseline correction was conducted.

Based on visual inspection of the grand averages and our hypotheses, two time windows were selected for the critical nouns and classifiers: 300–500 ms for the negative component (N400), 550–800 ms for the late positivity and the late negativity. For ERP responses to the critical nouns, 2 × 2 repeated-measures ANOVAs were conducted for the first four experimental conditions, with verb–noun congruency (congruent vs. incongruent) and classifier–noun congruency (congruent vs. incongruent) as two critical factors. Topographic factors (electrode groups) were included for midline and lateral analysis. The midline analysis had two factors: sentence type and electrode (Fz, FCz, Cz, CPz, and Pz). The lateral analysis has three factors: sentence type, region (anterior vs. posterior), and hemisphere (left vs. right). The hemisphere and the region were crossed, forming four regions of interest (ROIs), each of which was represented by four electrodes: F3, FC3, F7, FT7 for the left anterior; F4, FC4, F8, FT8 for the right anterior; CP3, P3, TP7, P7 for the left-posterior; and CP4, P4, TP8, P8 for the right posterior. ERPs from the four electrodes in each region were averaged before entering the ANOVAs. For comparisons that could not be covered by factorial ANOVAs, pairwise comparisons were conducted with sentence type as a critical factor, together with the topographic factors.

For ERP responses to the classifiers, trials in the first four conditions were combined to form a verb-classifier congruent condition while trials in the triple-mismatch condition formed the verb-classifier incongruent condition. ANOVAs with the verb-classifier congruency and topographic factors were conducted to determine the ERP effects of the verb-classifier congruency in the two time windows defined above. Greenhouse–Geisser correction was applied when there were significant interactions involving electrodes (Geisser & Greenhouse, 1959).

3.

3.1. Behavioral data

The accuracy in acceptability judgment was 99.5% for the double-mismatch sentences, 99.6% for the triple-mismatch sentences, 94.2% for the classifier–noun mismatch sentences, 95.2% for the verb–noun mismatch sentences, and 91.4% for the correct sentences. There was a main effect of sentence type in the one-way ANOVA, $F(1, 25) = 21.17$, $p < 0.001$. Pairwise comparisons revealed that accuracies in both the double- and triple-mismatch conditions were significantly higher than those in the correct and single-mismatch conditions, $ps < 0.005$, and accuracies for the single-mismatch conditions were higher than the accuracy for the correct sentences, $ps < 0.005$. Thus the more mismatches were involved, the higher the accuracy of judgment, indicating that the participants were attentive to the sentences.

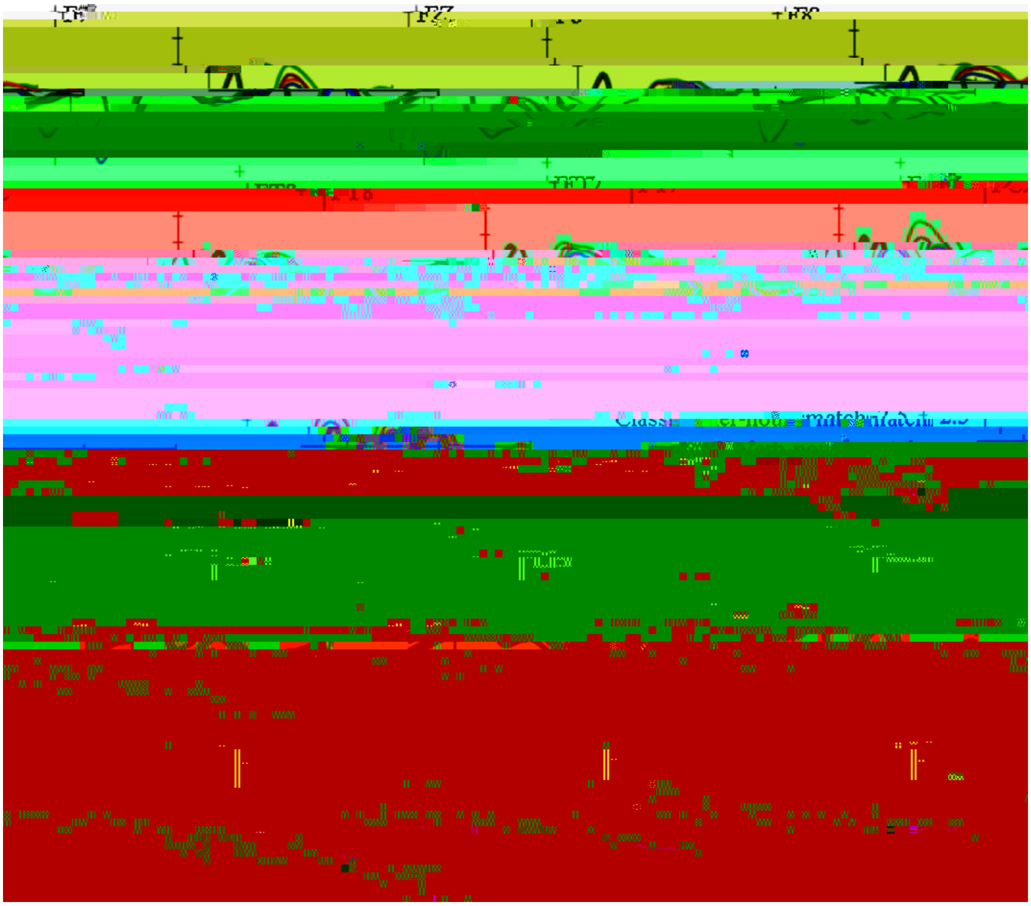
3.2. ERP data

Fig. 2 displays ERP responses to the object nouns violating semantic constraints from constituents at the lower-level of syntactic hierarchy (i.e., in the classifier–noun mismatch condition), the higher-level of syntactic hierarchy (the verb–noun mismatch condition) or both (the double-mismatch condition), with ERP responses to the nouns in correct sentences as the baseline. Fig. 3 depicts the scalp distributions of effects engendered by different types of mismatches at two time windows. Tables 3 and 4 present the results of statistical analyses in paired comparisons between each mismatch condition and the baseline, between the double-mismatch and the two single-mismatch conditions, and between the triple-mismatch and the double-mismatch conditions.

3.2.1. Object nouns in the 300–500 ms time window

The factorial ANOVAs revealed a significant main effect of verb–noun congruency in the midline, $F(1, 25) = 16.120$, $p < 0.001$, and in the lateral, $F(1, 25) = 12.719$, $p < 0.005$; a main effect of classifier–noun congruency in the midline, $F(1, 25) = 41.36$, $p < 0.001$, and in the lateral, $F(1, 25) = 38.94$, $p < 0.001$; and a significant two-way interaction between verb–noun congruency and classifier–noun congruency in the midline, $F(1, 25) = 10.40$, $p < 0.005$, and in the lateral, $F(1, 25) = 7.09$, $p < 0.05$. These findings suggested that the semantic mismatch in the lower-level or/and in the higher-level structure elicited an N400 effect compared with the baseline and the effect in the double-mismatch condition was not simply the sum of the effects in the two single-mismatch conditions.

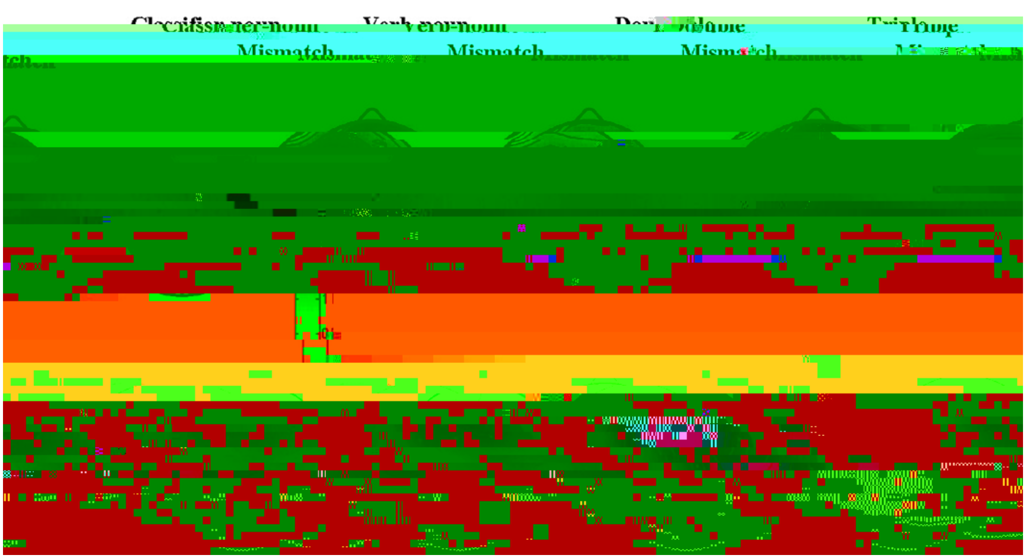
Further analyses were conducted to tear apart the interaction



. 2. Grand average ERP waveforms epoched from 200 ms before to 800 ms after the onset of the object noun at 13 exemplar electrodes.

the classifier–noun congruency effect (−0.53 μV) was significant in the lateral, $F(1, 25) = 5.09$, $p < 0.05$, but not significant in the midline, $F < 1$. The findings suggested that although the higher-level verb–noun congruency may affect the lower-level semantic integration process for the classifier and noun, the lower-level process may nevertheless take place even when the noun mismatched the verb at the higher-level.

The advantage of the local semantic process for the classifier and the noun can also be observed in the direct comparison between the classifier–noun mismatch condition and the verb–noun mismatch condition: there was a significant effect of sentence type in the midline, $F(1, 25) = 3.97$, $p < 0.05$, or in the lateral, $F(1, 25) = 4.17$, $p < 0.05$, with the mismatch at the lower-level engendered a more negative N400 component than the mismatch at the higher-level.



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3

Pairwise comparisons between the triple-mismatch condition and other conditions for the N400 effects on the object nouns in the 300–500 ms time window.

Type of comparison	Triple vs. baseline				Triple vs. classifier–noun				Triple vs. verb–noun				Triple vs. double			
	df	F	p	ε	df	F	p	ε	df	F	p	ε	df	F	p	ε
Midline																
S	1,25	39.73	<0.001	1.00	1,25	11.13	<0.005	1.00	1,25	15.51	<0.005	1.00	1,25	6.61	<0.05	1.00
S × E	4,100	7.87	<0.005	0.49	4,100	2.16	0.12	0.54	4,100	3.54	<0.05	0.59	4,100	2.21	0.12	0.53
Lateral																
S	1,25	39.42	<0.001	1.00	1,25	10.61	<0.005	1.00	1,25	12.44	<0.005	1.00	1,25	3.42	0.08	1.00
S × H	1,25	15.21	<0.005	1.00	1,25	8.13	<0.01	1.00	1,25	3.19	0.09	1.00	1,25	1.75	0.20	1.00
S × R	1,25	0.12	0.73	1.00	1,25	0.10	0.75	1.00	1,25	0.15	0.70	1.00	1,25	0.89	0.35	1.00
S × R × H	1,25	4.33	<0.05	1.00	1,25	2.00	0.17	1.00	1,25	3.90	0.06	1.00	1,25	3.57	0.07	1.00

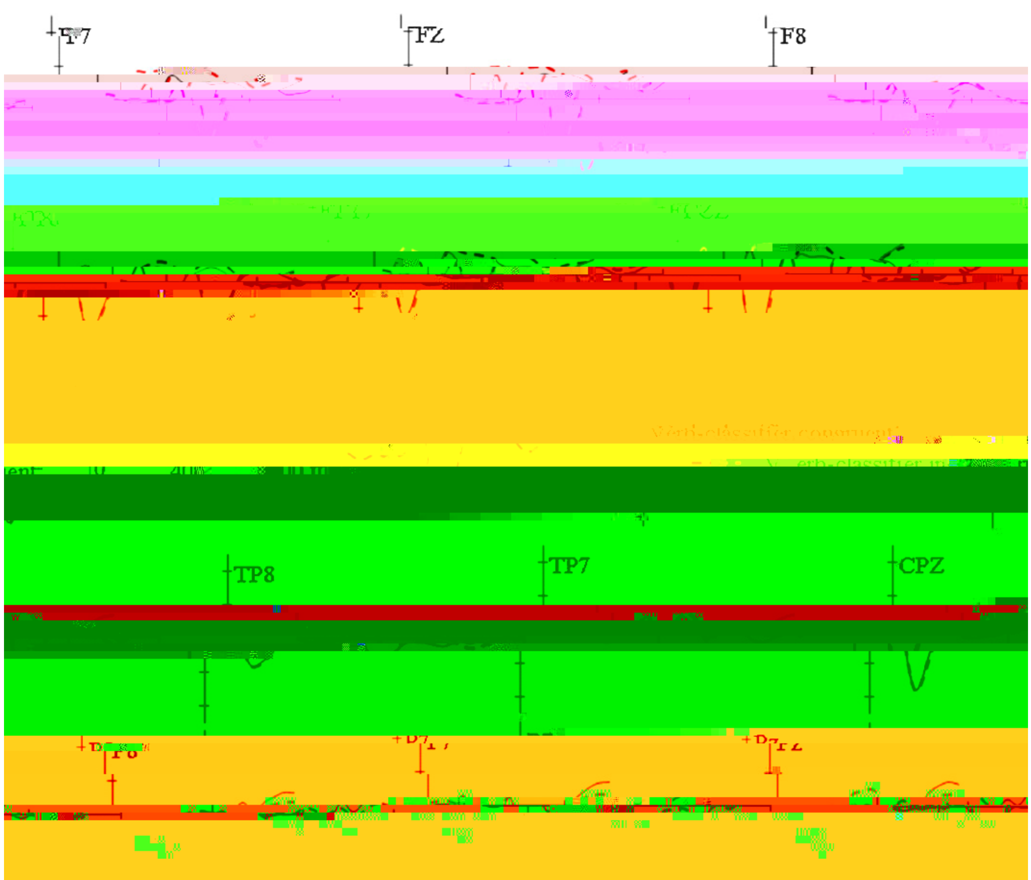
Note: S = sentence type; E = electrode; R = region; H = hemisphere.

4

Pairwise comparisons between the triple-mismatch condition and other conditions for the ERP effects on the object nouns in the 550–800 ms time window.

Type of comparison	Triple vs. baseline				Triple vs. classifier–noun				Triple vs. verb–noun				Triple vs. double			
	df	F	p	ε	df	F	p	ε	df	F	p	ε	df	F	p	ε
Midline																
S	1,25	26.46	<0.001	1.00	1,25	13.66	<0.005	1.00	1,25	29.23	<0.001	1.00	1,25	21.53	<0.001	1.00
S × E	4,100	10.69	<0.001	0.62	4,100	3.34	<0.05	0.56	4,100	2.51	0.09	0.56	4,100	13.25	<0.001	0.65
Lateral																
S	1,25	24.03	<0.001	1.00	1,25	10.39	<0.005	1.00	1,25	28.99	<0.001	1.00	1,25	19.10	<0.001	1.00
S × H	1,25	20.33	<0.001	1.00	1,25	18.18	<0.001	1.00	1,25	8.36	<0.01	1.00	1,25	0.24	0.63	1.00
S × R	1,25	10.36	<0.005	1.00	1,25	0.01	0.92	1.00	1,25	0.01	0.99	1.00	1,25	14.86	<0.005	1.00
S × R × H	1,25	0.16	0.69	1.00	1,25	1.56	0.22	1.00	1,25	0.37	0.55	1.00	1,25	0.04	0.85	1.00

Note: S = sentence type; E = electrode; R = region; H = hemisphere.



. **4.** Grand average ERP waveforms for the verb-classifier congruent and verb-classifier incongruent sentences at 13 exemplar electrodes, epoched from 200 ms before to 800 ms after the onset of the classifier.

To examine the effect of integrity/coherence of preceding context on the processing of the object noun, pairwise comparisons were conducted between the triple-mismatch condition and the other three mismatching conditions. As can be seen from Figs. 2 and 3 and Table 3, the triple-mismatch condition produced strongest N400 responses as compared with the other conditions, suggesting that more effort was devoted to integrating the object noun when the context was incoherent.

3.2.2. Object nouns in the 550–800 ms time window

ANOVAs revealed a significant main effect of classifier–noun congruency in the midline (−0.75 μV), $F(1, 25) = 5.97$, $p < 0.05$, and in the lateral (−0.56 μV), $F(1, 25) = 4.75$, $p < 0.05$, suggesting that the classifier–noun mismatch conditions elicited a negativity effect as compared with the match conditions. This effect interacted with electrode in the midline, $F(4, 25) = 20.30$, $p < 0.001$, $\varepsilon = 0.48$, and with region in the lateral, $F(1, 25) = 26.17$, $p < 0.001$, indicating that this late negativity appeared mostly in the anterior regions [see [illegible])]TJ02(0.67740TD;ns)-235.effns the midli:(
p < 0.0;(

4. D [illegible]

This study investigates the neural dynamics of semantic integration processes at different levels of syntactic hierarchy. A sentence with a hierarchical syntactic structure was ended with an object noun violating the semantic constraints from a constituent in the local, lower-level structure (the classifier–noun mismatch condition), in the higher-level structure (the verb–noun mismatch condition), or from constituents in the lower- and higher-level structures simultaneously (the double-mismatch condition). Compared with the correct condition, nouns in all the three mismatch conditions elicited significant N400 effects in the 300–500 ms time window and significant negativity effects in the 550–800 ms time window. In the N400 time window, the lower- and the higher-level semantic constraints interacted in a way that the effect elicited ciated with the magnitude of a particular ERP effect, it is unlikely that the N400 effects we observed on the object nouns reflect

4.3. The late negativity and semantic reinterpretation

We obtained a late negativity effect for each of the mismatch conditions against the baseline condition. These anteriorly maximized negativity effects started at 550 post-onset of the object nouns. But unlike the late positivity effects which ended at 800 ms post-onset of the nouns, these negativity effects lasted until 300 ms after the onset of the following full stop (not shown in Fig. 2). They are similar to the anterior negativity effect for maintaining information in working memory during sentence comprehension (i.e., in the comparisons of complex vs. simpler sentences, King & Kutas, 1995; Kluender & Kutas, 1993; Müller, King, & Kutas, 1997; referentially ambiguous vs. unambiguous sentences, Nieuwland & Van Berkum, 2008; Van Berkum et al., 1999, 2003; sentences with non-canonical vs. canonical word order, Münte, Schiltz, & Kutas, 1998). In this study, the increase of working memory load was not in terms of additional information but in terms of the degree of mismatch between sentence constituents. Sentences with more mismatches may have placed a heavier load upon working memory (Friederici et al., 1998; Gunter, Wagner, & Friederici, 2003; Novais-Santos, Gee, Shah, Troiani, Work, & Grossman, 2007), in which the difficulty in integrating word meaning into preceding context initiate a second-pass semantic reinterpretation process (Baggio, van Lambalgen, & Hagoort, 2008; Jiang et al., 2009). This reinterpretation process may take the form of replacing the mismatching object noun or the classifier with a plausible one based on the context. The more mismatches in a sentence, the more difficult the reinterpretation process, and the heavier the working memory load. Jiang et al. (2009) compared Chinese sentences with the universal quantifier (dou, all, every) preceded by a singular entity (the universal quantifier mismatch condition) with sentences with the universal quantifier preceded by a plural entity (the baseline condition). They observed an anteriorly maximized sustained negativity effect on the word immediately following the mismatching quantifier or on the mismatching quantifier itself, depending on the task demand. The authors suggest that a reinterpretation process takes place after the detection of mismatch in semantic scope, by either changing the singular entity represented by the NP into a plural one or dropping the mismatching quantifier. By analogy, it is possible that for the present sentences with mismatching constituents an effort was made to make sense of the mismatching object noun and/or the classifier, resulting in the late negativity observed.

An alternative approach to the late negativity effects is to attribute them to a sentence-final wrap-up process (Hagoort, 2003) which has been considered to include all the processes of semantic interpretation of the sentence in a broad sense, such as establishing its true-value properties, establishing the referents of free pronouns, establishing the speech act of the sentences (Molinaro et al., 2008). In this study, we found that the size of the negativity effect increased with the number of mismatch involved in the sentence and the degree of unacceptability judged by the reader. The more mismatches, the more effort devoted to the wrap-up process, and the larger the negativity effect. The late negativity effect for the triple-mismatch condition was significantly larger than the effects for the other three types of mismatch conditions, indicating that the most effortful wrap-up process was involved in establishing a coherent representation of a sentence. It should be noted, however, the wrap-up hypothesis for the late anterior negativity is not inconsistent with the reinterpretation hypothesis since the wrap-up process is assumed to include a component of reinterpretation. Indeed we would like to suggest that the negativity effects we observed in this study are likely to have contributions from both sources.

To conclude, by using sentences with a hierarchical structure in which the object noun is constrained by selectional restrictions from both the preceding classifier and from the verb at a higher-level of syntactic hierarchy and by manipulating the semantic congruency between different constituents, we observed both common and differential neural dynamics for semantic integration processes at the lower- and the higher-levels of the hierarchical structure. Moreover, we found that semantic processes at different levels act in concert to build up sentence representation, with neither process overriding the other.

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