

The role of animacy and thematic relationships in processing active English sentences: Evidence from event-related potentials

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Abstract

Recent event-related potential studies report a P600 effect to incongruous verbs preceded by semantically associated inanimate noun-phrase (NP) arguments, e.g., “eat” in “*At breakfast the eggs would eat...*”. This P600 effect may reflect the processing cost incurred when semantic–thematic relationships between critical verbs and their preceding NP argument(s) bias towards different interpretations to those dictated by their sentences’ syntactic structures. We have termed such violations of alternative thematic roles, ‘thematic role violations.’ Semantic–thematic relationships are influenced both by semantic associations and by more basic semantic features, such as a noun’s animacy. This study determined whether a P600 effect can be evoked by verbs whose thematic structures are violated by their preceding inanimate NP arguments, even in the absence of close semantic–associative relationships with these arguments or their preceding contexts. ERPs were measured to verbs under four conditions: (1) non-violated (“*At breakfast the boys would eat...*”); (2) preceded by introductory clauses and animate NPs that violated their pragmatic expectations but not their thematic structures (“*At breakfast the boys would plant...*”); (3) preceded by semantically related contexts but inanimate NPs that violated their thematic structures (“*At breakfast the eggs would eat...*”); (4) preceded by semantically unrelated contexts and inanimate NPs that also violated their thematic structures (“*At breakfast the eggs would plant...*”). Pragmatically non-thematic role violated verbs preceded by unrelated contexts and animate NPs evoked robust N400 effects and small P600 effects. Thematically violated verbs preceded by inanimate argument NPs evoked robust P600 effects but no N400 effects, regardless of whether these inanimate arguments or their preceding contexts were semantically related or unrelated to these verbs. These findings suggest that semantic-thematic relations, related to animacy constraints on verbs’ arguments, are computed online and can immediately impact verb processing within active, English sentences.

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1. Introduction

Most linguists would agree that the syntax and semantics constitute different types of information (Chomsky, 1965). For psycholinguists, a central question is how these different types of information come together to form a final

representation of meaning as we process language online. This question has been explored using a number of different psycholinguistic paradigms. Marslen-Wilson, Brown, and Tyler (1988) and Tyler (1992) measured times to monitor for target words that constituted different types of linguistic violations within sentences. Their findings suggested that both a verb’s semantic and syntactic information are used immediately and incrementally to buildup a representation of sentence meaning. More recently, reaction time and eye-movement studies provide further evidence that semantic,

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pragmatic, and syntactic information are rapidly combined to resolve local syntactic ambiguities within sentences (Boland & Tanenhaus, 1991; Ferreira & Clifton, 1986; Frazier & Rayner, 1982; MacDonald, Pearlmutter, & Seidenberg, 1994; Stowe, 1989; Tanenhaus & Carlson, 1989; Trueswell & Tanenhaus, 1994).

Additional insights into the fast, online interaction between semantic and syntactic processes come from event-related potentials (ERPs). ERPs, measured on the surface of the scalp, are a direct neurophysiological index of online brain activity. Traditionally, distinct ERP components have been closely associated with different levels of language processing. The N400 component—a negative-going waveform peaking at approximately 400ms post-stimulus onset—is modulated by semantic context (Kutas & Hillyard, 1980), cloze probability (Kutas & Hillyard, 1984) and the structure of semantic memory (Federmeier & Kutas, 1999; Kutas & Federmeier, 2000; Kutas & Hillyard, 1984). The N400 is thought to reflect the difficulty of integrating the *meaning* of a word into its preceding context (Holcomb, 1993). Syntactic anomalies and ambiguities, on the other hand, have been associated with an anteriorly-distributed negativity, sometimes left-lateralized and therefore called the LAN (Friederici, 1995; Kluender & Kutas, 1993; Neville, Nicol, Barss, Forster, & Garrett, 1991), and/or a later component with an onset between 500–800ms and a duration of several hundred milliseconds—the P600 (Hagoort, Brown, & Groothusen, 1993; Osterhout & Holcomb, 1992).

These associations between distinct ERP components and distinct levels of linguistic processing, however, are not perfect. The N400 is known to be modulated by the syntactic assignment of thematic roles to NPs within sentences as well as by lexico-semantic factors (Hoeks, Stowe, & Doedens, 2004; Van Petten, 1993). And the P600 evoked by syntactic violations or ambiguities is known to be modulated by semantic variables (Friederici & Frisch, 2000; Gunter, Friederici, & Schriefers, 2000; Gunter, Stowe, & Mulder, 1997). Perhaps the most striking example of a dissociation between semantic processing and the N400, and between syntactic processing and the P600 comes from a group of studies that have reported a robust P600 effect but an absent or very small N400 effect to unambiguously semantically violated verbs within simple sentences.

Kuperberg, Caplan, Sitnikova, Eddy, and Holcomb (2006) and Kuperberg, Sitnikova, Caplan, and Holcomb (2003) reported a P600 effect, and an absent N400 effect, to verbs such as “eat” in sentences such as, “*At breakfast, the eggs would eat every day.*” Kim and Osterhout (2005) also described a P600 effect and no N400 effect to verbs such as “*devouring*” in sentences such as “*The meal was devouring...*” Hoeks et al. (2004) demonstrated that sentence-final verbs such as “*thrown*” (that, in Dutch, occur after their arguments) in sentences such as “*The javelin has thrown the athletes*”/“*De speer heeft de atleten geworpen*” evoked a clear P600 effect but no N400 effect. And two recent studies by Kolk, Chwilla, van Herten, and Oor (2003) and van Herten, Kolk, and Chwilla (2005) document a significant P600

to verbs such “*fled*” (again occurring after their arguments) in sentences such as “*The cat that from the mice fled ran across the room*”/“*De kat die voor de muizen vluchtte rende door de kamer.*”

How can these findings be interpreted and what do they tell us about normal language processing? Although there is debate about exactly what process the P600 reflects—syntactic integration (Fiebach, Schlesewsky, & Friederici, 2002; Kaan, Harris, Gibson, & Holcomb, 2000), syntactic reanalysis (Friederici, 1995), thematic reanalysis or integration (Kuperberg, Sitnikova, et al., 2003) or monitoring (Kolk et al., 2003; van Herten et al., 2005)¹—there is a consensus that the P600 elicited in these studies reflects a processing cost that results when the semantic relationship between a critical verb and its preceding noun-phrase (NP) argument(s) biases towards a different interpretation of the sentence than that dictated by the syntax. In our studies, we have termed such violations of potential semantic relationships by syntactically assigned thematic roles, ‘thematic role (TR) violations’. The finding of a P600 to such TR violations is consistent with the idea that semantic information can have an immediate and online word-by-word impact on language processing (Boland & Tanenhaus, 1991; MacDonald et al., 1994; Tanenhaus & Carlson, 1989; Trueswell & Tanenhaus, 1994). It also leaves open additional questions regarding the precise types of semantic relationships that are strong enough to bias towards an interpretation that, when disconfirmed by the syntactic assignment of thematic roles, leads to a processing cost.

One possibility is that *only* close lexico-semantic associations between a verb, its preceding argument(s) and its preceding context will bias towards a potentially plausible interpretation that can conflict with the alternative interpretation dictated by the syntax, i.e., that the primary trigger for the P600 in TR violated sentences is a close lexico-semantic relationship between a critical verb, its preceding argument(s) and other content words. In all the studies discussed above, the critical verb that evoked a P600 was, at least to some degree, semantically related to its preceding noun argument(s): “*eggs*”; “*eat*” in Kuperberg et al. (2006, 2003); “*meal*”; “*devouring*” in Kim and Osterhout (2005) “*fled*”; “*cat*”; “*mice*” in Kolk et al. (2003) and van Herten et al. (2005), and “*javelin*”; “*athletes*”; “*thrown*” in Hoeks et al. (2004).

A second related possibility is that such lexico-semantic associations trigger a P600 because they are part of something even more fundamental about the relationship between a verb and its preceding argument(s). We have suggested that this may be their thematic relationship (Kuperberg, Sitnikova, et al., 2003)—the semantic relationship that ultimately determine the, higher order representation of the

¹ There is also controversy about whether the P600 constitutes part of the P300 family of waveforms and, consequently, whether it indexes a general updating of contextual information within memory (Donchin & Coles, 1988) rather than processes that are specific to the language system (Coulson, King, & Kutas, 1998; Osterhout & Hagoort, 1999).

sentence (Jackendoff, 1978). We suggested that all likely thematic relationships between nouns and arguments are evaluated in parallel to the assignment of syntactic structure and that it is the mismatch between these likely thematic roles and the thematic roles actually assigned by the syntax that leads to the processing cost reflected by the P600 (Kuperberg, Sitnikova, et al., 2003). Similar explanations were given by Kim and Osterhout (2005) and Hoeks et al. (2004) who also conceived of the P600 as reflecting a mismatch between the most likely and actual thematic roles assigned by a verb to its preceding argument(s).

Thematic relationships may encompass the lexico-semantic associations between a noun and its argument (Ladusaw & Dowty, 1988). However, they are also influenced by other information including the syntactic properties of the verb (Chomsky, 1981) and more basic semantic features that are generalizable across different verb and noun meanings. One such feature is animacy. In simple English sentences, the animacy of NPs is closely bound up with the particular thematic roles that such NPs are normally assigned by particular verbs (Jackendoff, 1972). For example, consider the verb “eat.” The thematic properties of this verb dictate that it must assign the role of Agent to an animate NP; the role of Theme would more likely be assigned to an inanimate NP. Thus, the sentence, “*For breakfast, the eggs would eat...*,” is anomalous because the thematic structure of “eat” is inherently incompatible with “eggs” being assigned the role of Agent. However, had the syntax allowed, the inanimate property of “eggs” could have allowed it to occupy the role of Theme. In our studies (Kuperberg et al., 2006; Kuperberg, Sitnikova, et al., 2003), the study by Kim and Osterhout (2005), (Experiment 1) and the study by Hoeks et al. (2004), the verb that evoked a P600 effect was preceded by an inanimate subject NP. We suggested that the inanimate nature of the subject noun in these sentences may have been a factor leading to the P600 on the critical verbs. For example, in the sentence, “*For breakfast, the eggs would eat...*,” it may have been the inanimate nature of the subject-noun “eggs” paired with the verb “eat”—not simply the fact that “eggs” is lexico-semanticly associated with “eat”—that led to a processing cost and a P600 on “eat” (Kuperberg, Sitnikova, et al., 2003).

ERP evidence for the role of animacy in processing simple, unambiguous sentences is somewhat conflicting. Kim and Osterhout (2005) conducted a follow-up experiment (Experiment 2) in which they introduced an animacy violation on a verb that was not lexico-semanticly related to its preceding content NP argument (they termed these “no attraction violations”), e.g., “*The dusty tabletops were devouring ...*”. These anomalies evoked an N400 effect but not a significant P600 effect. They concluded that, in the sentences of their Experiment 1, e.g., “*The meal was devouring...*”, it was the strong ‘semantic attraction’ between the verb and its argument subject NP, rather than the inanimacy of that subject NP, that was the critical factor in evoking the P600 effect. On the other hand, in the study by Hoeks et al. (2004), verbs that were not semantically related

or associated with their preceding context, such as “*summarized*” in the sentence, “*The javelin has summarized the athletes*”/“*De speer heeft de atleten opgesomd*”, did elicit a robust P600 effect. These anomalies, however, fell on sentence-final words that are known to evoke sentence ‘wrap-up’ related positivities, making the findings more difficult to interpret.

There is some evidence for the role of animacy in processing more complex sentences. Behavioral and eye-movement studies suggest that animacy can influence the resolution of syntactic ambiguity (Stowe, 1989; Tanenhaus & Carlson, 1989; Trueswell, Tanenhaus, & Garnsey, 1994), and the processing and/or interpretation of non-canonical sentences such as passives (Ferreira, 2003), object-clefts (Ferreira, 2003), and object-relative clauses (Chen, West, Waters, & Caplan, 2005; Traxler, Morris, & Seely, 2002). Moreover, an ERP study of object-relative clauses reported that, when the most likely thematic roles based on animacy information contradicted the thematic roles assigned by the verb, the cost in processing that verb was reflected by a P600 effect (Weckerly & Kutas, 1999).

The question we asked in the current study is whether, in simple, active, canonical English sentences, verbs that assigned the role of Agent to subject NPs would evoke a P600 or an N400 when such subject NPs were inanimate in nature but were not associated semantically with these verbs. We measured ERPs to critical verbs as subjects viewed the same types of sentences as in our previous study: (a) non-violated sentences, (b) sentences that were less plausible with respect to real-world knowledge than the non-violated sentences, and in which the subject NPs were animate in nature and did not violate the thematic structure of the critical verbs (‘pragmatically non-thematic role violated sentences’), (c) sentences in which the subject NPs were inanimate in nature, violating the thematic structure of the critical verbs, but lexico-semanticly associated with those verbs and/or other preceding content words (‘related animacy thematic role (TR) violated sentences’). In addition, we introduced a fourth sentence type: (d) sentences in which the subject NPs were again inanimate in nature, violating the thematic structure of the critical verb, but lexico-semanticly unrelated to either their preceding arguments or to other preceding content words. We termed such violations ‘unrelated animacy thematic role (TR) violations’. For examples of sentences and further explanation of our nomenclature, see Table 1.

As in our previous studies, we expected to see a P600 effect on the verb “eat” in related animacy TR violated sentences, e.g., “*For breakfast the eggs would eat...*” If the key factor that gave rise to this P600 effect was the relatively close lexico-semantic relationships between the critical verb (“eat”) and its preceding argument and content words (“eggs” and “breakfast”), then this would predict that unrelated animacy TR violated verbs such as “plant” in “*For breakfast the eggs would plant...*” would fail to evoke a P600 effect. Instead such verbs might, as in the study by Kim and Osterhout (2005), Experiment 2,

Table 1
Types of linguistic violation

Linguistic violation	Explanation	Example
(1) No violation	Baseline condition against which the other conditions are evaluated	<i>“For breakfast the boys would <u>eat</u> toast and jam”</i>
(2) Pragmatic ^a non-thematic role (non-TR) violation	The critical verb is replaced by another verb taken from another sentence scenario. This makes the sentence pragmatically/semantically implausible	<i>“For breakfast the boys would <u>plant</u> flowers in the garden”</i>
(3) Related animacy thematic role (TR) violation ^b	The animate subject NP preceding the critical verb is replaced by an inanimate subject NP that is lexico-semantically related to the preceding content words but that still makes the sentence pragmatically/semantically implausible	<i>“For breakfast the eggs would <u>eat</u> toast and jam”</i>
(4) Unrelated animacy thematic role (TR) violation ^b	The animate subject NP preceding the critical verb is replaced by an inanimate subject NP as described above but the critical verb is replaced by a critical verb from another scenario such that it is lexico-semantically unrelated to its preceding content words	<i>“For breakfast the eggs would <u>plant</u> flowers in the garden”</i>

Critical verbs (to which ERP responses were measured) are underlined in the examples.

^a We follow Marslen-Wilson et al. (1988) in the use of the term ‘pragmatic’ for these types of violations. We do not imply that they describe impossible scenarios: they all describe possible scenarios that are less plausible with respect to our real-world knowledge than the non-violated sentences. We also do not imply that real-world knowledge is not used in processing the animacy TR violated sentences. What distinguishes these pragmatically non-TR violated sentences from the animacy TR violated sentences in the current study is that the pragmatic violation could not be determined simply by considering the relationship between the subject noun and the verb: it could only be determined by relating the plausible noun–verb relationship to the incongruous preceding context (in this case, the adjunct prepositional phrase “for breakfast”).

^b Our use of the term ‘animacy TR violation’ conveys the fact that, in all of these sentences, an inanimate subject NP was used together with verbs that assign the role of an animate Agent to their preceding subject noun in simple English sentences (Agent-Theme or Experiencer-Theme verbs). In these sentences, the thematic structure of the critical verbs was violated.

generate an N400 effect because “*plant*” is semantically unrelated to its subject NP. If, on the other hand, the key factor that gave rise to the P600 effect to “*eat*” in the related animacy TR violated sentences was the inanimate nature of the subject NP, violating the inherent thematic structure of the verb “*eat*,” then this would predict that unrelated animacy TR violated verbs such as “*plant*” would evoke at least as large a P600 effect as related animacy TR violated verbs. This would provide evidence that thematic relationships are influenced by basic semantic features such as animacy—not just close lexico-semantic relationships—and that such features are evaluated online and can influence the parsing of simple unambiguous sentences.

In addition to our predictions about the modulation of the P600, we were also interested in how the N400 component would be modulated by each of these sentence types. As outlined above, in the studies by Kuperberg et al. (2006, 2003), Kim and Osterhout (2005) (Experiment 1), Hoeks et al. (2004), Kolk et al. (2003), and van Herten et al. (2005), verbs that evoked a P600 also evoked either an absent or a very small N400 effect. In all these sentences, critical verbs were lexico-semantically associated with their preceding argument(s) and/or content words. Thus, one reason for the attenuation of the N400 to critical verbs in these sentences is that they were lexico-semantically primed by their preceding argument(s) and other individual content words. Such lexico-semantic priming effects are known to operate within sentences (Foss & Ross, 1983) and can attenuate the amplitude of the N400 (Federmeier & Kutas, 1999; Kutas & Federmeier, 2000; Van Petten, 1993). A second possibility is that such lexico-

semantic priming was not the only factor attenuating the N400 to critical verbs in thematic role violated sentences, but that this attenuation was also driven by the thematic role violation itself, i.e., by the same variable that we suggest evokes a P600. On this account, the same underlying process, starting within a time-window of overlap between these two waveforms, both attenuates the N400 and evokes a P600. This could occur via two mechanisms: either the overlapping posteriorly-distributed P600 effect might cancel out any appearance of the N400 effect (of opposite polarity) at the scalp surface, and/or the cost of processing, indexed by the P600, might serve to attenuate the semantic/pragmatic integration, reflected by the attenuated N400.

The current study allowed us to determine what was the primary factor attenuating the N400 to thematic role violations: lexico-semantic priming or the presence of a P600 (reflecting the TR violation) beginning within the N400 time window. The role of lexico-semantic effects was assessed by comparing the amplitude of the N400 to related and unrelated animacy TR violations. Lexico-semantic priming would predict a smaller N400 to the related than to the unrelated animacy TR violations. The role of an overlapping P600 in attenuating the N400 was assessed by comparing the N400 to pragmatic non-TR violations with the N400 to unrelated animacy TR violations. If, in earlier studies, the main factor in attenuating the N400 to related animacy TR violations relative to pragmatic non-TR violations was lexico-semantic priming, the amplitude of the N400 to the unrelated animacy TR violations in the current study should be comparable to the N400 evoked by pragmatic non-TR violations. If,

on the other hand, the attenuation of the N400 was driven by the animacy TR violation itself, reflected by the overlapping P600, then the N400 should be smaller to unrelated TR animacy violations than to pragmatic non-TR violations.

2. Materials and methods

2.1. Participants

Sixteen (thirteen male and three female; mean age: 45) subjects were recruited by advertisement. All participants were right-handed as assessed using the modified Edinburgh Handedness Inventory (Oldfield, 1971; White & Ashton, 1976). All participants had normal or corrected-to-normal vision, were native speakers of English, were not taking any medication, and were screened to exclude the presence of psychiatric disorders and neurological disorders. Written consent was obtained from all subjects before participation according to the established guidelines of the Massachusetts General Hospital and the Tufts New England Medical Center Institutional Review Boards.

2.2. Construction and classification of stimuli

Two-hundred and forty verbs were selected and sentences providing a constraining context were constructed for each of them (see Table 1). All verbs assigned the role of Agent or Experiencer to the subject of an active sentence, e.g., “Mary” in “Mary kicked the table” or “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) auxiliary word. This was to minimize potential ERP carry-over effects of the NP onto the critical verb of interest. None of the critical verbs were sentence-final words: in all sentences the critical verb was followed by two to six words. The pragmatic non-TR violated sentences were constructed from the normal sentences by replacing the critical verbs with verbs that were chosen pseudorandomly from sentences of another list (see below), such that there were no lexico-semantic relationships between the critical verb and its preceding argument(s) and content words. All these sentences described scenarios that were possible but that were less plausible with respect to our real-world knowledge than the non-violated sentences. This was confirmed by plausibility ratings described by Kuperberg, Sitnikova, et al. (2003): non-violated sentences were rated as more plausible (mean: 6.5; *SD*: 0.6) than pragmatic non-TR violated sentences (mean: 3.3; *SD*: 1.03), $t(11) = 19.7, p < .0001, t(213) = 39, p < .0001$.

Related animacy TR violated sentences were constructed by replacing the animate NP with an inanimate NP. These inanimate NPs were chosen to be lexico-semanticly associated with the verb and/or one or more of the content words in the preceding context. Thus, sometimes the critical verbs were semantically related to the subject noun-phrase and sometimes to other content words in the

preceding context.² The unrelated animacy TR violated sentences were constructed from the related animacy TR violated sentences by replacing the critical verbs with verbs that were chosen pseudorandomly from sentences of another list (see below), such that there were no lexico-semantic relationships between the critical verb and its preceding argument(s) and content words.

So that no participant would encounter the same word more than once (leading to repetition priming effects) but so that, across all subjects, all critical verbs would be seen in all four conditions, the sentences were divided into four 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.

Thus, in each list, there were 240 test sentences (60 of each of the four experimental conditions: normal sentences, pragmatically non-TR violated sentences, related animacy TR violated sentences and unrelated animacy TR violated sentences). To summarize the distinctions between the three types of violated sentences: (a) Pragmatic non-TR violations differed from the related animacy TR violations in two ways: (i) the presence of an animate rather than an inanimate NP Agent (i.e., the absence of an animacy TR violation between the critical verb and its argument) and (ii) a more distant semantic fit between the critical verb and both its preceding argument and other preceding content words. (b) Related animacy TR violated verbs had a closer semantic fit with both their preceding arguments and other previous content words than the unrelated TR violated verbs. (c) Unrelated animacy TR violated sentences had an inanimate subject NP (an unlikely Agent), but pragmatic non-TR violated sentences had an animate subject NP (a likely Agent). All stimuli can be downloaded from <http://www.nmr.mgh.harvard.edu/kuperberglab/publications.htm>.

2.3. ERP procedure

Each subject was given 12 practice trials at the start of the experiment. Participants were randomly assigned to one of the four lists used for counterbalancing. 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 450 ms, followed by a 100 ms blank screen, followed by the first word. Each word appeared on the screen for 450 ms with an interstimulus interval (ISI) of 100 ms separating words.

² Although individual critical verbs and subject NPs were not all highly semantically related in these sentences, a previous rating study reported by Kuperberg, Sitnikova, et al. (2003) established that, as a group, the NP-verb combinations in the pragmatic non-TR violated sentences were rated as significantly less semantically related (mean: 2.8; *SD*: 0.9) than the NP-verb combinations in the related animacy TR violated sentences (mean: 3.3, *SD*: 0.7), $t(1) = 2.9, p < .01; t(239) = 2.9, p < .004$.

The final word of each sentence appeared with a period. A 750 ms blank-screen interval followed the final word in 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 their left or right thumb. Subjects were told that sentences may not make sense in different ways and that if sentences seemed at all “odd” or unlikely, they should indicate that it doesn’t make sense. “Yes” and “No” button responses 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 (Donchin & Coles, 1988).

2.4. Electrophysiological recording

Twenty-nine active tin electrodes were held in place on the scalp by an elastic cap (Electro-Cap International, Eaton, OH), see Fig. 1. 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). Eight extended 10–20 system sites were also 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 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 Hand 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.

2.5. ERP 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 violated sentences. Averaged ERPs were formed off-line from trials free of ocular and muscular artifact. The averaged ERPs elicited by critical verbs were quantified by calculating the mean amplitude values (relative to a 100 ms prestimulus baseline) for the voltage points in two time windows: 375–500 ms and 550–850 ms after stimulus onset.

Linearly interpolated voltage maps showing the scalp distribution of differences in ERPs elicited by critical verbs (violated minus non-violated) within the 375–500 ms and 550–850 ms time windows were produced by the EMSC Data Editor program (Source Signal Imaging).

The resulting data for each time window were analyzed with analyses of variance (ANOVAs) for repeated-measures. ERPs were analyzed separately for midline and lateral electrode sites. The ANOVA for midline electrodes included an electrode site factor (from anterior to posterior: FPz, Fz, Cz, Pz, and Oz). To examine distributional differences across the scalp in both left–right and anterior–posterior dimensions, we carried out ANOVAs comparing right and left-sided parasagittal columns: medial, lateral, and peripheral. The medial analysis had three levels of electrode site (FC1/FC2, C3/C4, and CP1/CP2) and two levels of hemisphere. The lateral analysis had four levels of electrode site (F3/F4, FC5/FC6, CP5/CP6, and P3/P4) and two levels of hemisphere. The peripheral analysis had five levels of electrode site (FP1’/FP2’, F7’/F8’, T3/T4, T5’/T6’, and O1’/O2’) and two levels of hemisphere.

We proceeded straight to planned simple effects ANOVAs that compared pairs of sentence types as we had specific a priori hypotheses for each of these comparisons. In these analyses, two levels of sentence type were within-subject factors in addition to the factors described above. To protect against Type I error resulting from violations of sphericity, the Geisser–Greenhouse correction (Greenhouse & Geisser, 1959) was applied to all repeated measures with more than one degree of freedom in the numerator. In these

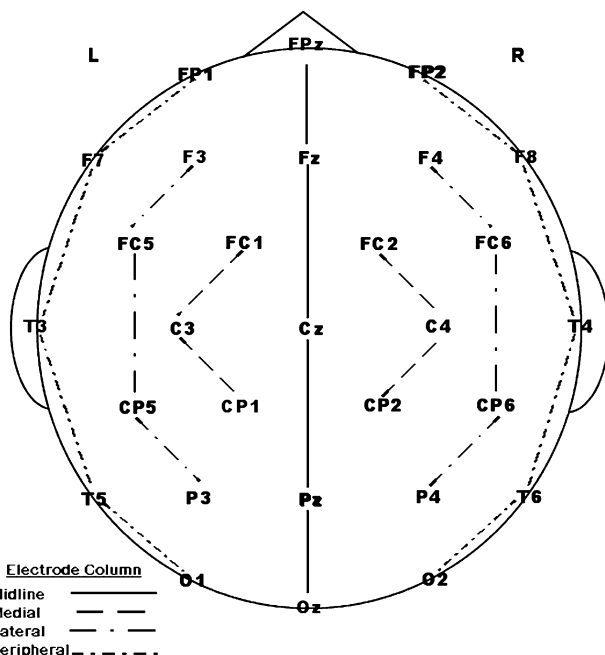


Fig. 1. Electrode montage. Analyses of variance were conducted at each of the four parasagittal columns of scalp electrodes shown (see Section 2.5).

cases, we report the original degrees of freedom and the corrected probability level. In reporting whether or not a particular effect was significant, we followed the modified Bonferroni procedure (Keppel, 1991) and set alpha to 0.025 for all comparisons.

3. Results

3.1. ERP data: Comparisons between the four main sentence types

Approximately 4% of the trials were rejected for artifact and there were no significant differences in the percentage of rejected trials across experimental conditions, $F(3,45)=0.97$, $p=.41$. Only trials that were answered correctly were included in the ERP analyses.

Grand-average ERPs elicited by the critical verbs in the four main conditions are shown at all electrode sites in Fig. 2 and at selected electrode sites in Fig. 3. A negative–positive complex in the first 300 ms after word onset (the N1–P2 complex) was followed by a negative-going component with a peak amplitude at around 450 ms—the N400. In some experimental conditions, the N400 was followed by a large late positive-going wave starting from approximately 550—the P600. Below, we report statistical analyses comparing ERPs elicited by the critical verbs within time windows selected to capture the N400 and P600 effects.

3.1.1. 375–500 ms: The N400

The N400 evoked by the pragmatic non-TR violations appeared to be more negative-going than the N400 evoked by critical verbs in all other sentence types. In contrasting pragmatic non-TR violations with non-violated verbs, there were significant main effects of sentence type at all but the medial electrode column (midline: $F(1,15)=9.15$, $p=.009$; medial: $F(1,15)=5.76$, $p=.03$; lateral: $F(1,15)=12.61$, $p=.003$; peripheral: $F(1,15)=12.52$, $p=.003$), and a significant sentence type by electrode site interaction at the peripheral column ($F(4,60)=4.37$, $p=.01$). In contrasting pragmatic non-TR violations with related animacy TR violations, there were significant main effects of sentence type at the lateral and peripheral columns (midline: $F(1,15)=6.17$, $p=.025$; medial: $F(1,15)=6.054$, $p=.026$; lateral: $F(1,15)=6.47$, $p=.022$; peripheral: $F(1,15)=6.315$, $p=.023$). In contrasting pragmatic non-TR violations with unrelated animacy TR violations, there was a significant main effect of sentence type at the midline column ($F(1,15)=6.43$, $p=.023$) and significant interactions with electrode site at all columns (midline: $F(4,60)=8.840$, $p=.001$; medial: $F(2,30)=13.113$, $p=.0001$; lateral: $F(3,45)=7.970$, $p=.001$; peripheral: $F(4,60)=4.93$, $p=.012$). In addition, there was a significant sentence type by hemisphere interaction at the lateral column ($F(1,15)=13.92$, $p=.002$) and significant sentence type by electrode site by hemisphere interactions at the medial ($F(2,30)=12.39$, $p=.0001$) and peripheral ($F(4,60)=7.54$, $p=.002$) columns. There were no signifi-

cant differences in the N400 evoked by either related or unrelated animacy TR violations relative to non-violated verbs (related animacy TR violated versus non-violated: all F 's < 2.4, all p 's > .16; unrelated animacy TR violated versus non-violated: all F 's < 3.4, all p 's > .05). A direct contrast between unrelated and related animacy TR violations also revealed no significant differences in the N400 amplitude (all F 's < 2.4, all p 's > .12).

3.1.2. 550–850 ms: The P600

As expected, the P600 elicited by the related animacy TR violations was more positive-going than that evoked by non-violated verbs, reflected by significant main effects of sentence type at all electrode columns (midline: $F(1,15)=17.54$, $p=.001$; medial: $F(1,15)=17.74$, $p=.001$; lateral: $F(1,15)=10.26$, $p=.006$; peripheral: $F(1,15)=7.46$, $p=.015$). There were significant sentence type by electrode site interactions at the midline ($F(4,60)=11.38$, $p=.0003$), lateral ($F(3,45)=15.792$, $p<.0001$) and peripheral ($F(4,60)=10.10$, $p=.0001$) electrode columns, reflecting a larger P600 effect at posterior than anterior sites (Figs. 2B and 3). This effect was left lateralized as reflected by significant sentence type by electrode site by hemisphere interactions at all electrode columns (medial: $F(2,30)=20.85$, $p<.0001$; lateral: $F(3,45)=4.86$, $p=.017$; peripheral: $F(4,60)=23.12$, $p<.0001$).

The P600 evoked by unrelated animacy TR violations was also more positive-going than that elicited by non-violated verbs (Figs. 2C and 3), manifest by significant main effects of sentence type at all but the peripheral electrode column (midline: $F(1,15)=10.33$, $p=.006$; medial: $F(1,15)=11.69$, $p=.004$; lateral: $F(1,15)=7.81$, $p=.014$; peripheral: $F(1,15)=5.39$, $p=.035$). Once again, this effect had a posterior and left-lateralized scalp distribution, as reflected by significant interactions between sentence type and electrode site at all columns (midline: $F(4,60)=12.62$, $p=.0003$; medial: $F(2,30)=7.00$, $p=.01$; lateral: $F(3,45)=20.49$, $p<.0001$; peripheral: $F(4,60)=14.04$, $p<.0001$) and significant interactions between sentence type, electrode site and hemisphere at all columns (medial: $F(2,30)=16.83$, $p<.0001$; lateral: $F(3,45)=10.74$, $p=.001$; peripheral: $F(4,60)=19.66$, $p<.0001$).

A direct comparison between the P600 elicited by unrelated and related animacy TR violations revealed some evidence of a more positive-going P600 effect to the unrelated than to the related animacy TR violations at some posterior and right-lateralized sites. This was reflected by a significant sentence type by electrode site interaction at the medial column ($F(2,30)=11.22$, $p=.001$) and interactions that approached significance between sentence type and electrode site (lateral: $F(3,45)=3.44$, $p=.034$), sentence type and hemisphere (lateral: $F(1,15)=3.48$, $p=.082$), and sentence type, electrode site and hemisphere (peripheral: $F(4,60)=3.46$, $p=.053$).

In comparing pragmatic non-TR violations and non-violated verbs, there was a small centro-posteriorly distributed P600 effect (Figs. 2A and 3). This was reflected by

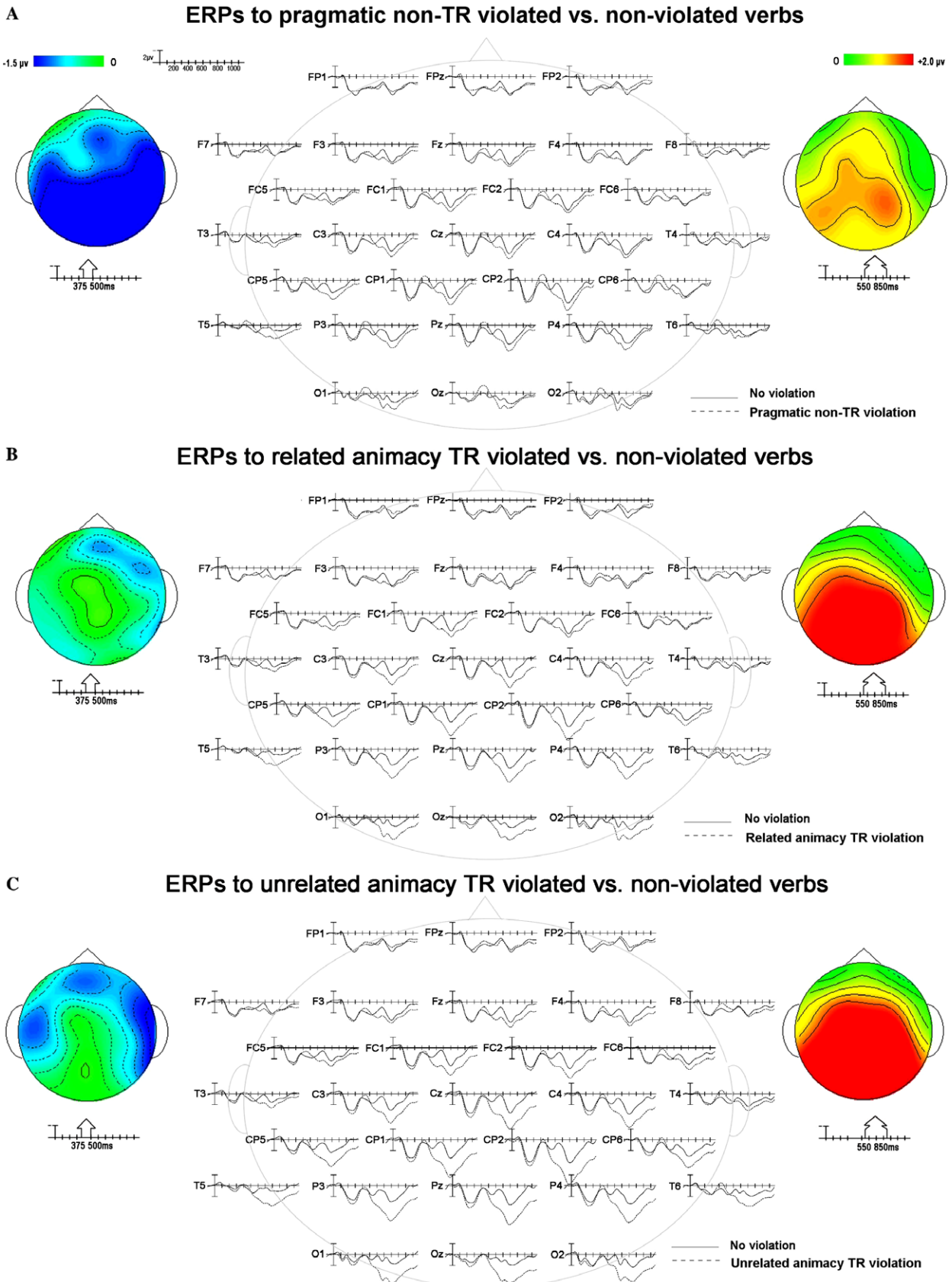


Fig. 2. Averaged waveforms elicited by non-violated verbs versus different types of violated verbs within sentences. For each comparison, ERPs elicited by non-violated (solid) and violated (dotted) critical verbs are shown at all electrode sites. Voltage maps illustrate the spatial distribution of the N400 effects (375–500 ms) and P600 effects (550–850 ms) on the left and right respectively to each type of violation versus non-violated verbs.

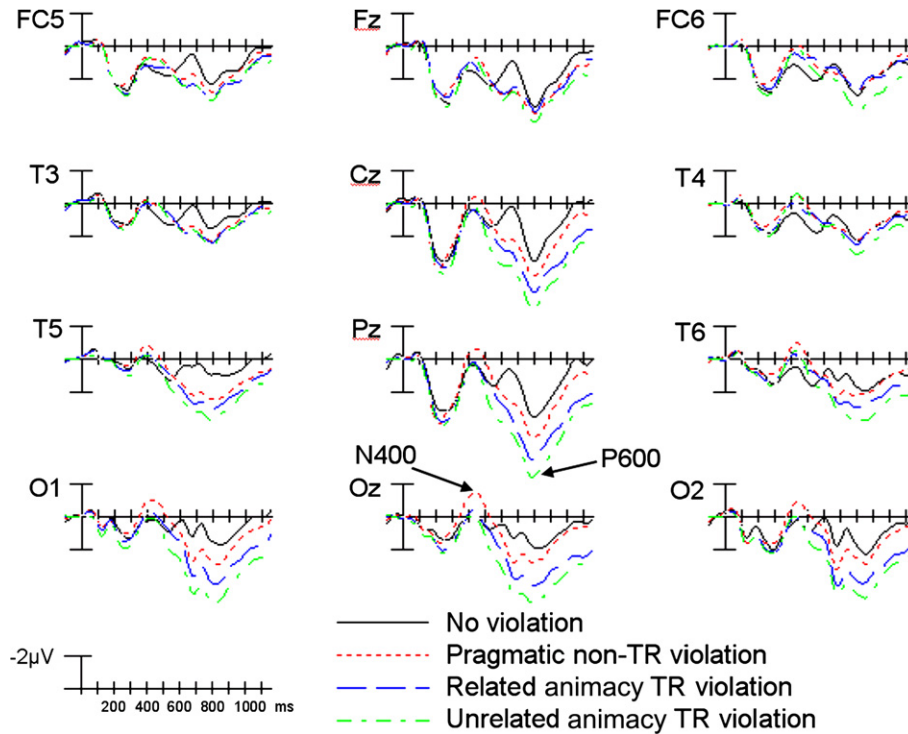


Fig. 3. Averaged waveforms elicited by critical verbs at four selected electrode sites. Non-violated verbs (black solid) versus pragmatically non-TR violated verbs (red dotted) versus related animacy TR violated verbs (blue long-dashed) versus unrelated animacy TR violated verbs (green bold solid).

main effects of sentence type at the medial column ($F(1, 15) = 6.31, p = .024$), as well as by significant interactions between sentence type and electrode site at the lateral ($F(3, 45) = 5.50, p = .009$) and peripheral ($F(4, 60) = 4.171, p = .014$) columns. This effect, however, was significantly smaller than the P600 effect evoked by both related and unrelated animacy TR violations, particularly at posterior and left-lateralized sites. This was reflected by significant interactions between sentence type and electrode site and/or hemisphere in comparing pragmatic non-TR violations with both related and unrelated animacy TR violations. Specifically, the contrast between pragmatic non-TR violations and related animacy TR violations revealed significant interactions between sentence type and electrode site at all but the medial column (midline: $F(4, 60) = 11.735, p < .0001$; medial: $F(2, 30) = 2.53, p = .105$; lateral: $F(3, 45) = 9.26, p = .0002$; peripheral: $F(4, 60) = 4.6, p = .006$), as well as significant interactions between sentence type electrode site, and hemisphere at the medial ($F(2, 30) = 19.73, p < .0001$) and peripheral ($F(4, 60) = 7.85, p = .0003$) columns. Similarly, the contrast between pragmatic non-TR violations and unrelated animacy violations revealed significant interactions between sentence type and electrode site at all columns (midline: $F(4, 60) = 20.282, p < .0001$; medial: $F(2, 30) = 18.66, p < .0001$; lateral: $F(3, 45) = 14.21, p < .0001$; peripheral: $F(4, 60) = 9.65, p < .0001$) and sentence type by electrode site by hemisphere interactions at the medial ($F(1, 15) = 23.16, p < .0001$) and peripheral ($F(4, 60) = 18.37, p < .0001$) columns.

3.2. ERPs to words preceding the critical verb

The amplitude of the N400 elicited by the inanimate subject nouns (in both types of animacy TR violated sentences) was significantly more negative-going than the N400 elicited by the animate subject nouns (in the non-violated sentences and pragmatic non-TR violated sentences), manifest by main effects of sentence type across all columns that reached or approached significance (all $F_s > 5.9$; all $p_s < .03$). There were no differences in the amplitude of the P600 evoked by animate versus inanimate subject nouns (no main effects of sentence type or interactions with electrode site, all $F_s < 2.2$; all $p_s > .15$). Auxiliaries following animate subject nouns evoked a slightly more negative ERP between 300–500 ms than those following inanimate subject nouns (main effects of sentence type across all columns: all $F_s > 7.9$; all $p_s < .02$), but there were no significant differences in the 500–800 ms time window (no main effects of sentence type or interactions with electrode site, all $F_s < 5.9$; all $p_s > .025$). It is therefore unlikely that electrophysiological differences on or after the animate versus inanimate subject NPs carried over on to the critical verbs.

3.3. Summary of ERP findings

Pragmatic non-TR violations evoked a robust, widespread N400 effect (relative to non-violated verbs) that was maximal at centro-posterior sites. Neither the related nor the unrelated animacy TR violations revealed significant N400 effects (relative to non-violated verbs). There

Table 2
Accuracy as a function of sentence type

Sentence type	Mean % correct (SD)
Non-violated	92.3 (5.27)
Pragmatically non-TR violated	82.1 (11.06)
Related animacy TR violated	96.7 (4.39)
Unrelated animacy TR violated	98.3 (1.83)

were no significant differences in the N400 evoked by related and unrelated animacy TR violations.

Both related and unrelated animacy TR violations evoked significant P600 effects that were widespread but maximal at left posterior electrode sites. Both related and unrelated animacy TR violated verbs elicited significantly more positive P600s than non-violated and pragmatically non-TR violated verbs.

3.4. Behavioral accuracy data

The accuracy of acceptability judgments (averaged over all participants) to all sentence types is shown in Table 2. An ANOVA revealed significant differences in accuracy across the four sentence types, $F(3,45) = 23.798$, $p < .001$. Pair-wise comparisons showed that subjects were less accurate in judging the acceptability of pragmatic non-TR violated sentences than non-violated sentences ($t(15) = 3.83$, $p < .01$), related animacy violated sentences ($t(15) = 5.52$, $p < .001$), or unrelated animacy violated sentences ($t(15) = 6.412$, $p < .001$). Acceptability judgments to non-violated sentences were less accurate than to related ($t(15) = 2.253$, $p < .05$) and unrelated ($t(15) = 4.717$, $p < .001$) animacy TR violated sentences. There were no significant difference in accuracy between the two types of animacy TR violated sentences, $t(15) = 1.71$, $p = .1$.

4. Discussion

This study explored the factors modulating the N400 and P600 ERP waveforms within simple, active, unambiguous English sentences. As in our previous studies (Kuperberg et al., 2006, 2003) and as demonstrated by other groups (Hoeks et al., 2004; Kim & Osterhout, 2005), verbs that were semantically related to their preceding inanimate argument or other preceding content words but that assigned this argument the implausible thematic role of Agent, evoked a significant P600 effect and no N400 effect. In this study, we further demonstrated that a robust P600 effect and an absent N400 effect were evoked by verbs that were neither semantically related to their preceding inanimate arguments, nor to other preceding individual content words, nor to the overall meaning of their preceding context.

4.1. Animacy, thematic roles, and the P600

The demonstration of a robust P600 to animacy violated verbs that were semantically unrelated to their preceding inanimate arguments is consistent with another study in

which we subdivided related animacy TR violated sentences into those in which there was a close potential thematic fit between the subject NP and the critical verb (e.g., eggs-eat) and those where this thematic fit was more distant (e.g., trumpets-curtsey) (Kuperberg et al., 2006). In that study, we defined ‘potential thematic fit’ as being the thematic fit between the critical verb and its preceding inanimate NP if that NP were to play the alternative thematic role of Theme around the verb.³ We found that both sentences with a close and more distant potential thematic fit between the critical verb and inanimate NP evoked a robust P600 effect. In fact, just as in the current study, the amplitude of the P600 was slightly more positive to verbs that had a more distant versus a closer potential thematic fit with their preceding inanimate NP. The current study builds upon this finding: because critical verbs in the unrelated animacy TR violated sentences were not only semantically unrelated to their preceding inanimate arguments, but also to other non-argument content words in the preceding context, our data suggests that neither semantically related contexts nor close lexico-semantic relationships between a verb and its argument are prerequisites for a P600 to be elicited by animacy TR violations.

Given that the main difference in constructing the pragmatic non-TR violations and the unrelated animacy TR violations in the current study was the animacy of the subject NP, we deduce that the animacy violation played a role in evoking a P600. Below, we argue that the P600 was evoked by the animacy violations in the current study because they constituted TR violations, i.e., because the thematic structure of such verbs required the subject NP Agent to be animate and their inherent thematic structure was violated by the inanimate nature of these NPs.

Animacy information has long been known to play a crucial role in assigning syntactic roles. Although encoded within the lexical semantic entry of the verb, the animacy of an argument affects the choice or interpretation of nouns in specific syntactic positions (Chomsky, 1965). For example, consider how the animacy of a subject NP is interpreted in relation to a particular verb: in the case of the verb “eat”, its subject NP will always be interpreted as animate, even if it has never been previously encountered. Thus, in the sentence, “The zogarions would eat,” the word “zogarions” is interpreted as being animate (Radford, 1997). Conceptualized in terms of thematic roles, a true Agent or Experiencer must be always animate for a sentence to be plausible (unless it is understood metaphorically) (Jackendoff, 1978). In the current study, we selected Agent-Theme or

³ In Kuperberg et al. (2006), potential thematic fit was operationalized by collecting plausibility ratings of passivized versions of the related animacy TR violated sentences. For example, in “When John arrived at the restaurant, the food would order...,” “food” is an unlikely Agent but a likely Theme for “order,” and the sentence, “When John arrived at the restaurant, the food would be ordered...” is plausible. In the sentence, “When they greeted the Queen of England the trumpets would curtsey...,” “trumpets” is not only an unlikely Agent but also an unlikely Theme for “curtsey,” and the sentence, “When they greeted the Queen of England the trumpets would be curtseyed...” is implausible.

Experiencer-Theme verbs that assigned the role of true Agent or Experiencer to their preceding subject NP, avoiding verbs that could plausibly assign inanimate NPs the role of PseudoAgent. Such pairings, regardless of the more precise lexico-semantic relationships between NPs and verbs, therefore violated the inherent thematic structure of such verbs, i.e., constituted thematic role violations.

4.2. Other studies examining the effects of animacy on sentence processing

Finding that animacy and thematic relationships between a verb and NP can lead to an online processing cost when such relationships contradict the interpretation assigned by the syntax, comes as little surprise to those who have examined the resolution of syntactic ambiguity. It has been known for some time that the animacy of a subject NP can influence the processing of a verb. In a classic experiment, Ferreira and Clifton (1986) examined eye fixations within sentences such as “*The defendant/evidence examined by the judge...*” Reading times were longer to the verb “*examined*” when it was preceded by an inanimate subject NP (“*evidence*”) than when it was preceded by an animate NP (“*defendant*”). Subsequent studies using similar types of sentences (Trueswell et al., 1994) and other syntactically ambiguous sentences have demonstrated that animacy and finer-grained thematic relationships, influencing the evaluation of plausibility, can have an immediate effect on syntactic disambiguation (MacDonald et al., 1994; Stowe, 1989; Tanenhaus & Carlson, 1989).

There is also evidence using a variety of techniques—behavioral, eye-movement, ERP, and fMRI—that animacy and thematic information play important roles in processing (and even interpreting) unambiguous non-canonical sentences that require thematic roles to be assigned in an atypical order. Ferreira (2003) and colleagues have shown that participants often wrongly identify the thematic roles of NPs in passive thematically violated sentences (e.g., “*The mouse was eaten by the cheese*”) and cleft-object sentences (e.g., “*It was the dog that the man bit*”). In an eye-movement study, Traxler et al. (2002) demonstrated longer first-pass eye-fixations on the clause of object-relative (OR) sentences in which the head noun of the relative clause was animate and the subject noun of the relative clause was inanimate (AI sentences, e.g., “*The director that the movie pleased received a prize at the film festival*”) in comparison with OR sentences in which the head noun of the relative clause was inanimate and the subject noun of the relative clause was animate (IA sentences, e.g., “*The movie that the director watched received a prize at the film festival*”). Analogous findings were reported by Weckerly and Kutas (1999) who, in an ERP study, reported a more positive P600 on verbs in the relative clause of AI than IA sentences and by Chen et al. (2005) who, in an fMRI study, documented increased activity in a network of regions (left inferior and dorsolateral prefrontal cortices as well as left inferior parietal regions) to AI relative to IA sentences. These longer fixa-

tion times, P600 effects and increased functional activation at the relative clause in AI (relative to the IA) sentences might, just as in the current study, reflect the processing cost associated with a discrepancy between the most likely roles of NPs around the verb and the roles actually assigned by the syntax: inanimate NPs (such as “*movie*” in the example above) are likely Themes but unlikely Agents, while animate NPs (such as “*director*”) are likely Agents but unlikely Themes. However, at the verb “*pleased*,” the syntax assigned the role of Agent to “*movie*” but the role of Theme to “*director*.”

4.3. A P600 is not always associated with animacy violations

Although we think that the animacy violations in the current study played an important role in evoking a P600, we are not arguing a P600 will always result when subject NPs are inanimate in nature. First, on a theoretical level, inanimate subject nouns can be plausibly paired with certain verbs, acting as PseudoAgents (e.g., “*the bus drove down the road*”). Second, evidence from other electrophysiological studies suggests that violations of animacy constraints do not always evoke a P600 (Kim & Osterhout, 2005, Experiment 2), and that a P600 can be evoked by unambiguous semantic/pragmatic violations without animacy constraints being violated (Kolk et al., 2003; van Herpen et al., 2005). Below, we discuss these two studies in more detail.

In their Experiment 2, Kim and Osterhout (2005) failed to evoke a P600 to verbs preceded by lexico-semantically unrelated inanimate NPs (their ‘no attraction violations’). Verbs such as “*devouring*” in sentences such as “*The dusty tabletops were devouring thoroughly*” evoked an N400 but not a P600 effect. One reason for this is that, in such sentences, the inherent thematic structure of the particular verbs that were used was not always violated: approximately 45% these verbs could have assigned thematic roles other than Agent (including PseudoAgents) to inanimate subject NPs. For example, although the verb “*curing*” is semantically violated in the sentence “*Billy’s unruly hair was curing...*,” this particular verb would be able to assign a plausible thematic role of PseudoAgent to a different inanimate subject NP, e.g., “*medicine*.”

A second difference between the sentences used by Kim and Osterhout (2005) and those used in the current study is that, in Kim and Osterhout’s study, sentences consisted of only a NP–verb–NP whereas in our sentences, there was usually a short preceding introductory clause prior to the subject NP. This context may have acted in several ways to lead to a P600 rather than an N400 to the unrelated animacy violated sentences in the current study. First, the very presence of a preceding context, in combination with the plausibility judgment task, might have motivated participants to consider potential semantic–thematic relationships between a critical verb and its preceding NP argument(s), increasing the conflict between such potential thematic relationships and the thematic roles actually assigned by the syntax. Second, the

preceding context may have biased parsers towards a considering an alternative syntactic structure and away from the NP–verb–NP structure of the main clause of the sentence, leading to increased syntactic processing difficulty at the point of the verb.⁴ Third, the incongruous pragmatic content may have interacted with the animacy violation to increase the implausibility of the thematic roles assigned by the verb. On this account, the P600 is modulated not only by the presence of alternative thematic–semantic relationships to those actually assigned by the syntax but by the degree of implausibility of the sentence once those roles are assigned. A role of plausibility in modulating the P600 could also help explain why the P600 was slightly larger to the unrelated TR violations than to the related TR violations at some electrode sites: the unrelated animacy TR violations were more implausible than the related animacy TR violations, both because of their more distant lexico-semantic associations between the critical verbs and inanimate subject NPs and because of their more incongruous pragmatic contexts.⁵

A fourth difference between the current study and Kim and Osterhout's study was in the types of control sentences used. Kim and Osterhout included a passive control plausible condition in which the verb was always semantically related to the NP (e.g., “*The hearty meal was devoured...*”). This might have biased participants towards considering only NPs that were *both* semantically associated with the subject NP and that were inanimate as potential Themes. In the current study, plausible passives weren't included, making it more likely that participants considered all inanimate NPs as potential Themes of our critical verbs.

Just as Kim and Osterhout's Experiment 2 illustrates that a P600 is not invariably evoked by animacy violations, there is also evidence that animacy violations are not required for a P600 to be elicited: a P600 can be evoked by semantic/pragmatic violations that do not violate the animacy constraints of their preceding argument. This is clearly illustrated by the experiments described by Kolk et al. (2003) and van Herten et al. (2005). The reversal violations used in

⁴ However, as in our previous studies (Kuperberg et al., 2003; Kuperberg, Sitnikova, et al., 2003), we saw no clear evidence for increased syntactic processing difficulty in the ERPs before the critical verb: there were no differences in the P600 (or a LAN) waveform to the inanimate relative to the animate NPs or to the word after the animate versus inanimate NPs. The inanimate subject nouns, however, did evoke a larger N400 than the animate nouns and it is possible that the increased semantic processing difficulty at the point of encountering the inanimate nouns may have encouraged subjects to try harder, at the point of the verb, to syntactically integrate or reanalyze the entire preceding context to make sense of these sentences, leading to a P600 on both related and unrelated animacy TR violated verbs.

⁵ We have suggested that a sensitivity of the P600 to plausibility may, in part, reflect the difficulty of making sense of these sentences through thematic or syntactic reanalysis, once a discrepancy between likely and assigned thematic roles has been detected (Kuperberg et al., 2006). On this account, the more positive P600 elicited by unrelated (relative to related) animacy TR violations may have reflected a more prolonged and/or greater attempt to reanalyze and repair such sentences across individual trials and subjects, see Kuperberg et al. (2006) for further discussion.

these studies (e.g. “*The cat that from the mice fled ran across the room/De kat die voor de muizen vluchtte, rende door de kaamer*”), however, still fall under our definition of thematic role violations, i.e. violations of potential thematic-semantic relationships by the implausible assignment of thematic roles by the syntax. In these sentences, the P600 was evoked on the verb “*fled*” that, in Dutch, comes after its arguments “*cat*” and “*mice*.” We would argue that this verb violated the most likely thematic roles that its preceding arguments, “*cat*” and “*mice*,” are likely to play around it: the actual assignment of thematic roles led to an implausible interpretation of the sentence. In this case, the violation is between a verb and more than one argument, but we would still consider the implausible assignment of thematic role(s) by a verb as contradicting more likely thematic role(s) that these argument(s) could play in this sentence.⁶

4.4. The relationship between the P600 and the N400

As in our other studies (Kuperberg et al., 2006, 2003), related animacy TR violations failed to evoke an N400 effect (relative to non-violated verbs). We had previously suggested that this attenuation of the N400 might be due to lexico-semantic priming of the critical verbs by preceding semantically-related individual content words (Federmeier & Kutas, 1999; Foss & Ross, 1983; Kutas & Federmeier, 2000; Van Petten, 1993). However, in the current study, the unrelated animacy TR violations also failed to evoke a significant N400 effect and there was no significant difference between the N400 to the related and unrelated animacy TR violations. Given that the pragmatic non-TR violations evoked a robust N400, this suggests that the N400 to both types of animacy violations—both related and unrelated—was attenuated by the thematic violation itself—the same factor that we suggest led to the P600 effect.

⁶ As pointed out by an anonymous reviewer, a previous study by Mecklinger, Schriefers, Steinhauer, and Friederici (1995) measured ERPs in German object-relative sentences in which the meaning of the past participle biased towards the assignment of different thematic roles to those that were most likely (at the point of the participle) on the basis of syntactic structure. For example, in sentences such as “*Das ist die Studentin, die die Professorinnen geprüft...(haben)*”/ “*This is the student that the professors examined (have)*,” before encountering the past participle, “*geprüft*,” the subject-object parsing preference biases towards “*Studentin*” taking the role of Agent and “*Professorinnen*” taking the role of Theme. However, upon encountering “*examined*,” the semantics biases towards the assignment of the opposite thematic roles (although, in these sentences, at the point of the participle, the meaning was still ambiguous and the syntax only unambiguously assigned thematic roles at the point of the auxiliary, “*haben*”). These sentences were compared with OR sentences in which the participle did not bias towards alternative thematic roles, e.g., “*Das ist die Studentin, die die Professorinnen gesucht...(haben)*”/ “*This is the student that the professors sought (have)*.” Mecklinger et al. (1995) showed no difference in the modulation of early positivities between such semantically biasing and neutral object-relative sentences at the point of the auxiliary. Interestingly, however, examination of the waveforms suggests that the participle may have evoked a larger P600 in the semantically biasing than in the neutral object-relative sentences. Activity within this time-window was not reported by Mecklinger et al. (1995).

One possibility is that the N400 was generated but appeared to be attenuated because of cancellation at the scalp surface by the overlapping P600.⁷ A second possibility is that, at least under circumstances where semantic-thematic and syntactic information conflict, the neurocognitive operations indexed by the N400 and the P600 might be functionally and reciprocally linked (see Kuperberg et al., 2003 for consistent fMRI evidence). In other words, semantic integration (reflected by the N400) may have been attenuated by the cost in processing reflected by the P600; once the thematic role violation was detected (reflected by the early part of the P600), participants may not have engaged in further attempts to semantic/pragmatically integrate the meaning of the verb into its preceding context (reflected by the attenuation of the N400). The current study cannot distinguish these two possibilities. What it does show, however, is that the underlying processes reflected by the N400 and P600 began within the same time window.

4.5. What process does the P600 reflect?

It is clear that P600 reflects a neurocognitive process that is influenced by syntactic, thematic and semantic information. Different models of language processing make different assumptions about whether thematic and semantic information exert their main influence before or after an initial syntactic or thematic structure is established, and therefore about the process reflected by the P600 and other earlier ERP positivities seen in association with language processing. In serial models (Frazier, 1987), syntactic structure is initially established, and the P600 is held to reflect a syntactic revision or reanalysis of this structure that can be influenced by thematic as well as pragmatic and contextual information (Friederici, 1995). If thematic roles have already been assigned by the syntax (e.g., on the basis of case markings), then positivities seen in association with verbs that disconfirm this thematic assignment are held to reflect the reanalysis of this thematic structure (Bornkessel, Schlewsky, & Friederici, 2002; Bornkessel, Schlewsky, & Friederici, 2003). Other models hold that alternative thematic roles that are computed earlier can remain active and exert their influence, even after the establishment of a particular thematic structure by the syntax. Indeed, there is evidence that, even when syntax unambiguously assigns one set of thematic roles on a verb, alternative roles can remain active and even influence interpretation, particularly of syntactically complex sentences (Ferreira, 2003). In constraint based models, such alternative thematic roles are thought to modulate the construction of syntactic representations (MacDonald et al., 1994; Tanenhaus, Spivey-Knowlton, Eberhard, & Sedivy, 1995) and the P600 would be considered to reflect the diffi-

culty of syntactic integration (Fiebach et al., 2002; Kaan et al., 2000). In heuristic models (Caplan & Waters, 2003; Ferreira, 2003), alternative thematic activations are conceived, not as necessarily modulating the activation levels of syntactic frames, but rather as acting directly, and the P600 might reflect the cost of monitoring or checking the incoming representation of the sentence against world-knowledge (Kolk et al., 2003; van Herten et al., 2005).

The current study provides evidence that alternative thematic roles are activated even in simple unambiguous sentences. However, we do not think that our findings distinguish between whether such alternative roles exert their effects as part of a first or a second stage process. Indeed, as we have discussed in another study (Kuperberg et al., 2006), the P600 evoked by violations of thematic roles may well reflect more than one process.⁸

4.6. When is a P600, rather than an N400 evoked by semantic violations?

Taken together with previous findings, the current study suggests that various factors may act in consort to trigger and modulate the P600. Specifically, we have suggested that a P600, as opposed to an N400, is evoked when participants consider alternative semantic-thematic relationships as opposed to the thematic roles actually dictated by the syntax. This may occur either when there exist plausible or congruous alternative thematic roles for NPs to play in a sentence or when the assigned thematic roles appear completely impossible (rather than just implausible). Participants may be more likely to consider alternative thematic roles when they are explicitly asked to attend such sentences' meaning during a plausibility judgment task, when the structure of surrounding sentences suggests that it is possible to make sense of the semantic violations, or in the presence of a preceding context that, by its very presence, may suggest to readers that it is possible to make sense of the violated sentences. Anything that could bias away from parsing the syntax correctly, such as syntactic ambiguity or syntactic complexity, might also encourage alternative semantic/thematic relationships to be considered, again leading to a P600 as opposed to an N400 on semantically violated verbs.

This leads to predictions about when a P600 can be evoked by semantic/pragmatic anomalies. Although conflicts between an impossible assignment of thematic roles and possible alternative thematic relationships will usually occur on argument-verb violations, it may be possible, under

⁷ Note, however, that the P600 does not invariably cancel out the N400 at the scalp surface: evidence from ERPs to semantic and syntactic 'double' violations suggests that these two component are additive and do not simply cancel out one another (Hagoort, 2003; Osterhout & Nicol, 1999). This argument would therefore hold that the P600 to these types of animacy thematic violations started earlier than the P600 to other types of syntactic violations.

⁸ The earlier portion of the P600 (perhaps overlapping in time with the N400) may be involved in detecting or monitoring the discrepancy between the actual and potential thematic roles, while the later portion may reflect the effort to syntactically or thematically repair the violation (see Footnote 5). If this is the case, then some of the factors that we have suggested modulate the P600 may act in opposite directions at these two stages. For instance, a lexico-semantic associative relationship between a verb and its argument may suggest an alternative thematic role, triggering a P600, but it may also tend to make sentences more plausible and easier to repair, attenuating the amplitude of the P600 once it is generated.

some circumstances, to evoke a P600 on pragmatic violations that do not violate verb–argument structures, but that arise through relating plausible noun–verb combinations to incongruous preceding contexts. Indeed, unlike our previous study using the same stimuli (Kuperberg, Sitnikova, et al., 2003), the pragmatic non-TR violations in the current study did evoke a small P600 effect (in addition to a robust N400 effect). This might have arisen because the plausibility judgment task and the high proportion (50%) of thematic role violated sentences biased participants towards considering the possibility of alternative semantic–thematic relationships. Future studies will determine whether it is possible to construct pragmatic violations that evoke even larger P600s, on the one hand by introducing potentially plausible semantic relationships between the critical words and other content words (biasing towards alternative interpretations) and, on the other hand, by constructing contexts that increase the implausibility of the actual thematic roles assigned by the syntax. Another more general question is whether a P600 can be evoked by words that do not violate thematic–semantic constraints but that violate other types of semantic constraints that are closely linked to syntactic structure (see Casado, Martin-Loeches, Munoz, & Fernandez-Frias, 2005; Kemmerer, Weber-Fox, Price, Zdanczy, & Way, 2007, for recent evidence that this may be the case).

5. Summary and conclusion

To conclude, our findings suggest that animacy plays a role in influencing the computation of thematic relationships between a verb and its argument(s) during online sentence comprehension. They suggest that thematic roles that are not expressed by the syntax of a sentence are computed online, even in simple, active, unambiguous semantically violated sentences, and that these thematic relationships have an immediate and online impact on processing verbs. We have argued that, in the current study, the thematic relationships dictated by the inanimate nature of the subject NPs and the thematic structure of the particular verbs we used were strong enough to exert their influence on online sentence comprehension, even in the absence of lexico-semantic associations between these NPs and these verbs, or between these verbs and non-argument context prior to the NP. We do not, however, suggest that animacy is the only factor that determines the thematic relationship between a NP and a verb. Indeed, lexico-semantic associative relationships can act alone in biasing towards an alternative thematic structure that can be violated by the syntax and evoke a P600 as in the studies by Kolk et al. (2003) and van Herten et al. (2005).

We have argued that, when there is a thematic violation between the verb and its argument(s), the P600 starts within the N400 time-window and that the two components may be functionally related such that the neurocognitive process driving the P600 ‘switches off’ semantic integration indexed by the N400. Finally, taken together with previous studies, our data suggest that several factors may bias a parser towards considering alternative semantic–thematic relation-

ships and away from interpreting the thematic relationships dictated by the syntax, leading to a P600 rather than an N400 to semantic/pragmatic violations in sentences. Future studies will address how all these factors come into play during normal language processing and exactly how the balance between the syntactic and semantic neural systems is coordinated in healthy individuals and in patients with language disorders (Kuperberg, Sitnikova, Goff, & Holcomb, 2006).

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