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Research report

Electrophysiological distinctions in processing conceptual relationships within simple sentences

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Abstract

The aim of this study was to determine whether or not the brain distinguishes between two types of conceptual relationships between noun-phrases (NPs) and verbs during online processing of simple, unambiguous English sentences. A total of 15 participants read and made plausibility judgments on sentences that were presented word-by-word. Event-related potentials elicited by critical verbs were measured. In all cases, the critical verb assigned a thematic role of 'agent' to its subject NP. In non-violated sentences (e.g. ''For breakfast the boys would only eat . . . ''), the preceding NP was animate (''boys'') and was a likely agent for a given verb (''eat'') given its preceding context (''For breakfast''). In both types of conceptually violated sentences, the NPs were unlikely agents for the verbs given their preceding contexts. In 'thematic role animacy violations' (e.g. ''For breakfast the eggs would only eat . . . ''), the NP was inanimate (''eggs'') and was therefore more likely to occupy the role of 'theme' than 'agent', i.e. eggs, being inanimate, cannot eat but they can be eaten. In 'non-thematic role pragmatic violations' (e.g. ''For breakfast the boys would only bury . . . ''), the thematic role of agent assigned by the verb (''bury'') to its preceding NP (''boys'') is inherently acceptable (boys can bury), but the sentence is still pragmatically incongruous given the preceding context (''At breakfast''). As expected, the non-thematic role pragmatic violations elicited a significant N400 effect. The thematic role animacy violations elicited a smaller N400 effect that only approached significance across all participants. The thematic role animacy violations, however, elicited a significant P600 effect—an ERP component that is most commonly associated with processing syntactic information during language comprehension. We discuss the possibility that the P600 was elicited by the thematic role animacy violations (but not by the non-thematic role pragmatic violations) because, in the former but not the latter, there was an online attempt to structurally repair and make sense of the sentences by reassigning the thematic role of the NP that preceded the critical verb from 'agent' to 'theme'. Our findings suggest a qualitative neural distinction in processing these two types of conceptual anomalies within simple, unambiguous sentences.
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1. Introduction

In this paper, we explore the neurophysiological correlates of processing the conceptual relationship between a noun phrase (NP) that precedes a verb and the verb itself. We examine the electrophysiological correlates of two types of violations of conceptual relationships that occur between nouns and verbs in simple, unambiguous sentences: violations of the likely thematic role played by a noun around a verb regardless of context, and violations of the likelihood that a particular thematic role played by a noun around a verb would occur in a particular context.

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The first of these violations affects 'local' semantic relationships between nouns and verbs. Such relationships have been expressed in theories of lexical and grammatical structures in several ways. In early work on the lexicon (dating back to Chomsky's Aspects [2]), verbs were said to impose 'selectional restrictions' on NPs that played certain grammatical roles, such as subject and object. Selectional restrictions were thought to dictate the animacy and humanness of NPs in these positions. Later theories have viewed selectional restrictions as one aspect of the thematic roles that are assigned to NPs by verbs [20]. Thematic roles describe 'modes of participation'—generalizable across a variety of verb or sentence meanings—that are played by the NPs in a sentence, e.g. 'agent', 'goal', 'instrument', 'patient', 'location'. In Government-and-Binding-Theory [3,4], thematic roles are viewed as elements that play a critical role in syntax, as they are closely associated with the verb's argument structure and therefore affect the syntactic configurations into which NPs can be placed around a verb (though they do not completely determine these structures).

In the second of these violations, the particular thematic role played by the NP around the verb is intrinsically plausible. Yet, the verb is still pragmatically/semantically unlikely with respect to its preceding context.

Examples of these types of violations are shown in Table 1. Sentence (1) in Table 1 is coherent. Both sentences (2) and (3) are pragmatically/semantically incongruous. In both these sentences, the NP is an unlikely agent for the verb of the sentence. In sentence (2), the thematic role of 'agent' assigned by the verb (''eat'') to its preceding NP (''eggs'') renders the sentence semantically and pragmatically incongruous: eggs cannot eat (except in a metaphorical sense). Sentence (2) violates the thematic role requirements that the verb (''eat'') imposes on its preceding NP (''eggs''). However, the NP ''eggs'' is consistent with the prior context (''At breakfast'') and could potentially fill an alternative thematic role—it could well be the 'theme' of ''eat'', i.e. eggs can be eaten. In sentence (3) in Table 1, the thematic role of agent assigned by the verb (''bury'') to its preceding NP (''boys'') is inherently acceptable (boys can bury), but the sentence is still pragmatically incongruous given the preceding context (''At breakfast''). To summarize, in sentence (2), the particular thematic role played by a NP given its subsequent verb is violated. However, if the syntax allowed, the semantic properties of the NP would allow it to occupy an alternate thematic role around the verb. In sentence (3), the implausibility of the verb is dictated by its preceding context taken as a whole and there is no alternative thematic role that the NP could occupy given a particular verb. The differences between sentences (2) and (3) lie in the precise relationship between the verbs, their preceding NPs, and their preceding contexts.

Thus far, we have considered these sentences from the perspective of language representation. The question that we addressed in the current study is whether the violations exemplified in sentences (2) and (3) are distinguishable with respect to the functional processes they engage during online comprehension. How are the lexical properties of verbs used in combination with the lexico-semantic information of their NP arguments and their preceding contexts during online language processing?

In sentence (2) in Table 1, it is possible that, upon encountering the verb (''eat''), participants might contemplate a 'repair' whereby the NP (''eggs'') is taken to be the theme of the verb (''eat''). Such a repair requires a syntactic re-analysis, since the sentence, as presented, cannot convey this thematic role. Thus, a possible response to sentence (2) might include an attempt to reanalyze the syntactic structure of the sentence to turn the agent NP into the theme of the verb in a (doomed) effort to preserve discourse coherence. In sentence (3) in Table 1, there is no point in attempting such a re-analysis. Both boys burying something or someone burying boys are incoherent in the context of ''At breakfast''.

Table 1
Types of linguistic violation

Linguistic violation	Explanation	Example
(1) No violation	Baseline condition against which the other conditions are evaluated.	''For breakfast the boys would only eat toast and jam.''
(2) Thematic role animacy violation	The animate NP preceding the critical verb is replaced by an inanimate NP that makes the sentence pragmatically/semantically implausible.	''For breakfast the eggs would only eat toast and jam.''
(3) Non-thematic role pragmatic violation	The critical verb is replaced by another verb taken from another sentence scenario. This makes the sentence pragmatically/semantically implausible.	''For breakfast the boys would only bury toast and jam.''

We used event-related brain potentials (ERPs) to address the question of whether these two types of violations evoke different neurophysiological responses during online processing. The rationale for measuring ERPs to different types of anomaly is as follows: if two types of anomaly are associated with qualitatively different ERP waveforms, this suggests that they engage different neural and functional processes. A purely quantitative difference in ERPs between two sentence types suggests different levels of engagement of the same neural and functional processes.

Below we briefly review the different ERP components that have been described during different aspects of language processing that are relevant to the contrasts we examined in the present study.

1.1. The N400

The ERP component that is traditionally associated with conceptual (i.e. semantic and pragmatic) violations is the N400. This component was originally described as a negative shift in the ERP waveform occurring ~400 ms following the onset of contextually inappropriate words within sentences, such as to the word ''dog'' in the sentence ''He took coffee with sugar and dog'' [25]. The difference in N400 amplitude between the contextually incongruous and congruous words was termed the N400 effect. Later studies established that an N400 effect was elicited not only by words that were semantically incongruous, but also by words that were congruous with the rest of the sentence but of low cloze probability. For example, a larger N400 was elicited by the critical word ''thought'' in the sentence ''He mailed the letter without a thought'' than when the critical word was ''stamp'' [26]. Recent findings show that a robust N400 effect is elicited by words that are congruous with respect to the sentence in which they occur but that are incongruous within the context of whole discourse [40]. Moreover, words that are semantically related to expected endings elicit less negativity even when they are anomalous and their cloze probability is zero [26], and recent studies suggest that the N400 amplitude is sensitive to the organization of semantic memory during online sentence processing [7,27]. In summary, the amplitude of the N400 is sensitive to both the organization of long-term semantic memory as well as the sentential or discourse context in which a word is presented.

1.2. The LAN and the P600

Two main ERP components have been described in association with the manipulation of syntactic parameters. First, several studies have reported an anteriorly distributed negativity (often left-lateralized and therefore termed the LAN) in association with function words and a variety of syntactic anomalies in sentences [10,23,31]. It has been proposed that the LAN reflects a first stage of syntactic parsing [10]. There is also evidence that anteriorly distributed negativities may be involved in working memory operations that hold and retrieve sentence constituents online [8,22,23].

Second, several groups have described a centro-parietal positive wave, elicited by a variety of violations, with an onset between 500 and 800 ms and a duration of several hundred milliseconds, variously labeled the 'late positive component', the 'syntactic positive shift' and the 'P600' [19,33]. A P600 is almost always elicited by syntactic violations including anomalies of phrase structure [13,31,33], number and verb-tense violations between subject-NPs and verbs [19,35] and subcategorization violations [33,36]. It is also elicited by words that at first appear anomalous but can be recovered in syntactically ambiguous or garden-path sentences [28,29,33,34,36]. Although there has been some debate about whether the P600 is specific to the language system [5], it is generally acknowledged that it is a sensitive marker of syntactic processes during language processing. There have been several suggestions of the functional significance of the P600. It has been proposed that it reflects syntactic reanalysis and repair processes in a two-stage model of sentence parsing [10], the 'cost of syntactic processing' [36] and/or processes of syntactic integration [8,21].

The amplitude of the P600 can also be modulated, under certain circumstances, by parameters that appear to be lexico-semantic or referential, rather than syntactic in nature [1,12,17,18,24,30,42]. Most have argued that such observations provide evidence that, under certain circumstances, lexico-semantic information can have a direct and immediate influence on the assignment of syntactic structure [1,12,42][1].

In summary, the LAN and P600 are sensitive to syntactic factors. Under certain circumstances, the P600 can be modulated by semantic and pragmatic parameters. Although the precise functional significance of these different waveforms is debated, it is generally agreed that they are distinct from one another and from the N400 ERP component.

1.3. The current study

In the current study, we used ERPs to determine whether or not the brain recognizes a distinction, either quantitative or qualitative, in processing the two types of noun-verb conceptual anomalies exemplified in sentences (2) and (3) in Table 1. ERPs were measured to critical verbs that, in

[1]Some authors, however, have argued that, because the P600 is not seen in specific association with syntactic parameters, it is not a reliable index of syntactic processing at all [30].

assigning the role of 'agent' to their preceding NPs, violated the pragmatic/semantic constraints of their preceding context. These preceding NPs were either inanimate or animate. As discussed above, from a theoretical perspective, the animacy of NPs is closely bound up with the particular thematic roles they are normally assigned within simple English sentences. Throughout the current article, we refer to the violations exemplified in sentence (2) in Table 1 as 'thematic role animacy violations'. Our use of the term 'animacy violations' conveys the fact that, in all of these sentences, an inanimate NP preceded verbs that assign the role of agent to this NP in simple English sentences (agent-theme or experiencer-theme verbs). Our use of the term 'thematic role violations' indicates that, in these sentences, the inanimate property of the NP was inconsistent with the thematic role of 'agent' that it was assigned by the verb, but that, if the syntax had allowed, the inanimate NP could occupy an alternate thematic role ('theme').

Throughout the current article, we refer to the violations exemplified in sentence (3) as 'non-thematic role pragmatic violations'. We follow Tyler [44] in the use of the term 'pragmatic' for these types of sentences. We do not imply that real-world knowledge is not used in processing the thematic role animacy violated sentences. However, in sentences such as (3), the anomaly could not be determined simply by considering the relationship between the verb and its preceding NP; it could only be determined by considering the entire context of the sentence with respect to one's real world pragmatic knowledge. We use the term 'non-thematic role violations' to underline the fact that, in these sentences, the assigned thematic role of 'agent' to the NP was *not* inconsistent with the fact that a thematic role of agent is likely to be assigned by the verb to its preceding animate NP arguments.

As the detection of both the thematic role animacy and the non-thematic role pragmatic violations requires a pragmatic/semantic analysis, we expected that both types of semantic/pragmatic violations would elicit an N400 effect, the waveform most commonly associated with violations of meaning. If, during online sentence processing, the brain is additionally sensitive to a discrepancy between the thematic role actually assigned to an NP and an alternative thematic role that is more consistent with its animacy features, we predicted that the animacy violations would elicit a qualitatively different waveform from the pragmatic violations. One candidate for this waveform was the P600. This is because, as discussed above, by some theoretical accounts, the thematic relationships between a verb and its arguments are bound up with syntactic information [3,4] to which the P600 is known to be sensitive and/or because, in an attempt to make sense of the sentences, participants might attempt to reassign thematic roles, entailing a syntactic reanalysis, repair [10] or integration [8,21] process.

2. Materials and methods

2.1. Participants

A total of 15 (seven male and eight female) undergraduates from Tufts University aged 18–20 (mean: 19) participated. All participants were right-handed as assessed using the modified Edinburgh Handedness Inventory [32,43]. Selection criteria required all participants to have normal or corrected-to-normal vision and to be native speakers of English. Written consent was obtained from all subjects before participation according to the established guidelines of the Tufts Human Subjects Research Committee.

2.2. Construction of stimuli

A total of 240 verbs were chosen as critical words and sentences providing a constraining context were constructed for each of them (Table 1). All verbs were agent-theme verbs (that assigned the role of agent to the subject NP of an active sentence, e.g. ''Mary'' in ''Mary kicked the table'') or experiencer-theme verbs (that assigned the role of experiencer to the NP of an active sentence (e.g. ''Bill'' in ''Bill feared the mugger''). Each sentence contained an animate NP that was separated from the critical verb by one (and occasionally more than one) word. This was to minimize potential ERP carry-over effects of the NP onto the subsequent critical verb of interest.

In half these sentences, the critical verb was the final word of the sentence and in the other half, the sentence continued with one to five words after the critical verb. This additional manipulation (sentence-embedded versus sentence-final) was introduced because sentence-final words are subject to wrap-up, evaluative and decision processes that could potentially confound more immediate online processes and can modulate the ERP response to critical violated verbs [14]. We were therefore keen to examine the influence of word position on processing these two types of violations.

The thematic role animacy violated sentences were constructed by replacing the animate NP that was assigned the role of agent by the critical verb by an inanimate NP. In all these sentences, the sentence became anomalous on the critical verb. In order that this inanimate NP would not constitute an anomaly in its own right, it was chosen to be in keeping with the overall preceding context of the sentence (although direct semantic relationships with the critical verb were avoided). The non-thematic role pragmatically violated sentences were constructed by replacing the critical verbs with verbs that were chosen pseudo-randomly from sentences of another list (see below).

So that no participant would encounter the same word more than once (leading to repetition priming effects) but

that, across all subjects, all critical verbs would be seen in all four conditions, the sentences were divided into three lists that were counterbalanced between subjects. This excluded the possibility that any differences found between conditions were due to differences in participants' recognition of different words.

The experimental sentences were mixed in with filler sentences that all had inanimate NPs but that used verbs that did not render the sentences violated, e.g. ''If the bomb goes off the whole building will explode''. These fillers ensured that participants read the same number of sentences with critical verbs that were preceded by inanimate NPs as by animate NPs as well as the same number of normal sentences as anomalous sentences. This ensured that participants would not adopt a strategy specific to this particular experiment of predicting that a sentence would be anomalous simply because an inanimate NP was encountered. Thus, in each list, there were 320 sentences: 240 test sentences (80 of each experimental condition) and 80 filler sentences. The same fillers were used in each list (see http://neurocog.psy.tufts.edu/animacyMaterials.htm for a list of all materials).

2.3. Ratings of stimuli

In order to aid the interpretation of some of our findings, we conducted two rating studies to determine (a) overall plausibility of the three sentence types and (b) the semantic relatedness between the critical verbs and their preceding noun in each of the three sentence types.

2.3.1. Overall plausibility

We asked 12 volunteers who did not participate in the ERP study to rate the sentences for plausibility on a 7-point scale, with a 7 indicating that the sentences were very plausible and a 1 indicating that the sentences were implausible. As for the main ERP experiment, the sentences were divided into three lists (each seen by four of the volunteers) to allow for counterbalancing of experimental conditions between participants. Congruous sentences had an average plausibility rating of 6.5 (S.D.: 0.6), sentences with thematic role animacy violations had a rating of 2.7 (S.D.: 0.9) and sentences with non-thematic role pragmatic violations had a rating of 3.3 (S.D.: 1.03). The three sentence types differed significantly in their plausibility on a subjects analysis (in which ratings for each individual were collapsed across items), $F1(2, 22)=60.9$, $P<0.0001$ and on an items analysis (in which ratings for each of the 240 individual sentence scenarios were collapsed across the 12 volunteers), $F2(2, 426)=1196$, $P<0.0001$. Planned pair-wise t-tests showed that the normal sentences were rated as more plausible than the non-thematic role pragmatically anomalous sentences, $t1(11)=19.7$, $P<0.0001$; $t2(213)=39$, $P<0.0001$. On the items analysis (but not the subjects analysis), the non-thematic role pragmatically violated sentences were rated as significantly more plausible than the thematic role animacy violated sentences, $t2(213)=6$, $P<0.0001$.

2.3.2. Semantic relatedness between critical verbs and preceding nouns

We conducted an additional rating study in which we extracted just the critical verbs and their preceding nouns from the sentences and presented these word pairs to an additional 12 volunteers who did not participate in either the ERP study or the plausibility ratings (above). Again, the stimuli were divided into three lists (each seen by four of the volunteers) to allow for counterbalancing of experimental conditions between subjects. These volunteers were asked to give ratings on a 7-point scale according to how closely the noun-verb pairs were related in meaning, with a 7 indicating that the words were highly related and a 1 indicating that the words were unrelated in meaning. Noun-verb pairs from the normal sentences had an average rating of 5 (S.D.: 0.9), noun-verb pairs from the sentences with thematic role animacy violations had an average rating of 3.3 (S.D.: 0.7) and noun-verb pairs from the sentences with non-thematic role pragmatic violations had a rating of 2.8 (S.D.: 0.9). Subjects and items analysis ANOVAs revealed that noun-verb word pairs from the three sentence types differed significantly in their relatedness ($F1(2, 46)=129.49$, $P<0.0001$ and $F2(2, 478)=181.82$, $P<0.0001$, respectively). Planned pair-wise t-tests showed that the noun-verb pairs from the normal sentences were rated as more related in meaning than those from the sentences with thematic role animacy violations, $t1(24)=15.2$, $P<0.0001$; $t2(239)=14.5$, $P<0.0001$, that were, in turn, rated as more related in meaning than noun-verb from the sentences with non-thematic role pragmatic violations $t1(24)=2.9$, $P<0.01$; $t2(239)=2.9$, $P<0.004$.

2.4. Procedure

Experimental participants were randomly assigned to one of three lists used for counterbalancing between participants. Participants sat in a comfortable chair in a dimly lit room separate from the experimenter and computers. Sentences were presented word-by-word on a computer monitor. Each trial (one sentence) began with presentation of a fixation point at the center of the screen for 300 ms followed by a 100-ms blank screen followed by the first word. Each word appeared on the screen for 300 ms with an interstimulus interval (ISI) of 100 ms separating words. The final word of each sentence appeared with a period. A 1100-ms blank-screen interval followed each sentence followed by a ''?''. This cue remained on the screen until the subject made his/her response at which point the next trial started. The subject's task was to decide whether or not each sentence made sense by pressing one of two buttons on a response box with either the left or

right thumb. ''Yes'' and ''No'' response hands were counterbalanced across subjects. Subjects were instructed to wait until the ''?'' cue before responding. This delayed response was designed to reduce any contamination of the ERP waveform by response sensitive components such as the P300 [6]. Each subject was given 12 practice trials at the start of the experiment.

2.5. Electrophysiological recording

A total of 29 active tin electrodes were held in place on the scalp by an elastic cap (Electro-Cap International, Eaton, OH). Several of these electrodes were placed in standard International 10–20 System locations. These included five sites along the midline (FPz, Fz, Cz, Pz, and Oz) and eight lateral (four over each hemisphere) sites (F3/F4, C3/C4, T3/T4, and P3/P4). Also eight extended 10–20 system sites were used (FC1/FC2, FC5/FC6, CP1/CP2, and CP5/CP6) and eight additional 10–20 sites were altered to form a circle around the perimeter of the scalp. These altered sites included FP1′/FP2′ (33% of the distance along the circle between T3/T4), F7′/F8′ (67% of the distance between FPz and T3/T4), T5′/T6′ (33% of the distance between T3/T4 and Oz), and O1′/O2′ (67% of the distance between T3/T4 and Oz). Electrodes were also placed below the left eye and at the outer canthus of the right eye to monitor vertical and horizontal eye movements. Electrodes were also placed on the left and right mastoids.

The EEG signal was amplified by an Isolated Bioelectric Amplifier System Model H&W-32/BA (SA Instrumentation, San Diego, CA) with a bandpass of 0.01–40 Hz and was continuously sampled at 200 Hz by an analogue-to-digital converter. The stimuli presented to participants and their behavioral responses were simultaneously monitored by the digitizing computer.

2.6. Data analysis

Accuracy was computed as the percentage of correct responses. A correct response was a judgment of acceptable for the normal sentences and unacceptable for the anomalous sentences.

Averaged ERPs were formed off-line from trials free of ocular and muscular artifact. The mean of the right and left mastoids was subtracted from all electrode sites to produce algebraically linked mastoids as the reference. All ERPs were time-locked to the critical verb in each sentence. The averaged ERPs were quantified by calculating the mean amplitude values (relative to a 100-ms prestimulus baseline) for the voltage points in three time windows (0–300, 300–500 and 500–800 ms after stimulus onset). The latter two time windows roughly correspond to the windows associated with the N400 and P600 components often reported in studies using linguistic stimuli. The resulting data for each time window were analyzed with analyses of variance (ANOVAs) for repeated-measures. Four separate analyses were performed in order to examine parasagittal columns of scalp electrodes along the anterior–posterior axis of the head (Fig. 1). The midline analysis had repeated-measures on five levels of electrode site from anterior to posterior (FPz, Fz, Cz, Pz, Oz). The medial analysis had three levels of electrode site (FC1/FC2, C3/C4, CP1/CP2) and two levels of hemisphere. The lateral analysis had four levels of electrode site (F3/F4, FC5/FC6, CP5/CP6, P3/P4) and two levels of hemisphere. The peripheral analysis had five levels of electrode site (FP1′/FP2′, F7′F8′, T3/T4, T5′/T6′, O1′/O2′) and two levels of hemisphere. In all cases, sentence type (normal, thematic role animacy violated, non-thematic role pragmatically violated) and the position of the critical verb (sentence-final, sentence-embedded) acted as additional within-subjects variables.

Significant main effects and interactions in these ANOVAs were followed up by planned simple effects ANOVAs that allowed comparisons between each sentence type. In the results tables, significance at $P<0.05$, $P<0.01$, $P<0.001$, and $P<0.0001$ is indicated for each ANOVA. In deciding whether or not a particular effect was significant, we used a standard significance level of $\alpha=0.05$. The Geisser-Greenhouse correction [16] was applied to all repeated measures with more than one degree of freedom in the numerator. In these cases, we report the original degrees of freedom and the corrected probability level.

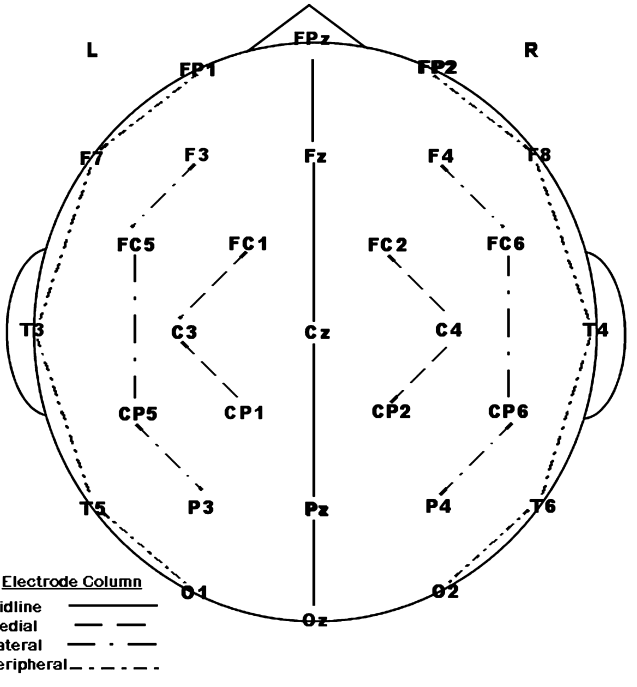

Fig. 1. Electrode montage. Analyses of variance were conducted at each of the four parasagittal columns of scalp electrodes shown (see Materials and methods).

3. Results

3.1. Behavioral data

The accuracy rate (averaged over all subjects) for non-anomalous sentences, thematic role animacy violated and non-thematic role pragmatically violated sentences, was 91, 96 and 88%, respectively. The difference in accuracy rate between the three sentence types approached significance, $F(2, 28)=3.07$, $P=0.062$, with post-hoc pair-wise comparisons showing significantly greater accuracy for the thematic role animacy violated sentences than either the control sentences, $F(1, 14)=5.3$, $P<0.037$, or the non-thematic role pragmatically violated sentences, $F(1, 14)=5.4$, $P<0.035$.

3.2. ERP data

Of all trials, 4 and 8% were rejected for artifact in the sentence-embedded and sentence-final conditions, respectively, and these were roughly evenly distributed across conditions.

ERPs at Pz, Cz and Fz to critical verbs falling at the sentence-embedded and sentence-final positions are shown in Fig. 2. A clear negative–positive complex is seen in the first 300 ms following word onset (the N1–P2 complex). There were no significant main effects of sentence type, condition or hemisphere (Fs<1) and no significant interactions between any of these factors (Fs<1) in the 0–300-ms time-window. The N1–P2 complex is followed by a negative-going component with a peak amplitude around 400 ms (the N400). The amplitude of the N400 elicited by the sentence-embedded critical verbs was generally more negative than that elicited by the sentence-final critical verbs as reflected by significant main effects of word position at all electrode columns (Fs>10, Ps<0.007) in the 300–500-ms time window. These effects were more marked posteriorly than anteriorly, as reflected word position by electrode site interactions at the midline and lateral columns (Fs>5, Ps<0.02) in the 300–500-ms time window.

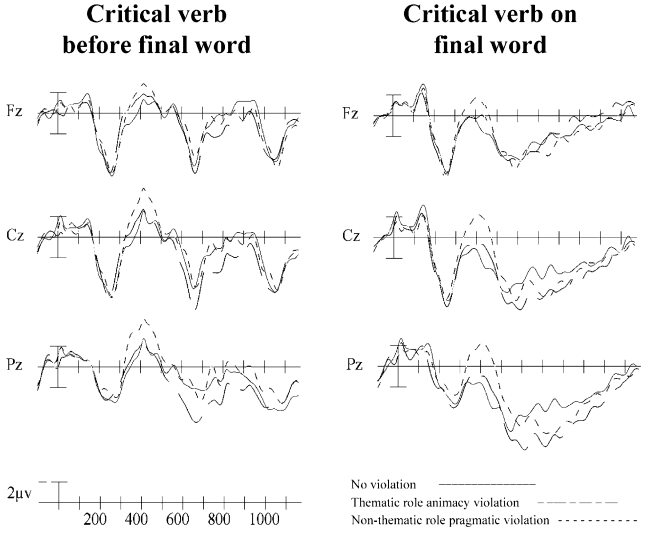

Fig. 2. Averaged waveforms elicited by critical verbs that occur before the end of the sentence (left) and at the end of the sentence (right) at Fz, Cz and Pz. Non-violated verbs (solid) versus thematic role animacy violated verbs (dashed) versus non-thematic role pragmatically violated verbs (dotted).

In some experimental conditions, the N400 waveform was followed by a large late positive-going wave from ~500 to 900 ms (P600). The amplitude of the P600 elicited by the sentence-final critical verbs was generally more positive than that elicited by the sentence-embedded critical verbs as reflected by significant main effects of word position at all electrode columns (Fs>8, Ps<0.01) in the 500–800-ms time window. These effects were more marked posteriorly than anteriorly, as reflected word position by electrode site interactions at the midline and lateral electrode columns (Fs>5; $P<0.01$) in the 500–800-ms time window.

Importantly, there were no significant two-way or three-way interactions that involved both sentence type and word position at any of the electrode columns (all Ps>0.5) for either the 300–500-ms time window or the 500–800-ms time window. Therefore, in Fig. 3, we show the waveforms, at all electrode sites, elicited by critical verbs, collapsed across the sentence-final and sentence-embedded word positions. Below we report the findings of most theoretical interest, i.e. the effects and interactions that involved sentence type at each time window.

3.2.1. Effects and interactions involving sentence type: 300–500 ms

In the 300–500-ms time window, there were significant main effects of sentence type (Table 2, left) and sentence type by electrode site interactions (Table 2, right) at all electrode columns. There were no significant interactions between sentence type and hemisphere. We carried out three planned simple-effects analyses to determine which sentence types differed from each of the other sentence types.

The N400 amplitude elicited by the non-thematic role pragmatic violations was significantly more negative-going than that that elicited by the non-violated verbs, with significant main effects of sentence type at all electrode columns (Table 3, left), and significant interactions between sentence type and electrode site at the midline, lateral and peripheral columns (Table 3, right). These interactions arose because the N400 effect was least marked at the most frontal sites (Fig. 3).

On the other hand, the difference in the N400 amplitude between the thematic role animacy violated and non-violated verbs failed to reach significance at the midline column (all Ps>0.3), and there was only a trend towards significance at the medial ($F(1,14)=4.02$, $P=0.065$),

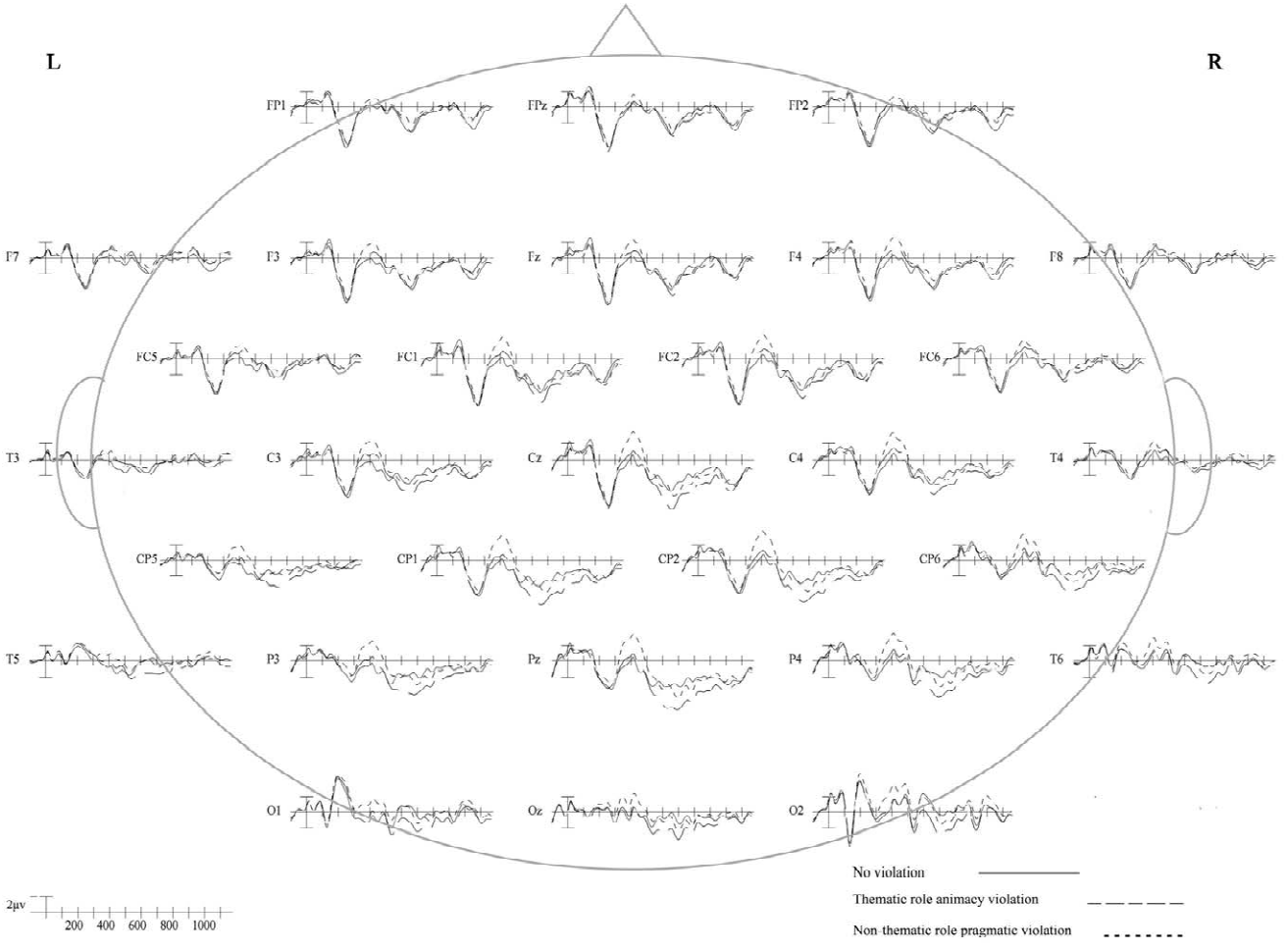

Fig. 3. Averaged waveforms elicited by non-violated verbs (solid) versus thematic role animacy violated verbs (dashed) versus non-thematic role pragmatically violated verbs (dotted) at all scalp electrodes.

lateral ($F(1,14)=3.90$, $P=0.068$) and peripheral ($F(1,14)=3.71$, $P=0.075$) columns. There were no significant sentence type by electrode site interactions at any of the electrode columns (Ps>0.1).

The critical comparison was between the non-thematic role pragmatically violated and the thematic role animacy violated verbs: here the main effect of sentence type was significant at midline and medial electrode columns (Table 4, left), and there were significant interactions between sentence type and electrode site at all four electrode columns (Table 4, right). These interactions again arose because the differences in N400 amplitude between these two sentence types were more marked at central and posterior sites than at frontal sites (Fig. 3).

Table 2
ERP analyses of parasagittal columns of scalp electrodes: 300–500 ms

Analysis	Main effect of sentence type		Interactions between sentence type and electrode site	
	df	F value	df	F value
Midline	2, 28	8.33**	8, 112	3.95**
Medial	2, 28	9.29**	4, 56	3.88*
Lateral	2, 28	7.87**	6, 84	4.08*
Peripheral	2, 28	7.04**	8, 112	4.25*

Main effects of sentence type (three levels) and interactions with electrode site.
*$P<0.05$.
**$P<0.01$.

Table 3
ERP analyses of parasagittal columns of scalp electrodes: 300–500 ms

Analysis	Main effect of sentence type		Interactions between sentence type and electrode site	
	df	F value	df	F value
Midline	1, 14	15.19**	4, 56	7.09**
Medial	1, 14	16.72**	2, 28	3.40
Lateral	1, 14	14.28**	3, 42	4.39*
Peripheral	1, 14	13.96**	4, 56	5.07*

Simple effects ANOVAs: no violation versus non-thematic role pragmatic violations. Main effects of sentence type and interactions with electrode site.
*$P<0.05$.
**$P<0.01$.

Table 4
ERP analyses of parasagittal columns of scalp electrodes: 300–500 ms

Analysis	Main effect of sentence type		Interactions between sentence type and electrode site	
	df	*F* value	df	*F* value
Midline	1, 14	7.42*	4, 56	4.22*
Medial	1, 14	5.64*	2, 28	7.06**
Lateral	1, 14	4.37	3, 42	9.52**
Peripheral	1, 14	3.39	4, 56	9.36**

Simple effects ANOVAs: thematic role animacy violations versus non-thematic role pragmatic violations. Main effects of sentence type and interactions with electrode site.
*$P<0.05$.
**$P<0.01$.

Table 6
ERP analyses of parasagittal columns of scalp electrodes: 500–800 ms

Analysis	Main effect of sentence type		Interactions between sentence type and electrode site	
	df	*F* value	df	*F* value
Midline	1, 14	5.11*	4, 56	5.93*
Medial	1, 14	3.56	2, 28	9.03**
Lateral	1, 14	1.99	3, 42	13.52****
Peripheral	1, 14	1.65	4, 56	7.10**

Simple effects ANOVAs: normal versus animacy violated sentences. Main effects of sentence type and interactions with electrode site.
*$P<0.05$.
**$P<0.01$.
***$P<0.001$.
****$P<0.0001$.

3.2.2. Effects and interactions involving sentence type: 500–800 ms

An overall ANOVA revealed differences in the amplitude of the P600 between the three sentence types with main effects of sentence type that were significant at midline sites (Table 5, left) and highly significant interactions between sentence type and electrode site at all electrode columns (Table 5, right). There were no significant interactions between sentence type and hemisphere.

Simple-effects analyses comparing the thematic role animacy violated verbs with the non-violated verbs revealed a main effect of sentence type at the midline electrode column (Table 6, left) and significant sentence type by electrode site interactions at all electrode columns (Table 6, right). These interactions arose because these differences in the P600 were greater posteriorly than anteriorly (Fig. 3).

As expected, in comparing non-thematic role pragmatically violated verbs with non-violated verbs, there were no significant main effects of sentence type and no sentence type by electrode site interactions at any of the electrode columns (all Ps>0.1).

The P600 elicited by thematic role animacy violated verbs was significantly more positive-going than that elicited by non-thematic role pragmatically violated verbs with significant main effects of sentence type (Table 7, left) and interactions between sentence type and electrode site at all electrode columns (Table 7, right). Again these interactions arose because differences in the amplitude of the P600 were greater posteriorly than anteriorly (Fig. 3).

Table 5
ERP analyses of parasagittal columns of scalp electrodes: 500–800 ms

Analysis	Main effect of sentence type		Interactions between sentence type and electrode site	
	df	*F* value	df	*F* value
Midline	2, 28	4.95*	8, 112	4.32**
Medial	2, 28	3.30	4, 56	5.90**
Lateral	2, 28	2.50	6, 84	8.70****
Peripheral	2, 28	2.96	8, 112	5.63**

Main effects of sentence type (three levels) and interactions with electrode site.
*$P<0.05$.
**$P<0.01$.
***$P<0.001$.
****$P<0.0001$

3.2.3. ERPs to words preceding the critical verb

Fig. 4 shows the ERPs at Pz elicited by the subject NP that preceded the critical verb for each of the three sentence types. The amplitude of the N400 elicited by the inanimate noun (in the thematic role animacy violated sentences) appeared to be slightly more negative-going than that elicited by the animate nouns in the non-violated sentences. This effect was very small (mean voltage difference at Pz: 1.16 μV) and was significant within the 300–500-ms time window only at the midline and medial columns (significant main effects of sentence type at $P<0.02$; no sentence type by electrode site interactions). There were no differences between sentence types in the amplitude ERPs elicited by animate versus inanimate nouns at any of the electrode columns within the 500–800-ms time window (Fs<1). There were no significant differences

Table 7
ERP analyses of parasagittal columns of scalp electrodes: 500–800 ms

Analysis	Main effect of sentence type		Interactions between sentence type and electrode site	
	df	*F* value	df	*F* value
Midline	1, 14	8.41*	4, 56	5.02*
Medial	1, 14	4.79*	2, 28	5.81*
Lateral	1, 14	5.73*	3, 42	7.93**
Peripheral	1, 14	9.20**	4, 56	5.89*

Simple effects ANOVAs: non-thematic role pragmatically anomalous sentences versus animacy violated sentences. Main effects of sentence type and interactions with electrode site.
*$P<0.05$.
**$P<0.01$.
***$P<0.001$.
****$P<0.0001$.

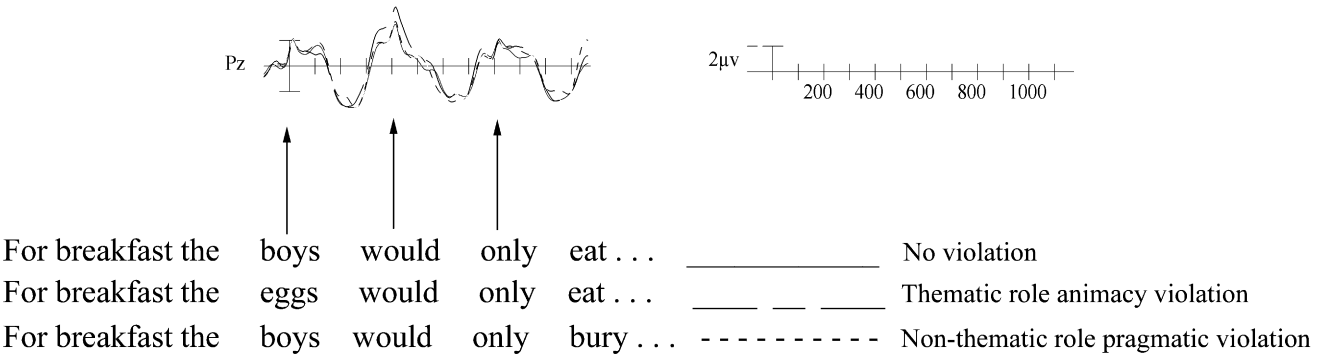

Fig. 4. Averaged waveforms at Pz elicited by words preceding the critical verb (the noun and following words) in non-violated sentences (solid), and thematic role animacy violated sentences (dashed) versus non-thematic role pragmatically violated sentences (dotted).

between sentence types in the ERPs elicited by the words following these nouns but preceding the critical verb in any of the electrode columns in either the 300–500-ms time window or the 500–800-ms time window.

4. Discussion

In this study, we measured ERPs elicited by verbs that were identical across three experimental conditions and across all participants. The only parameter that changed between the three experimental conditions was the verb's preceding context. Our results were clear: when compared to control sentences the non-thematic role pragmatic violations elicited a robust and widespread N400 effect while the thematic role animacy violations elicited a posteriorly distributed P600 effect. Neither of these findings was dependent on whether the critical verb fell in the middle or at the end of a sentence.

The remainder of this discussion focuses on two questions that, for clarity, we consider separately. First, why was the amplitude of the N400 elicited by the non-thematic role pragmatic violations greater than that elicited by the thematic role animacy violations? Second, why was a P600–a waveform traditionally associated with syntactic anomalies–elicited by thematic role animacy violations that, in linguistic terms, are usually considered to be semantic in nature?

4.1. The N400

As discussed in the Introduction, the waveform most commonly associated with violations of meaning is the N400. The amplitude of the N400 elicited by an incongruous word is related to its cloze probability [26]. Both the thematic role animacy and non-thematic role pragmatically violated verbs were very unpredictable. Moreover, the thematic role animacy violated sentences were rated overall as *less* plausible than the non-thematic role pragmatically violated sentences. Therefore, one important question is why the N400 elicited by the thematic role animacy violations was *smaller* (less negative-going) than that elicited by the non-thematic role pragmatic violations. A related question is why the N400 effect elicited by the thematic role animacy violated verbs (in comparison with non-violated verbs) failed to reach significance.

The amplitude of the N400 is thought to reflect the effort of semantically/pragmatically integrating a target into its preceding context. The relatively small N400 effect elicited by the thematic role animacy violated verbs suggests that participants do not engage in this semantic/pragmatic integration process to the same degree as when processing verbs that violated non-thematic role pragmatic constraints. As discussed in the Introduction, the thematic role animacy violations constituted violations of single thematic role assigned by the verb to its preceding NP. It may be that, once this thematic role violation had been detected and the anomaly of the sentence had been established, participants did not attempt to integrate the meaning of the verb into its preceding context to the same degree as in the non-thematic role pragmatic violations, leading to an attenuation of the N400.

A second possibility is that the N400 elicited by the thematic role animacy violations was 'pulled down' by the larger P600 component that followed it (see below), i.e. that there was an interaction between the N400 and P600 components that, to some degree, overlapped in time. This argument, however, would predict that P600/N400 interactions would be largest towards the end of the 300–500-ms epoch and that the N400 effect elicited by the thematic role animacy violations would reach significance at the beginning of this epoch. In fact, there were no significant differences in amplitude between the waveform elicited by thematic role animacy violated verbs and non-violated verbs amplitude at the beginning of this epoch (300–350 ms) at any of the electrode columns.

A third explanation is that the N400 elicited by the critical verb was modulated by the semantic relationship between the critical verb and its preceding subject NP. In constructing the thematic role animacy violated sentences, the inanimate noun was chosen to be in keeping with the overall semantic content of the sentence (although direct

semantic relationships between the subject noun and critical verb and its preceding noun were excluded). A rating study (see Materials and methods) suggested that the nouns and critical verbs used in the thematic role animacy violated sentences were more closely related than those used in the non-thematic role pragmatically violated sentences. Lexico-semantic effects have been shown to operate within sentences in behavioral studies [9]. Moreover, the N400 effect to critical words in sentences can be modulated by the semantic relationships between its individual lexical items [7,27,41]. In the current study, such semantic relationships between the NP and the critical verb may have led to a reduced N400 to the thematic role animacy violated verbs in comparison with the non-thematic role pragmatically violated verbs. This explanation would also account for the trend towards significance in the N400 window for the contrast between thematic role animacy violated and non-violated verbs as there was difference in noun/verb relatedness, albeit a smaller one.

The amplitude of the N400 elicited by the inanimate noun (in the thematic role animacy violated sentences) was slightly more negative-going than that elicited by the animate nouns of the normal sentences. Given the small amplitude of this effect and that the animate and inanimate nouns were not explicitly matched for variables such as frequency and concreteness, this finding should be interpreted with caution. Nonetheless, it is consistent with a previous report that inanimate nouns show larger amplitude N400 effects in the subject positions of sentences [42].

4.2. The P600

Perhaps the most surprising finding in this study was that a P600—a waveform traditionally associated with syntactic anomalies—was elicited by thematic role animacy violations, traditionally considered to be lexico-semantic in nature. Before discussing this finding more fully, we first describe some previous ERP studies of the P600 that are directly relevant to the interpretation of this finding.

As discussed in the Introduction, a P600 effect has been associated with both recoverable and irrecoverable violations of syntax. This waveform has also been associated with syntactic integration difficulty in grammatical, non-garden path sentences [21]. Most relevant to the current findings are reports that the amplitude of the P600 can be modulated by cloze probability and referential information in the discourse preceding the critical word [1,18,39]. Other studies have reported P600 effects in syntactically unambiguous sentences that appear to be modulated *only* by the semantic or pragmatic relationship between that critical word and its preceding context [12,24,42]. For example, Weckerly and Kutas [42] demonstrated a larger amplitude P600 to verbs in relative clauses that were headed by a main animate NP ('Animate (Inanimate)' sentences) than in relative clauses that were headed by a main inanimate NP ('Inanimate (Animate)' sentences). For example, a larger P600 was elicited by the verb, ''inspired'' in the 'Animate (Inanimate)' sentence, ''The novelist that the movie inspired praised the director for staying true to the complicated ending'' than by its counterpart ''praised'' in the 'Inanimate (Animate)' sentence ''The movie that the novelist praised inspired the director to stay true to the complicated ending''. Kolk and colleagues [24] described a significant P600 to verbs that violated the pragmatic constraints of their preceding arguments, e.g. to the verb ''fled'' (that, in Dutch, occurs after its arguments ''cat'' and ''mice'') in a sentence such as ''The cat that fled from the mice ran across the room''/''De kat die voor de muizen vluchtte, rende door de kamer''. Friederici and Frisch [12] reported a significant P600 to verbs that were violated with respect to the thematic constraints of their arguments when these arguments preceded the verb.

These studies have come to the same main overall conclusions that, under some circumstances, semantic and pragmatic parameters can have an immediate (i.e. online word-by-word) influence on the build up of the structure of a sentence. What is remarkable about the findings in the current study is that the conceptually anomalous critical verbs that elicited the P600 effect were presented within simple, unambiguous English sentences.

One potential explanation for these findings presupposes that the P600 is elicited because it is sensitive to violations of generalizable rules (see evidence that the P600 is sensitive to violations in rhythm in music in Ref. [37]). By this argument, a P600 was elicited by violations of animacy information because these constitute violations of generalizable lexico-semantic rules. There are, however, several arguments against this explanation. First, it is difficult to draw clear boundaries between some semantic features that are uniquely 'generalizable' (such as animacy information) and other finer-grained semantic distinctions. Second, as discussed above, under some circumstances, a P600 can also be elicited by semantic/pragmatic violations that do not violate animacy constraints [24]. Third, a P600 is not always elicited by animacy selectional restriction violations: Rösler and colleagues [38] measured ERPs to critical verbs in selection restriction (including animacy) violated sentences such as ''the honey is being murdered''. In these sentences, the verb appeared in its passive participle form. Although the NP arguments (e.g. ''honey'') violated the animacy constraints of the critical verb (e.g. ''murder''), an N400, rather than a P600, was elicited.

Our favored explanation for why a P600 was elicited by the animacy violated verbs is that lexico-semantic animacy information was used to build up a thematic structure during language processing and the P600 is sensitive to violations in this thematic structure. In the thematic role animacy violated sentences, the inanimate subject NP (''eggs'' in sentence (2), Table 1) is likely to occupy the

thematic role of 'theme', i.e. ''eggs'', being inanimate, can be eaten. When ''eggs'' is assigned the role of 'agent' by the critical verb, a P600 is elicited as a result of the discrepancy between its probable thematic role and its assigned thematic role. In the pragmatically violated sentences, the thematic role assigned by the verb to its preceding NP (''boys'') is consistent with its animate lexico-semantic properties and a P600 is not elicited.

We do not conceive of the build-up of thematic structure as a slow-acting, strategic expectancy mechanism that began before the verb is encountered and involved the generation of a particular expectancy set. The reason that plausible fillers containing inanimate NPs were included was to discourage such a strategy. Rather, we suggest that, when the verbs that rendered the sentences pragmatically/semantically anomalous were encountered, this triggered a process by which the thematic roles actually assigned to individual words were evaluated against the thematic roles that are most consistent with each word's lexico-semantic features. Consistent with this explanation is the finding that, although the animacy of the nouns that preceded the critical verbs in these sentences was registered (see earlier discussion of the N400 elicited by animate versus inanimate nouns), there were no significant differences between sentence types in the amplitude of the ERP effects elicited by the words that followed the nouns and that preceded the critical verbs. This suggests that the animacy information only had a real impact once the verb was presented.

This raises the question of exactly what process was indexed by the P600. There are several possibilities that cannot be distinguished by the current experiment. One account is that the P600 reflects the monitoring or checking process itself [24]. A second possibility is that the P600 reflects the cost of syntactically integrating the verb into the ongoing thematic structure (see Gibson [15] for a similar account). Kaan [21] proposed that the amplitude of the P600 indexed the cost of such integration. A third possibility is that the P600 reflects an online attempt to structurally repair the sentence by reassigning thematic roles so that the sentences make pragmatic/semantic sense [11]. Thus, in sentence (2), ''eggs'' would be reassigned the role of 'theme'. By this account, the more difficult it is to reassign the thematic role of previously encountered lexical items, the greater the amplitude of the P600. This would predict that the amplitude of the P600 effect would be influenced by the precise fit between the critical verb and its preceding inanimate NP if this NP were to play the role of 'theme' in the sentence. We are currently carrying out an experiment to test these predictions.

Regardless of the precise mechanism by which the P600 is generated, these findings have two important implications. First, the fact that the P600—a waveform generally associated with *syntactic* variables—is sensitive to violations in likely thematic structure is consistent with the idea that the same or similar neurocognitive processes are engaged in processing thematic and syntactic information. We are currently testing this hypothesis directly by comparing the morphology and scalp distribution of the P600 elicited by these types of animacy violations with morphosyntactic violations. Second, the fact that this P600 is distinct from the N400 effect elicited by non-thematic role pragmatic violations in the same experiment, suggests that different neural processes can be engaged in processing different types of noun-verb semantic relationships within simple English sentences.

It is possible that, in the current experiment, the N400 and P600 are functionally related. Recall that, in the discussion of the N400 above, we suggested that the N400 elicited by the thematic role animacy violated verbs was small (relative to that elicited by the non-thematic role pragmatically violated verbs) because, once participants had detected the thematic role violation, they did not engage in further attempts to semantic/pragmatically integrate the meaning of the verb into its preceding context. Here we suggest that at least part of the process of attempting to integrate or repair the thematic role violations is reflected by the P600[2].

5. Summary and conclusion

We have demonstrated qualitatively different waveforms elicited by two different types of conceptual noun-verb violations in simple English sentences. The N400 arose when the particular thematic role assigned by the verb to its preceding NP was inconsistent with the overall context of the sentence. We suggest that the P600 was elicited by the animacy violations and not by the pragmatic violations because, in the former but not the latter, the verb assigned a thematic role to an NP that was different from the thematic role dictated by the inanimate lexico-semantic property of that NP. This may have triggered efforts to repair the sentences that involved syntactic restructuring. Such processes may be reflected, in part, by the P600 component although the precise determinants of this waveform remain to be more fully described.

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[2]This account presumes that the processes reflected by N400 and P600 overlap, to some degree, in time. The earlier part of the process reflected by the P600 might affect the latter part of the process reflected by the N400.

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