LANGUAGE AND COGNITIVE PROCESSES
2011, 26 (9), 1402–1456

Psychology Press
Taylor & Francis Group

Electrophysiological evidence for use of the animacy hierarchy, but not thematic role assignment, during verb-argument processing

Martin Paczynski[1] and Gina R. Kuperberg[1,2]

[1]Neurocognition Laboratory, Department of Psychology, Tufts University, Medford, MA, USA
[2]Department of Psychiatry, Massachusetts General Hospital, Charlestown, MA, USA

Animacy is known to play an important role in language processing and production, but debate remains as to how it exerts its effects: (1) through links to syntactic ordering, (2) through inherent differences between animate and inanimate entities in their salience/lexico-semantic accessibility, and (3) through links to specific thematic roles. We contrasted these three accounts in two event-related potential (ERP) experiments examining the processing of direct object arguments in simple English sentences. In Experiment 1, we found a larger N400 to animate than inanimate direct object arguments assigned the Patient role, ruling out the second account. In Experiment 2, we found no difference in the N400 evoked by animate direct object arguments assigned the Patient role (prototypically inanimate) and those assigned the Experiencer role (prototypically animate), ruling out the third account. We therefore suggest that animacy may impact processing through a direct link to syntactic linear ordering, at least on postverbal arguments in English. We also examined processing on direct object arguments that violated the animacy-based selection-restriction constraints of their preceding verbs. These violations evoked a robust P600, which was not modulated by thematic role assignment

Correspondence should be addressed to Martin Paczynski, Department of Psychology, Tufts University, 490 Boston Ave., Medford, MA 02155, USA. E-mail: martin.paczynski@tufts.edu

Gina R. Kuperberg was supported by NIMH (R01 MH071635) and NARSAD (with the Sidney Baer Trust). We thank Evan C. Ruppell for his help developing experimental sentences and assisting in running participants in the ERP portion of the study. We are also grateful to Phil Holcomb, Ray Jackendoff, David Caplan, and Neal Pearlmutter for helpful comments on earlier versions of this manuscript.

http://www.psypress.com/lcp http://dx.doi.org/10.1080/01690965.2011.580143

or reversibility, suggesting that the so-called semantic P600 is driven by overall propositional impossibility, rather than thematic role reanalysis.

Keywords: Animacy hierarchy; Thematic roles; Event-related potentials; Sentences.

GENERAL INTRODUCTION

One of the key questions within psycholinguistics is how semantics and syntax interact to build overall sentence meaning. The animacy of a noun phrase (NP) is known to influence both language comprehension and production, and is central to the syntax–semantic interface. However, it remains unclear how it exerts its effects. Several possibilities have been discussed. One account, explored primarily in the production literature, is that animacy acts directly by influencing the linear ordering of syntactic constituents. A second account, also mainly considered in the production literature, is that the effects of animacy arise through inherent differences in salience/lexico-semantic accessibility of animate and inanimate entities. A third possibility, explored in both production and comprehension literature, is that animacy acts by influencing the assignment or reassignment of thematic roles. We designed two experiments to distinguish between these three accounts by examining the processing of direct object arguments in active English sentences using event-related potentials (ERPs).

In addition to influencing the processing of plausible sentences, animacy is known to influence the processing of implausible sentences containing selection-restriction violations. Once again, however, the mechanism by which it exerts its effects is unclear, with different models of language processing predicting different types of interactions between the animacy of an argument and the selection restrictions of a verb. The second aim of this study was to distinguish between these models by examining how animacy and thematic role reversibility influenced the processing of direct object arguments that violated the animacy-based selection restrictions of their preceding verbs.

In this General Introduction, we first review evidence that animacy can impact the linear ordering of syntactic constituents, mainly from cross-linguistic studies and studies of language production. We also consider evidence from the production literature that the effects of animacy may be driven by inherent differences between animate and inanimate entities in their salience/lexico-semantic accessibility, regardless of linear order. We then discuss evidence for an association between animacy and thematic roles, from both behavioural and electrophysiological studies of sentence comprehension. Finally, we outline the specific questions addressed in the current study.

Associations between animacy and linear ordering

The animacy hierarchy, described by Silverstein (1976), as well as Dixon (1979) and Aissen (2003), refers to a preference for organising entities along an animacy continuum, with humans ranking the highest, abstract concepts ranking lowest, with animals, plants, and inanimate objects falling in between. In the present study, we will use "animate" to refer to humans and animals, and "inanimate" to refer to inanimate objects. There is now fairly compelling evidence, from cross-linguistic studies and studies of language production, that the animacy hierarchy may be linked directly to the order of syntactic constituents.

Cross-linguistic evidence

In several languages, the animacy hierarchy is formally encoded in syntactic structure, constraining the linear ordering of arguments within a sentence. For example, in Navajo (Hale, 1972), Lakhota (Van Valin & LaPolla, 1997), and Mayan (Jakeltek: Craig, 1977; Mam-Mayan: Minkoff, 2000), animate nouns must always precede inanimate ones in transitive constructions. Thus, *The rock hit the man* is ungrammatical, and the utterance must instead be expressed as *The man was hit by the rock*. Minkoff (2000) demonstrated that such constraints are based on relative, rather than absolute animacy. Thus, *The dog bit the man* is ungrammatical as humans outrank animals, but *The rock hit the window* is grammatical as both entities are inanimate; thus, neither outranks the other. In English, a similar animacy-based constraint is placed on the realization of the double object ditransitive construction. Such constructions are ungrammatical when the indirect object is inanimate and direct object is animate, for example, **The president sent England the ambassador*. They require the use of the prepositional alternation, for example, *The president sent the ambassador to England* (cf. Levin, 1989). Again, such constraints are relative, as *The man got the car new tires* is grammatically felicitous.

Importantly, the tendency to place animate before inanimate nouns can be observed even without formal syntactic constraints on animacy ordering, as shown by several corpus studies. Examining German subordinate clauses, Kempen and Harbusch (2004) demonstrated that animate nouns tended to precede inanimate ones, independent of grammatical function. Øvrelid (2004) found that, in Norwegian, subject nouns were either higher or of equal animacy status as objects in over 97% of the transitive constructions reviewed by the author. Snider and Zaenen (2006) reported similar results in the English "Switchboard" corpus, finding that animate nouns were three times more likely to appear as subject arguments than inanimate nouns,

while the reverse was true for the grammatical objects. Such effects are not limited to verb arguments. Rosenbach (2005) reported that, in English, possessive constructions vary depending on the animacy of the arguments, with the *captain's table* being preferred over the *table of the captain*, but *the man of the mountain* being preferred over *the mountain's man*.

Evidence from studies of language production

Consistent with the trends observed in language use outside of the laboratory, experimental studies of language production show that animacy influences the linear ordering of arguments within a sentence. During both spoken and written production, animate nouns are consistently placed at the sentence initial position. In a series of studies, Bock demonstrated that, when asked to describe pictures containing an inanimate Actor and an animate Undergoer, participants employed the passive voice up to 74% of the time, compared to never when the Actor was animate (Bock, 1986; Bock & Loebell, 1990; Bock, Loebell, & Morey, 1992). Ferreira (1994) likewise found that, when the verb required an animate direct object argument (in canonically ordered sentences), participants tended to use the passive voice when the arguments differed in animacy, placing the animate noun in subject position (*The man was alarmed by the news*), while no such preference was seen when both arguments were animate (*The vagabond alarmed the man*). Similar biases have been observed in delayed recall tasks, in which participants frequently misremember the original grammatical form of sentences, placing the animate argument before the inanimate one. This effect was found to be independent of grammatical voice in English (McDonald, Bock, & Kelly, 1993) and Japanese (Tanaka, Branigan, & Pickering, 2005), while in Greek, which allows relatively free argument ordering, participants often reordered the arguments without changing grammatical voice (Feleki & Branigan, 1997). These production biases appear to be learned at an early age (English: Dewart, 1979; Fiji: Byrne & Davidson, 1985; Sesetho: Demuth, Machobane, Moloi, & Odato, 2005). Indeed, Demuth et al. (2005) found that children attained adult proficiency in using animacy hierarchy constraints in Sesetho several years prior to attaining adult proficiency in use of thematic roles.

In their 1992 study, Bock, Loebell, and Morey found that participants were more likely to generate sentences with animate subjects after reading prime sentences with animate subjects (similarly for inanimates). They were also more likely to produce active sentences following active primes and passive sentences following passive primes. Importantly, their choice of grammatical voice was unaffected by the animacy of the subject in the prime sentences. This lack of interaction between Animacy and Voice led the authors to conclude that, during production, animacy information may act

independently of thematic roles, suggesting a more direct mapping between animacy features and syntactic arguments.

One reason that has been proposed for the "animate first" bias in production is that animate entities are generally more salient, predictable, or accessible than inanimate items. Generally, more things can be said about animate entities than inanimate ones (see Bock et al., 1992). For example, both an athlete and a car may move fast and come from Germany, but only the former is likely to be described as humble and intelligent. According to this view, more accessible or salient items are assigned to the more prominent syntactic position of a sentence (e.g., Bock et al., 1992); that is, there is a direct mapping between the increased salience of conceptual features and the first, most prominent argument position. Support for this hypothesis comes from Prat-Sala and Branigan (2000) who found that, during production, entities made more salient either through a discourse context or through an animacy manipulation showed a similar pattern of being placed first.

Associations between animacy and thematic roles

Besides influencing the linear ordering of syntactic constituents, animacy has also been proposed to influence language through its associations with thematic roles. Thematic roles are a means of describing the semantic roles that a noun plays within a sentence construction. For example, in the sentence *Jane broke the vase*, *Jane* is considered an Agent, as she is the initiator of an action, while *vase* is a Patient, the entity that is affected by the action. In the current paper, we focus on three thematic roles, each of which has a prototypical relationship with animacy: Agent, Patient, and Experiencer.[1] Animate entities are considered more ideal Agents because they can be volitional initiators of actions, while inanimate entities are considered more ideal Patients. The Experiencer role has even stronger associations with animacy than the Agent or Patient role, in that it refers to any argument that experiences an emotional or cognitive state. Thus Experiencers are necessarily animate.

Most studies of comprehension have interpreted effects of animacy as arising from its effect of facilitating the assignment or reassignment of thematic roles. This evidence comes from both behavioural studies and studies using ERPs, a direct online measure of neural activity.

[1] There has been extensive discussion within the linguistic community about the exact nature of thematic roles/relations. Here we take a position influenced by Jackendoff (1987), who stated that "thematic relations are to be reduced to structural configurations in conceptual structure; the names for them are just convenient mnemonics for particularly prominent configurations" (p. 378). Thus by Agent, we refer to any argument that describes the entity which causes an action to happen, while a Patient is an entity which is affected by the action. We do not consider more fine-grained distinctions such as between an Agent and Causer, or Patient and Theme.

Behavioural studies of sentence processing

The first formal processing model that considered a role of animacy in thematic role assignment was introduced by Frazier and Rayner (1982) who discussed a thematic processing stream which relied on a small set of semantic features, such as animacy, to aid in thematic role assignment. In their original study, the authors examined the effects of animacy on the processing of reduced relative clauses (e.g., *The witness examined by the lawyer*...) compared with their unreduced counterparts (e.g., *The witness that was examined by the lawyer*...). Frazier and Rayner showed that the reading time penalties on the disambiguating "by" phrase in reduced relatives were greatly reduced when the initial sentence argument was inanimate rather than animate (*The evidence examined by the lawyer*...). These results were replicated by Rayner, Carlson, and Frazier (1983) and by Ferreira and Clifton (1986). The authors suggested that after the initial (incorrect) syntactic parse of reduced relative clauses, the thematic processing mechanism aided in thematic role reanalysis. Specifically, because inanimate nouns are more Patient-like than Agent-like, the reassignment of the subject noun to the Patient role was easier in the inanimate-first than the animate-first sentences.

Subsequent studies suggested that animacy exerted its effects at an even earlier stage of processing (MacDonald, Pearlmutter, & Seidenberg, 1994; Trueswell, Tanenhaus, & Garnsey, 1994). The authors of these studies suggested that, rather than aiding in thematic role reanalysis, animacy information was used immediately, leading readers to more readily interpret inanimate nouns as Patients during their initial parse of the sentence.

Animacy has also been shown to influence the processing of nonambiguous noncanonical sentences. For example, Traxler, Morris, and Seely (2002), in English, and Mak, Vonk, and Schriefers (2002, 2006) in Dutch, reported that the reading time penalty normally incurred in reading object relative clauses, for example, *The cop that the crook shot*..., was eliminated when the initial argument was inanimate, for example, *The gun that the crook shot*.... Likewise, Ferreira (2003) reported that participants were more accurate in assigning the correct thematic roles in simple passives (e.g., *The cat/ball was chased by the dog*) and object-cleft constructions (e.g*., It was the cat/ball that the dog chased*...) in inanimate-first than animate-first sentences (in the above examples, they more accurately indicated that the *dog* was the Agent of *chased* when the other argument was *ball* than when it was *cat*). Once again, this facilitation was interpreted as reflecting the easier assignment of inanimate than animate arguments to the Patient role, which was consistent with the role assigned to that argument by the syntactic structure.

In sum, there is clear evidence that animacy exerts an effect on sentence comprehension. While there remains some debate as to whether these effects occur during a second stage of processing (serial models, e.g., Ferreira & Clifton, 1986; Rayner et al., 1983; Rayner & Frazier, 1982), or during a single stage of processing (constraint-based models, e.g., MacDonald et al., 1994; Trueswell et al., 1994), within both types of architectures animacy has been suggested as exerting its effects through thematic role processing.

ERP studies of sentence processing

Evidence that animacy can influence sentence comprehension also comes from ERP studies examining both plausible sentences, where effects of animacy are seen primarily on the N400 component, and implausible selection-restriction violating sentences where effects are seen on both the N400 and P600 components.

Effects of animacy on processing plausible sentences: Effects on the N400

The N400 is a negative-going waveform peaking at approximately 400 ms poststimulus onset. Its amplitude is thought to reflect the semantic fit between that word's conceptual features, the meaning of its preceding context, and information stored at various grains within semantic memory (see Kutas & Federmeier, 2000, for a review). During sentence processing, a decrease in the N400 amplitude has been generally interpreted as indicating that a word is easier to integrate into its preceding sentential context.

There is a growing body of work that has implicated the N400 as sensitive to thematic role processing, most often explored through manipulations of argument animacy. Several studies in English have reported a decrease in the N400 amplitude to inanimate relative to animate subject nouns (Kuperberg, Sitnikova, Caplan, & Holcomb, 2003; Nakano, Saron, & Swaab, 2010; Paczynski & Kuperberg, 2009; Weckerly & Kutas, 1999). Several of these authors (e.g., Nakano et al., 2010; Weckerly & Kutas, 1999) have interpreted this finding as indicating that animate arguments are more easily assigned the Agent role than inanimate nouns. Interestingly, this N400 effect is modulated by reading ability (Weckerly & Kutas, 1999) and working memory span (Nakano et al., 2010), with the effect of animacy being most pronounced for more proficient readers and those with higher working memory spans (e.g., high span readers showing a larger N400 amplitude to inanimate than animate subject nouns). Nakano et al. interpreted this as suggesting that only high span readers were able to make immediate use of noun animacy information to aid in thematic roles assignment.

In German, a verb-final language where animacy may play an even more critical role during initial thematic role assignment, Frisch and Schlesewsky (2001) found that, following an animate nominative (i.e., subject) argument, a second nominative argument evoked a smaller N400 effect (compared with correctly marked accusative arguments) when it was inanimate than when it was animate. The authors argued that this occurred because inanimate arguments were more easily assigned the thematic role of Patient than animate arguments, thus allowing a semantically coherent interpretation of the sentence. Converging evidence for the use of animacy information in guiding thematic role assignment in German comes from two studies which reported a larger N400 to inanimate nominative arguments than animate ones following clause initial animate accusative arguments (Frisch & Schlesewsky, 2001; Roehm, Schlesewsky, Bornkessel, Frisch, & Haider, 2004). The authors interpreted these results as indicating that, following an animate Patient, the language parse expected an ideal, that is, animate, Agent.

This link between thematic roles, animacy, and N400 modulation during verb-argument processing has been articulated within a recent model proposed by Bornkessel and Schlesewsky (2006). Within the extended Argument Dependency Model (eADM), it is proposed that several prominence hierarchies, including animacy, are used during a distinct stage of processing (*compute prominence*) to guide the assignment of an NP to either the Actor or Undergoer role: the higher the prominence, the more likely the argument is to be interpreted as an Actor (Agent in our nomenclature). Importantly, Bornkessel-Schlesewsky and Schlesewsky (2008, p. 71) state that in English, animacy plays an important role in computing the prominence of arguments within a sentence, with mismatches between different prominence hierarchies being associated with an increase in the N400 amplitude.

Effects of animacy on the processing of implausible sentences: The semantic P600 and its relationship with the N400

The P600 is a positive-going waveform that peaks between 600- and 1,000-ms poststimulus onset. It was originally described in association with syntactic processing in sentences (Hagoort, Brown, & Groothusen, 1993; Osterhout & Holcomb, 1992). However, it is also evoked by animacy-based selection-restriction violations between verbs and arguments, as well as by other types of highly semantically implausible words within sentences (reviewed by Kuperberg, 2007). For example, Kuperberg et al. (2003) examined ERPs evoked by verbs in two types of implausible sentences: those that were implausible only with respect to real-world knowledge (e.g., *Every morning at the boys would *plant*...), and those in which the

subject NP violated animacy-based selection-restriction constraints of the verb (e.g., *Every morning at breakfast the eggs would *eat*...). Consistent with other research (e.g., Hagoort, Hald, Bastiaansen, & Petersson, 2004), real-world incongruities evoked the classic N400 effect. Surprisingly, the animacy-based selection-restriction violations failed to evoke an N400 effect but rather produced a P600 effect. Similar so-called semantic P600 effects to animacy-based selection-restriction violations, sometimes in the absence of N400 effects, have also been reported by Kim and Osterhout (2005) in English and by Hoeks, Stowe, and Doedens (2004) in Dutch. Although this effect has most frequently been reported on verbs, more recent studies have demonstrated a similar P600 effect on selection-restriction violating direct object NP arguments, at least under some experimental conditions (e.g., Kuperberg, Choi, Cohn, Paczynski, & Jackendoff, 2010; Nieuwland & Van Berkum, 2005). Such semantic P600 effects may again be dependent on reading span, as Nakano et al. (2010) reported that only high span readers showed a P600 effect to animacy violations on verbs (e.g., *The box *bit*...), while low span readers showed an N400 effect. Importantly, animacy-based selection-restriction violations are not always necessary or even sufficient to trigger a semantic P600 effect (e.g., Kolk, Chwilla, van Herten, & Oor, 2003), and several other factors have been proposed that may bias towards the additional analysis reflected by this component, including sentential and discourse context and the experimental task (discussed by Kuperberg, 2007). Several frameworks have been proposed to explain why a P600 effect, often (although not always) with an attenuation of the N400 effect, is seen on animacy-based selection-restriction violations.

One of the first accounts came from Herman Kolk and colleagues who proposed an Error Monitoring model (reviewed by van de Meerendonk, Kolk, Chwilla, & Vissers, 2009). According to this model, the P600 is indicative of general executive error monitoring processes that can trigger a reanalysis of the entire preceding input. For semantic errors to evoke this effect, the meaning of the entire proposition must be highly implausible (see also van de Meerendonk, Kolk, Vissers, & Chwilla, 2010). Thus, the reason why animacy-based selection-restriction violations evoke a P600 effect is that they are always highly implausible (eggs can never eat). According to Kolk's account, monitoring, and thus the magnitude of the P600 effect is increased when such a highly implausible proposition conflicts with an alternative plausible, or even partially plausible interpretation (van Herten, Chwilla, & Kolk, 2006). This alternative interpretation is generated by a heuristic mechanism that draws upon semantic relationships between content words (thus, although eggs can never eat, they can be eaten). The heuristically generated alternative plausible interpretation also serves to attenuate the N400 to these selection-restriction violations.

A slightly different account was proposed by Kim and Osterhout (2005) who suggested that the critical factor in triggering the P600 to these types of animacy selection-restriction violations was not animacy or implausibility per se, but rather the more specific semantic "attraction" between the verb and its argument(s). Semantic attraction was operationalised by the plausibility of a clause if the arguments had taken alternative thematic roles around the verb, that is, by their semantic reversibility. Semantic attraction between verbs and arguments was also proposed to attenuate the N400 effect. Thus, **The hearty meals were devouring*... evokes a P600 effect but no N400 effect because the Agent (*meals*) serves as an excellent Patient for *devour.* In support of this hypothesis, Kim and Osterhout reported that an N400 effect but no P600 effect was evoked by verbs in nonattracted animacy-based selection-restriction violation sentences like **The dusty tabletops were devouring*... Note, however, that other studies have reported P600 effects to nonattracted semantic violations, including Kuperberg, Caplan, Sitnikova, Eddy, and Holcomb (2006), Kuperberg, Kreher, Sitnikova, Caplan, and Holcomb (2007), and Stroud and Phillips (2009).

Hagoort, Baggio, and Willems (2009) offer a similar account to that of Kolk and colleagues as well as Kim and Osterhout. They suggest that the P600 effect is evoked when cues for a well-formed syntax are weaker than for a plausible semantic interpretation. Thus, for sentences such as *For breakfast the eggs would eat*... or *The hearty meals were devouring*..., a P600 is observed as the initial cues for semantic information being correct are very strong (the subject argument can take an alternative, plausible, role about the verb). On the other hand, for sentences such as *The dusty table tops were devouring*..., the subject argument and verb are only weakly related; thus, the semantic cues are relatively weak compared to syntactic cues, resulting in an N400 effect.

In their eADM, Bornkessel and Schlesewsky (2006) suggest that the semantic P600 results from increased costs at later stages of processing: a *generalised-mapping* step (in which numerous sources of information, including real-world knowledge, are utilised in fully integrating the argument into its syntactic structure) and/or a *well-formedness evaluation/repair* processing step, which evaluates the overall well-formedness of the proposition, and which may be modulated by an experimental task. The *generalised-mapping* step is dependent on earlier phases of processing. For example, if sufficient processing costs are incurred during the *compute prominence* step (see above), the *generalised-mapping* processing step is blocked. However, the *well-formedness* processing step always occurs.

Finally, in her 2007 review of studies describing the semantic P600 effect, Kuperberg noted that no single factor could account for the full range of findings, and proposed a hybrid, dynamic framework in which she suggested

that, in parallel with a full, syntactically driven combinatorial analysis, there are continuous attempts to match semantic relationships in the input against semantic associative and featured relationships, stored at various grains of representation within semantic memory, i.e., semantic memory-based processing. She argued that N400 attenuation was driven primarily by matches between the input and these stored relationships (see Federmeier & Kutas, 1999)—semantic memory-based analysis. She suggested that the P600 effect to semantic violations reflected additional analysis or reanalysis, triggered by conflict between the implausibility of the full (syntactically determined) proposition, and the output of this semantic memory-based analysis. Thus, similar to Kolk, Kuperberg (2007) emphasises the degree of implausibility of the syntactically determined propositional representation as a factor that influences the amplitude of the P600 to animacy selection-restriction violations. However, unlike the accounts described above, Kuperberg (2007) also raised the possibility that the competing nonsyntactic analysis may not necessarily reflect heuristic attempts to come up with alternative *plausible* interpretations (by switching around thematic roles). Rather, it may simply reflecting a matching or resonance between incoming semantic relationships and those that are expected and stored—the semantic memory-based analysis. Evidence for this is that neither the P600 nor the N400 evoked to verbs is necessarily modulated by the semantic-thematic reversibility of a sentence (see Kuperberg et al., 2006, 2007; Stroud & Phillips, 2009).

The current study

The current study had two main aims. The first was to examine the mechanism by which animacy influences the processing of direct object arguments in plausible, syntactically simple, active English sentences: (1) through links to syntactic ordering, (2) through inherent differences between animate and inanimate entities in their salience/lexico-semantic accessibility, (3) through links to specific thematic roles. In Experiment 1, we manipulated the animacy of the direct object argument while keeping the thematic role constant. This allowed us to determine whether animate nouns are generally more salient/lexico-semantically accessible, and thus easier to process than inanimate nouns, independent of syntactic position or thematic role assignment. In Experiment 2, we kept the animacy of the direct object argument constant while manipulating its thematic role assigned by the verb: the Patient role, which biases towards inanimate nouns, or the Experiencer role, which requires animate ones. This allowed us to determine whether animacy impacts processing though its relationship with thematic roles, or through biases based on the linear ordering of arguments within a sentence.

Our second aim was to examine the effects of animacy and thematic roles on the processing of direct object arguments that violated the selection restrictions (SRs) of their preceding verbs. As discussed in the preceding section, several theoretical frameworks have been attempted to explain the so-called semantic P600. Each makes somewhat different predictions for when a semantic P600 is evoked and when an N400 is attenuated. We were particularly interested in examining how thematic role reversibility modulated the P600 and N400 in selection-restriction violating sentences, with the level of reversibility being varied across the two experiments.

EXPERIMENT 1

Introduction

As discussed in the General Introduction, both behavioural and ERP comprehension studies have generally attributed the effects of animacy to a mapping between animacy and specific thematic roles. In contrast, production studies provide evidence for a direct mapping between animacy features and the linear ordering of syntactic constituents; that is, animate items are most easily mapped directly onto the initial sentence position, which is usually the subject argument in simple English sentences. However, a third possibility has been implied in some theories of language production: that animate nouns generally more accessible or salient than inanimate ones, "*invariant across contexts*" (Prat-Sala and Branigan, 2000, p. 169). Thus, rather than being driven by animacy hierarchy-based biases, the "animate first" preference seen in production studies might reflect a more general facilitation for the processing of animate than inanimate nouns. The first aim of Experiment 1 was to contrast this third hypothesis with the first two.

In order to address this first aim, we constructed a set of plausible, canonical active English sentences with Agent–Patient verbs, that is, ones in which the subject (always animate) was assigned the Agent role while the direct object argument was assigned the Patient role by the verb. We manipulated the animacy of the direct object argument, creating two types of plausible sentences, those with animate arguments (condition 1; see Table 1) and those with inanimate arguments (condition 2). If animacy influences processing either through a mapping of the animacy hierarchy onto linear order (less animate arguments should appear later in the sentence) or through specific thematic role entailments (inanimate arguments are more Patient-like), this would predict that the amplitude of the N400 evoked by inanimate Patient direct object arguments (*. . .plowed the meadow...*) should be *smaller* than that evoked by animate ones (e.g., *. . .penalised the*

TABLE 1
Example sentences in Experiment 1, including semantic similarity value (SSV) based on Latent Semantic Analysis, and plausibility ratings

Condition	*Example*	*SSV*	*Plausibility ratings*
Nonviolating, animate direct object Patient	At the homestead the farmer penalized the **laborer** for laziness	0.22	5.35
Nonviolating, inanimate direct object Patient	At the homestead the farmer plowed the **meadow** on Thursday	0.21	5.54
Selection-restriction violating, animate direct object Patient	At the homestead the farmer plowed the ***laborer** on Thursday	0.22	2.15
Selection-restriction violating, inanimate direct object Patient	At the homestead the farmer penalized the ***meadow** for laziness	0.20	2.24

Critical direct object arguments, to which ERP responses were measured, are bolded in the example sentences.

labourer...). If, on the other hand, animate items are generally easier to process because of their intrinsic salience or lexico-semantic accessibility, regardless of their syntactic position in a sentence, this would predict the opposite pattern of N400 modulation: inanimate direct object arguments should evoke a *larger* N400 than that evoked by inanimate ones.

The second aim of this study was to examine the effects of animacy and thematic reversibility on the processing of direct object arguments in implausible sentences in which the direct object *mismatched* the selection restrictions of their preceding verbs (see Table 1, conditions 3 and 4). As noted in the General Introduction, animacy-based selection-restriction violations on verbs (...**eggs would eat*...) failed to evoke an N400 effect, despite being highly semantically anomalous (Kim & Osterhout, 2005, Experiment 1; Kuperberg et al., 2003, 2006, 2007; Hoeks et al., 2004), instead evoking a robust P600 effect. Several possibilities have been discussed for this pattern of findings.

With regard to the reduced N400 effect in these selection-restriction violating sentences, one possibility is that the animacy of the argument plays a key role: Kuperberg et al. (2003) suggested that when a reader's course-grained expectations of the animacy of an argument are violated, further, full semantic memory-based analysis, reflected by full N400 modulation, can be "switched off". Kim and Osterhout's (2005) proposal suggests that the N400 effect would be reduced only when an argument can play an alternative thematic role around a specific verb. Similarly, Kolk and colleagues

(van Herten et al., 2006) propose that the N400 can be attenuated when a heuristic mechanism drawing upon semantic relationships between content words comes up with an alternative plausible interpretation, for example, when sentences are at least partially semantically reversible (see also Hagoort et al., 2009). The eADM (Bornkessel & Schlesewsky, 2006) offers two ways in which animacy may affect processing in selection-restriction violating sentences: (1) animate arguments assigned to the Patient role should incur a processing cost during the *compute prominence* step, blocking the *plausibility* step (similar to Kuperberg's proposal) or (2) animate nouns, being plausible Agents, would not lead to processing costs during the initial *plausibility* step, as this step is noncombinatorial (similar to heuristic processing in Kolk's proposal).

In the current experiment, all these proposals make similar predictions with regard to modulation of the N400: they all predict an attenuation of any N400 effect to selection-restriction violating (vs. nonviolating) animate direct object arguments, but the presence of an N400 effect to violating (vs. nonviolating) inanimate direct object arguments. Based on animacy alone, animate direct object arguments are less expected than inanimate direct object arguments; thus a full semantic memory-based analysis between the argument, verb, and context is blocked, and no N400 effect would be observed, despite the violation of the selection restrictions of the preceding verb (Bornkessel & Schlesewsky, 2006; Kuperberg, 2007; Kuperberg et al., 2003). Similarly, because implausibilities on animate direct objects are partially reversible (e.g., **. . .plowed the labourer. . ./. . .plowed by the labourer. . .*), a plausibility heuristic (Bornkessel & Schlesewsky, 2006; van Herten et al., 2006), a semantic-attraction mechanism (Kim & Osterhout, 2005), or multiple semantic cues (Hagoort et al., 2009) could come up with a plausible interpretation, once again reducing the N400 effect to these violating (vs. nonviolating) arguments. Note that this is not true for sentences with selection-restriction violating *inanimate* direct object arguments, which are not semantically reversible (e.g., **. . .penalised the meadow. . ./*. . .penalised by the meadow. . .*).

Turning to the P600, the semantic-attraction framework (Kim & Osterhout, 2005) predicts that *only* animate selection-restriction violating direct object arguments should evoke a P600 effect as only these can plausibly occupy an alternative thematic role around the verb. A similar prediction is made by Hagoort et al. (2009). The Error Monitoring framework predicts that a P600 effect would be evoked by both animate and inanimate selection-restriction violating arguments because they both result in highly implausible propositions (van de Meerendonk et al., 2009). However, it also predicts that the magnitude of the P600 effect will be larger to violations on animate than inanimate direct object arguments because the highly implausible selection-restriction violating animate direct object arguments would

conflict with the partially plausible output of the plausibility heuristic (e.g., *plowed by the labourer*...). On the other hand, the eADM predicts a P600 effect to both animate and inanimate selection-restriction violations, again because neither is well formed, leading to increased costs during the *well-formedness* step. Unlike the other proposals, the eADM does not predict the *well-formedness* step to be affected by thematic role reversibility.

Kuperberg (2007) also predicts that both animate and inanimate selection-restriction violating direct object arguments should lead to a P600 effect. This is because in both cases, the full syntactic-based interpretation for both types of violations would be equally (im)plausible. This, combined with a plausibility judgment task and the presence of some semantically constraining context, should lead to conflict with matches in a semantic memory-based analysis, and thus result in continued combinatorial processes, indexed by the P600. Kuperberg (2007) outlined different accounts of how animacy might modulate the P600. If animacy functions as part of a separate combinatorial "thematic" stream that assigns thematic roles purely on the basis of animacy, independently of syntax, this might lead to increased conflict and a larger P600 to the animate (vs. inanimate) selection-restriction violations. If, however, the main source of conflict arises simply from matches within a semantic memory-based stream, then the P600 should not be modulated by animacy-based thematic assignment within the sentences, and the amplitude of the P600 would be equal to animate and inanimate selection-restriction violations. Kuperberg (2007) also stressed that the P600 is not necessarily modulated by semantic reversibility (for other evidence suggesting that the P600 is *not* modulated by the reversibility of thematic roles, see Kuperberg et al., 2006, 2007; Stroud and Phillips, 2009). A summary of all predictions is presented in Table 2.

Methods

Development and pretesting of materials

Two lists of transitive Agent–Patient verbs were generated—one list with 166 verbs that selected for animate direct object arguments (animate-selecting) and the other with 166 verbs that selected for inanimate direct objects (inanimate-selecting). Initial assessment of animacy restrictions was based on authors' intuitions. One hundred and sixty-six pairs of sentence stems were then created from each of these verbs: each consisted of a short introductory context, an animate subject argument, an animate-selecting or an inanimate-selecting verb that was semantically congruous with the context and subject, and a definite article.

To confirm verb selection-restriction biases, a completion experiment was carried out in which these sentence stems, counterbalanced across two lists, were presented in random order to 20 Tufts undergraduate students (10 per

TABLE 2
Experiment 1. Predictions made by different proposals regarding the modulation of the N400 and P600 by animacy and selection-restriction violations

Proposal	*N400*	*P600*
Nonviolating patient arguments		
Animate nouns more salient/accessible than Inanimate nouns	Animate < Inanimate	
Animacy as a proxy for Thematic Role	Inanimate < Animate	
Animacy Hierarchy/ Linear Position	Inanimate < Animate	
Violating versus Nonviolating Patient Arguments		
Kuperberg et al.	Animate: No N400 effect due to "switching off" of additional semantic analysis when animacy mismatches expectations based on selection restrictions of the verb as well as either thematic role or linear position Inanimate: N400 effect	Animate: P600 effect Inanimate: P600 effect Effects driven by implausibility/impossibility of final interpretation conflicting with some match in semantic memory-based analysis, with no effect of thematic reversibility
Kolk et al.	Animate: No N400 effect due to heuristic mechanisms leading to partially plausible interpretation (partial thematic reversibility) Inanimate: N400 effect	Animate: P600 effect (larger) Inanimate: P600 effect (smaller) Effects driven by reanalysis triggered by detection of highly implausible interpretation (error) Larger effect for *animate* arguments driven by greater difficulty in resolving detected error due to heuristic mechanisms leading to partially plausible interpretation (partial thematic reversibility)
Kim & Osterhout	Animate: No N400 effect due to semantic attraction (reversibility) between verb and argument Inanimate: N400 effect	Animate: P600 effect driven by semantic attraction (reversibility) between verb and argument Inanimate: No P600 effect
eADM	Animate: No N400 effect due to processing cost incurred during *compute prominence* step blocking initial *plausibility* step Inanimate: N400 effect	Animate: P600 effect Inanimate: P600 effect Effects driven by real-world implausibility detection during *well-formedness* step

(*Continued*)

Table 2 (*Continued*)

Proposal	*N400*	*P600*
Hagoort et al.	Animate: No N400 effect due to semantic cues being stronger than syntactic cues (partial thematic reversibility) Inanimate: N400 effect	Animate: P600 effect driven by semantic cues being stronger than syntactic cues (partial thematic reversibility) Inanimate: No P600 effect

list) who were asked to write down the word that was the most likely continuation of the sentence stem, with explicit instructions that this word need not be the final one of the sentence. Two independent raters then judged the animacy of each participant's response: whether the word described an animate, inanimate, or ambiguous entity. Twenty-two scenarios in which more than 10% of continuations failed to conform to a priori animacy expectations were rejected, leaving 144 acceptable scenarios.

For each of these 144 pairs of sentence stems, a plausible animate or inanimate direct object was chosen to complete each sentence and an additional two to four words were added so that the direct object never fell on the sentence final word. Nouns which appeared as responses for a given sentence in the completion task (described above) were not used as direct objects to minimise N400 attenuation in the plausible conditions due to high word expectancy. Each direct object appeared only once with the exception of four animate nouns and two inanimate nouns which appeared twice.

Implausible sentences with selection-restriction violations were then created by swapping animate and inanimate direct objects within a pair of sentences; that is, for a given sentence pair, the plausible animate direct object following an animate-selecting verb became the implausible direct object following the inanimate-selecting verb, and vice versa. This generated 144 sets of sentences, each with four conditions: (1) normal with animate direct objects (following animate-selecting verbs); (2) normal with inanimate direct objects (following inanimate-selecting verbs); (3) selection restriction violating with animate direct objects (following inanimate-selecting verbs), and (4) selection restriction violating with inanimate direct objects (following animate-selecting verbs). Each set of four sentences is henceforth referred to as a "scenario". Example sentences for one scenario are shown in Table 1. A larger sample of example stimuli is available for download at the following URL: //kuperberglab.nmr.mgh.harvard.edu/materials.htm

The frequency (Kucera & Francis, 1967) of the animate direct objects was not significantly different from that of the inanimate direct objects (44.48 vs. 49.88, per million), $t(143) = 0.68$, $p = .41$. The animate direct objects were, on average, one letter longer than the inanimate direct objects (7.5 vs. 6.6),

$t(358) = 5.89$, $p < .001$, and the mean concreteness (Coltheart, 1981; Pavio, Yuille, & Madigan, 1968) of the animate direct objects was slightly, though significantly, less than that of the inanimate direct objects (510.8 vs. 525.1), $t(132) = 2.56$, $p < .05$.

One-hundred and twenty-eight pairs of normal and semantically implausible filler sentences were then created. In each normal filler sentence, an animate subject was followed by a transitive main verb, followed by a direct object argument and then by an adjunct argument that contained a noun that was related to the preceding sentence context, for example, *The hooligan hid his identity with a mask and sun glasses.* Anomalous versions were created by pseudorandomly substituting critical noun on the adjuncts from other fillers such that they were somewhat semantically associated but were highly implausible, for example, *The hooligan hid his identity with a *pistol and sun glasses.*

Four counterbalanced lists were created, each containing 144 experimental scenarios (36 sentences in each of the four sentence types) and 128 filler sentences (64 normal and 64 implausible). A given scenario was presented only once within a list and, across lists, each scenario appeared in all four conditions. The order of scenarios was pseudorandomised within each list such that no more than two sentences in a row were of the same condition.

Plausibility ratings and LSA values

To gather plausibility ratings, all sentences (experimental and fillers) were presented, counterbalanced across the four lists, up to the point of the critical noun to 16 undergraduate participants (four per list) who did not participate in any other portion of the study. Three periods after the critical nouns were used to indicate that the sentences could continue after the critical noun. Participants were told that they were seeing "beginnings of sentences" and were asked to give ratings from 1 through 7, with 1 indicating that the sentence fragment described something that would be very unlikely to occur in the real world and 7 indicating that the sentence fragment described something that would be very likely to occur in the real world. Several examples were given but subjects were told to go with their first instincts and that there were no right or wrong answers.

The mean plausibility ratings of the four types of sentences are shown in Table 1. A 2×2 (Animacy $\times$ Violation) ANOVA revealed no main effect Animacy on either the subjects, $F(1, 15) = 1.17$, $p = .29$, or the items, $F(1, 143) = 0.40$, $p = .53$, analysis. However, as expected, a significant main effect of Violation was found on both subjects, $F(1, 15) = 305.2$, $p < .0001$, and items, $F(1, 143) = 1525.1$, $p < .0001$, analysis. There was no interaction

between Animacy and Violation on the subjects analysis, $F(1, 15) = 2.96$, $p = .11$, but the interaction approached significance on the items analysis, $F(1, 143) = 2.88$, $p = .08$. Follow-up pairwise comparisons indicated that this was due to normal inanimate sentences being slightly, although not significantly, more plausible than normal animate sentences, $F(1, 143) = 2.52$, $p = 0.12$, but there being no difference in plausibility between violated animate and inanimate violated sentences, $F(1, 143) < 1$, $p = .438$. Filler items showed a main effect of Violation on both subjects, $F(1, 15) = 700.4$, $p < .0001$, and items, $F(1, 127) = 564.6$, $p < .0001$, analysis.

To confirm the authors' intuitions that critical direct object arguments were semantically related to the preceding context we calculated semantic similarity values (SSVs) using Latent Semantic Analysis (LSA) (Landauer & Dumais 1997; Landauer, Foltz, & Dumais, 1998; available on the internet at http://lsa.colorado.edu), for all four conditions, using a term-to-term comparison between the critical word and its preceding context. Scenarios for which SSVs could not be obtained (14) were removed from analysis. The mean SSVs of the four types of sentences are shown in Table 1. These values were all at or above 0.2, similar to the SSV between "mop" and "broom" (0.21). Although very similar to each other (0.20–0.22), a 2 (Animacy) × 2 (Violation) ANOVA indicated a main effect of Violation, $F(1, 129) = 23.43$, $p < .001$, as well as a significant Animacy × Violation interaction, $F(1, 129) = 6.33$, $p < .05$. Follow-up pairwise comparisons indicated that the mean SSV for the inanimate selection-restriction violating direct objects was significantly smaller than that for the nonviolating inanimate direct objects, $F(1, 129) = 20.42$, $p < .001$; the mean SSV for the animate violating direct objects was also smaller than that for the nonviolating animate direct objects, but this difference only approached significance, $F(1, 129) = 2.91$, $p = .09$. There was no significant difference in SSV between plausible animate and inanimate direct object arguments, $F(1, 129) < 1$, $p = .54$, or implausible animate and inanimate arguments, $F(1, 129) = 1.52$, $p = .22$.

ERP experiment

Participants. Twenty-four undergraduate native English speakers from Tufts University were recruited. Participants had normal or corrected-to-normal vision, were not taking psychoactive medications, had no learning disability, no history of neurological or psychiatric disorders, and had not learned languages other than English before the age of 5. All were right handed as assessed through a modified version of the Edinburgh handedness inventory (Oldfield, 1971). Written consent was obtained from all

subjects before participation according to the established guidelines of Tufts University. Participants were paid for their participation.

Stimulus presentation. Each participant was randomly assigned to one of the four lists (six participants per list). Participants sat comfortably in a dimly lit room, separate from the experimenter. Stimuli were presented on a video monitor. Each trial was preceded by the word "READY" and participants pressed a button to initiate the trial. Each trial began with a fixation-cross displayed in the centre of the screen for 500 ms followed by 100 ms blank screen. The sentence was then presented one word at a time. Each word was presented for 450 ms with 100 ms blank screen interstimulus interval, with the exception of the sentence final word which was followed by a blank screen for 750 ms before a "?" that cued participants to press one of two buttons on a response pad, depending on whether they judged the sentence to make sense or not. Participants were asked to refrain from blinking or moving during the trial. Stimuli were presented in eight blocks of 40 trials, with short breaks between blocks. Participants viewed 12 practice trials prior to the start of the experiment.

Electrophysiological recording. Twenty-nine active tin electrodes were held in place on the scalp by an elastic cap (Electro-Cap International, Inc.,

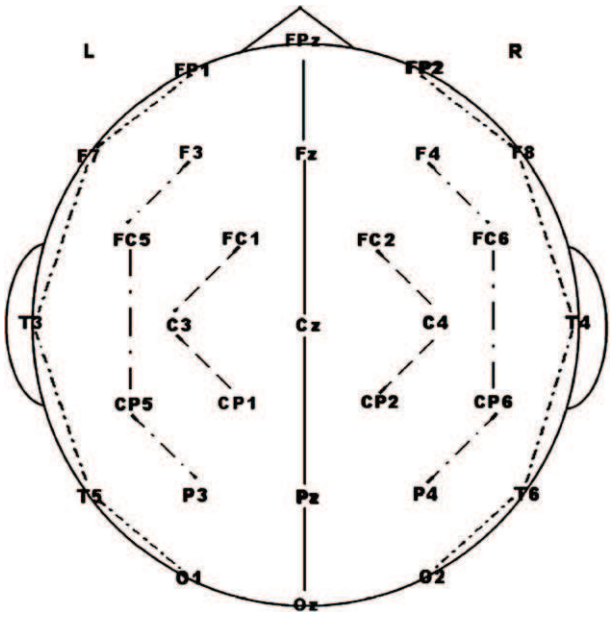

Figure 1. Electrode montage: Analyses of variance were conducted at midline, medial and lateral electrode columns shown (see the Methods section).

Eaton, OH), see Figure 1. Electrodes were also placed below the left eye and at the outer canthus of the right eye to monitor vertical and horizontal eye movements, and on the left and right mastoids. Impedance was kept below 2.5 kΩ for all scalp and mastoid electrode sites and below 10 kΩ for the two eye channels. The EEG signal was amplified by an Isolated Bioelectric Amplifier System Model HandW-32/BA (SA Instrumentation Co., 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 and behavioural responses were simultaneously monitored with a digitising computer.

Data analysis. ERPs were formed by off-line averaging of artifact-free trials, time-locked to the onset of critical words in each sentence. Only trials that were correctly classified were averaged. Each trial was baselined to a 100 ms prestimulus onset. However, when a significant effect of experimental manipulation was found within the 0–100 ms time window (noted in the Results section and likely due to artifact), trials were rebaselined to 0–100 ms *post*stimulus onset, in order to reduce the possibility that any later effects were driven by artifact. We report results in three time windows of interest: 350–500 ms, 500–700 ms, and 700–900 ms. We also carried out analyses across the 100–250 ms time window to determine if any early effects could explain any main effects or interactions within these later time windows. Modulation of average ERPs within each of these time windows was examined using analyses of variance (ANOVAs) for repeated measures at each of three electrode columns (see Figure 1). The midline column had five levels of electrode sites along the anterior–posterior distribution (AP Distribution) of the scalp (FPz, Fz, Cz, Pz, Oz), the medial column had three levels for AP Distribution and two levels for Hemisphere (FC1/FC2, C3/C4, CP1/CP2), and the Lateral column had four levels for AP Distribution and two levels for Hemisphere (F3/F4, FC5/FC6, CP5/CP6, P3/P4). At each electrode column, we carried out 2 (Animacy) $\times$ 2 (Violation) ANOVAs, with AP Distribution and Hemisphere (for the medial and lateral columns) as additional within-subject factors. These were followed up with planned simple effect ANOVAs, contrasting each sentence type with one another. Significance was set at alpha equal to .05. A Geisser–Greenhouse correction was applied to all repeated measures with more than one degree of freedom, for which original degrees of freedom and corrected probability levels are reported.

Results

Behavioural results

On average, participants' acceptability classifications during the ERP experiment matched a priori classifications 90% of the time, see Table 3. There

TABLE 3
Experiment 1. Percentage of trials for each type of sentence in which participants' acceptability judgments during the ERP experiment matched the originally defined conditions

Condition	*Mean* (SD) *% accuracy*
Nonviolating, animate direct object Patient	85.3 (8.9)
Nonviolating, inanimate direct object Patient	89.3 (6.3)
Selection-restriction violating, animate direct object Patient	90.1 (17.7)
Selection-restriction violating, inanimate direct object Patient	93.4 (10.6)

was no main effect of Violation or Animacy, nor a Violation × Animacy interaction, all Fs = <2.79, $p > .12$.

ERP results: The critical direct object argument

Early effects. In the 0–100 ms interval, there was a significant Violation × AP Distribution interaction at the midline, $F(4, 92) = 6.80$, $p < .01$, medial, $F(2, 46) = 10.60$, $p < .01$, and lateral, $F(3, 69) = 10.28$, $p < .01$, electrode columns. The effects were due to a significantly greater positivity over anterior electrode sites to selection-restriction violating direct object arguments, compared to nonviolating ones. Because these effects appear to begin prior to stimulus onset, they may have been driven by artifact. Subsequent analyses were therefore carried out using a poststimulus 0–100 ms baseline. Using the poststimulus baseline, in the 100–250 ms time window (the P2), there were no significant main effects of either Violation or Animacy at any electrode columns, all Fs < 1. Similarly, the Violation × AP Distribution, Animacy × AP Distribution, and Violation × Animacy interactions were all nonsignificant, all Fs < 1.22.

350–500 ms. Within the 350–500 ms time window, there was a main effect of Violation at the midline, $F(1, 23) = 12.11$, $p < .01$, medial, $F(1, 23) = 15.76$, $p < .001$, and lateral, $F(1, 23) = 13.22$, $p < .01$, electrode columns, due to selection-restriction violating direct objects evoking larger N400s than nonviolating direct objects. This effect was larger at posterior than anterior midline sites, as reflected by a Violation × AP Distribution interaction at the midline electrode column, $F(4, 92) = 3.50$, $p < .0001$. There were no main effects of Animacy or interactions between Animacy and spatial variables, with the exception of an Animacy × Hemisphere interaction at the lateral column (follow-ups comparing ERPs animate and inanimate direct objects at each level of Hemisphere, however, failed to reveal significant effects).

Of most interest, a Violation × Animacy interaction was significant at the midline, $F(1, 23) = 5.76$, $p < .01$, and medial, $F(1, 23) = 4.62$, $p < .05$, columns,

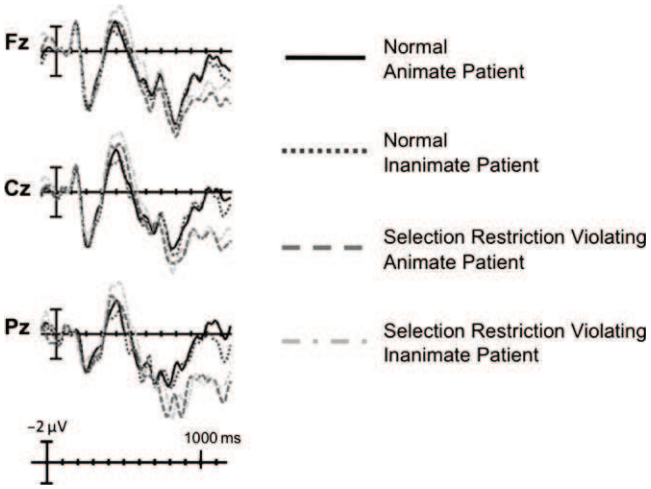

Figure 2. Experiment 1: ERPs evoked by direct object arguments in all four experimental conditions along the midline. The solid black line indicates normal animate nouns, the dotted blue line indicates normal inanimate nouns, the dashed red line indicates selection violating animate nouns, and the dash-dotted green line indicates selection-restriction violating inanimate nouns. The plots are shown using a 0–100 ms poststimulus baseline (consistent with how the statistics were carried out). The modulation across the four conditions, however, was the same using a prestimulus −25 to 0 ms baseline, see http://www.nmr.mgh.harvard.edu/kuperberglab/materials.htm [To view this figure in colour, please visit the online version of this Journal.]

and approached significance at the lateral column, $F(1, 23) = 3.40$, $p = .08$. See Figure 2 for a comparison of all four conditions along the midline electrode column. Planned pairwise comparisons were carried out to further examine the source of this interaction. The inanimate violating direct objects evoked a significantly larger N400 than inanimate normal direct objects at the midline, $F(1, 23) = 16.64$, $p < .001$, medial, $F(1, 23) = 18.91$, $p < .001$, and lateral, $F(1, 23) = 16.87$, $p < .001$, columns, see Figure 3B, but there was no significant effect of Violation on the animate direct objects (all Fs < 1.48, ps $> .24$), see Figure 3A. In addition, selection-restriction violating inanimate arguments evoked significantly a larger N400 than selection-restriction violating animate arguments at the midline, $F(1, 23) = 9.88$, $p < .001$, medial, $F(1, 23) = 7.12$, $p < .05$, and lateral, $F(1, 23) = 6.88$, $p < .05$, columns. Finally, while there was no significant main effect of Animacy between normal inanimate and animate direct objects (Fs < 1.943, ps $> .15$), there was a significant Animacy by AP Distribution effect along the midline, $F(4, 92) = 3.35$, $p < .05$, due to normal animate direct object arguments evoking a larger N400 amplitude at centro-posterior sites, than to normal inanimate direct object arguments.

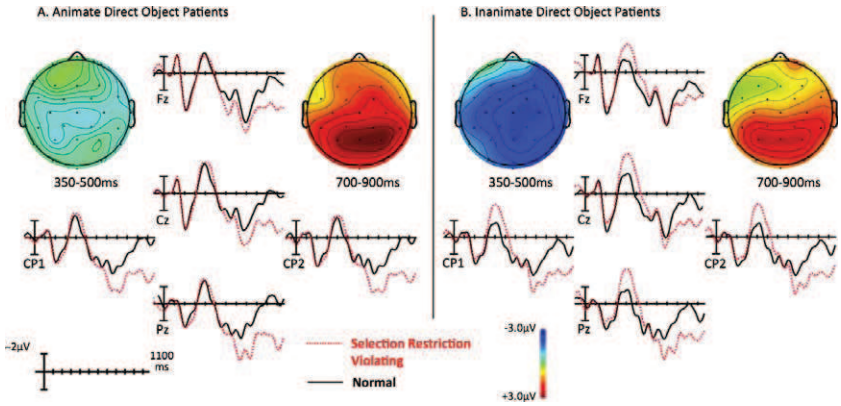

Figure 3. Experiment 1: ERPs evoked by direct object arguments that were either animate (A) or inanimate (B). ERPs to normal nonviolating direct object arguments are shown in a solid line, while those to selection-restriction violating animate noun arguments are shown in a dotted line. Voltage maps show an average voltage difference between normal and selection–restriction violating arguments in the N400 (left) and P600 (right) time windows. [To view this figure in colour, please visit the online version of this Journal.]

500–700 ms. There were no main effects of Violation, Animacy, or interactions involving Violation or Animacy, with the exception of a main effect of Animacy that approached significance at the lateral column, $F(1, 23) = 3.84$, $p = .06$.

700–900 ms. There were no main effects or interactions involving Animacy. However, the main effect of Violation was significant at the midline, $F(1, 23) = 15.92$, $p < .001$, medial, $F(1, 23) = 14.47$, $p < .001$, and lateral, $F(1, 23) = 14.26$, $p < .001$, due to a P600 effect to the violating (vs. normal) direct objects, see Figures 2 and 3. This effect had a more posterior than anterior distribution, as reflected by interactions between Violation and AP Distribution that reached significance at the medial, $F(1, 23) = 8.74$, $p < .01$, and lateral, $F(1, 23) = 10.96$, $p < .01$, columns and approached significance at the midline column, $F(1, 23) = 3.04$, $p = .06$.

Discussion

Experiment 1 examined ERPs to direct object NPs that were either animate or inanimate, and that either violated or did not violate the selection restrictions of their preceding verbs. Within the N400 time window, we observed a significant Animacy by Violation interaction. Pairwise comparisons indicated that this interaction arose because of a significant N400 effect to selection-restriction violating (vs. nonviolating) inanimate, but not animate, direct object arguments. In the plausible sentences, the N400

(at posterior sites) was slightly larger to the animate than inanimate direct objects, whereas in the violating sentences, it was larger to the inanimate than animate direct objects. Within the P600 time window we observed only a main effect of Violation: selection-restriction violating (vs. nonviolating) direct objects evoked a P600 effect, regardless of animacy.

Before discussing these findings in more detail, we consider two alternative explanations for the pattern of findings within the N400 time window. The first is that it was primarily driven by differences between conditions in the semantic relatedness across content words, rather than animacy per se. This seems unlikely. Although there were differences in the semantic relatedness between the critical word and its preceding contexts (as indexed by average SSVs on an LSA) across the four conditions, these differences were very small and, as is clear from Table 1, the pattern of SSVs across the four conditions did not pattern with the modulation of the N400. Specifically, the nonviolating inanimate arguments were *less* semantically related to their contexts than the nonviolating or selection-restriction violating animate arguments, predicting the largest N400 in this condition. In fact, the smallest N400 was seen to these inanimate nonviolated arguments.

A second alternative possibility is that the results were driven by inherent differences in the selection restrictions of animate-selecting and inanimate-selecting verbs. Selection restrictions, beyond those of animacy, may have led to different degrees of match/mismatch with the semantic features of the direct objects. Inanimate-selecting verbs not only select for inanimate direct objects but will also tend to select for more fine-grained semantic features. For example, the verb *sip* will not only select for an inanimate entity such as *brandy*, but will also select for more specific features such as *is a beverage*. In contrast, an animate selecting verb such as *thank* will tend to select only for animate direct objects, without selecting for further fine-grained features. Thus, during processing, encountering an inanimate-selecting verb, particularly after a fairly constraining context, might have allowed for a more accurate prediction of the direct object. This account can explain why the N400 was smaller to nonviolating inanimate than animate direct object arguments: inanimate direct objects are more likely to have matched all the selection restrictions of their preceding verb. However, it does not easily explain why there was an *enhanced* N400 to selection-restriction violating inanimate, relative to violating animate direct objects. Encountering an animate direct object after an inanimate-selecting verb would violate more selection restrictions than encountering an inanimate direct object after an animate-selecting verb. This might have predicted a larger N400 to animate than inanimate violating direct objects—the opposite pattern of findings to those observed here.

Effects of animacy on the processing of plausible sentences

As noted in the introduction, the first aim of Experiment 1 was to contrast the hypothesis that animate nouns are more salient/lexico-semantically accessible independent of syntactic position or whether animacy impacts processing through a mapping of the animacy hierarchy onto linear order or specific thematic role entailments. Our results clearly rule out this first alternative. Unlike previous studies, which have demonstrated a larger N400 amplitude to inanimate subject arguments (Kuperberg et al., 2003; Nakano et al., 2010; Paczynski & Kuperberg, 2009; Weckerly & Kutas, 1999), in the current experiment we found an effect in the opposite direction: inanimate direct object arguments evoked an attenuated N400 compared with animate ones. This result is incompatible with the proposal that animate nouns are generally more salient/lexico-semantically accessible. Instead, our results indicate that semantic processing of inanimate direct objects was facilitated relative to animate direct objects. This facilitation may have been driven either by animacy hierarchy-based biases on linear order, or through a link between animacy and thematic role. As noted in the introduction, Experiment 1 cannot distinguish between these two possibilities.

In previous studies examining the effect of animacy on subject NPs, any effects on the N400 have primarily been observed in good comprehenders (Nakano et al., 2010; Weckerly & Kutas, 1999). Although we did not test reading spans in our participants, it is possible that, as Nakano et al. suggest, only high span readers are able to use animacy information online. In addition, Nakano et al. reported that the N400 effect to inanimate versus animate subject NPs had an anterior distribution, similar to the distribution of the analogous effect reported by Paczynski and Kuperberg (2009), and for *poor* comprehenders by Weckerly and Kutas (1999). This contrasts with the results of the present experiment that showed that the N400 effect to nonviolated animate versus inanimate direct objects was largest over central sites. However, the distribution of the effect found in the present study is in keeping Weckerly and Kutas' (1999) finding that, for *good* comprehenders, the animacy N400 effect on the subject was centrally distributed, a finding similar to Kuperberg et al.'s (2003). Future studies will be necessary to determine the functional significance of these differences in scalp distribution across experiments.

Effects of animacy on processing selection-restriction violating sentences

As summarised above, we saw an interaction between Animacy and Violation on the N400, but only a main effect of Violation on the P600. As discussed in the Introduction, different accounts have placed different

emphases on the triggers of the P600 effect, and its relationship to the N400 effect in semantically anomalous sentences that violate verb-argument structure (see Table 2). Below we discuss the present findings in relation to these frameworks.

The findings are somewhat consistent with Kolk's Monitoring hypothesis that, as discussed in the introduction, predicted the attenuated N400 effect we observed to the violating (vs. nonviolating) animate direct argument NPs, but not on the violating (vs. nonviolating) inanimate direct object arguments. This framework also predicted the P600 effect we observed to both animate and inanimate selection-restriction violating arguments as they are both highly implausible. However, according to the Monitoring hypothesis, this P600 effect should be larger to reversible animate selection-restriction violations than to irreversible inanimate selection-restriction violations. While visual inspection of the waveform suggests a possible trend in this direction, the interaction between Animacy and Violation did not approach significance (all Fs < 1). Nonetheless, it is possible that the lack of a significant interaction between Animacy and Violation in this experiment was because thematic role reversibility was only partial: although the selection-restriction violating animate direct object arguments could have plausibly acted as Agents for their preceding verbs (e.g., **. . .plowed the labourer. . ./. . . plowed by the labourer. . .*), the subjects of these verbs could not plausibly be assigned the Patient role (e.g., ** . . .the farmer was plowed by the labourer. . .*). We investigate this possibility in Experiment 2.

The pattern of findings is inconsistent with both the "semantic-attraction" hypothesis (Kim & Osterhout, 2005), and the proposal by Hagoort and colleagues (2009). Although both these frameworks predicted the attenuated N400 effect and P600 effect we observed to semantically attracted animate violating (vs. nonviolating) direct object arguments, they failed to predict the P600 effect seen to the nonsemantically attracted inanimate violating (vs. nonviolating) arguments.

The findings are consistent with the eADM framework. With regard to the attenuation of the N400 effect for selection-restriction violating animate arguments, the eADM offers two possible explanations. First, animate arguments (high prominence) assigned Patient role (low prominence) could have incurred processing cost during the *compute prominence* step, thus blocking initial evaluation of *plausibility*. Alternatively, because the *plausibility* processing step within the eADM is noncombinatorial, no processing costs were incurred as the violating animate arguments could serve as plausible Agents of the preceding verb. In contrast, violating (vs. nonviolating) inanimate arguments did incur costs during initial *plausibility* evaluation, as these could not play a plausible alternative role about the verb, leading to the N400 effect to these types of violations. According to

the eADM, the P600 effect to both inanimate and animate selection-restriction violations reflected increased costs during the later *well-formedness* step.

Finally, the findings are consistent with Kuperberg (2007). Similar to Kuperberg et al. (2003), we suggest that mismatches between animacy-based expectations and the input "switched off" a full, more detailed (fine-grained) semantic memory-based analysis between verb and argument, leading to the reduced N400 effect to selection-restriction violating (vs. nonviolating) animate direct object arguments. In the present study, selection-restriction violating animate arguments mismatched expectations that inanimate arguments should be encountered in the direct object position. This switched off a more detailed semantic memory-based analysis between the selection restrictions of the verb and the semantic features of the argument, and thus the N400 effect to the violating (vs. nonviolating) animate arguments was attenuated (this attenuation may have been further driven by the semantic associations between the context and the critical word). We elaborate further on this idea in the General Discussion.

Kuperberg (2007) also suggested that the P600 effect is triggered by the conflict between the propositionally impossible arguments (determined by a fully combinatorial analysis with a syntactic assignment of thematic roles) and a match between the context and stored information within semantic memory (semantic memory-based processing). This conflict is most likely to occur given a semantically constrained context and when participants explicitly judge plausibility (Kuperberg, 2007). In the present study, we suggest that the P600 effect to both types of violations was triggered by the conflict between the propositionally impossible direct objects (it is impossible to plow a labourer or to penalise a meadow) and the relatively close semantic association between these arguments and their preceding content words in the context. Importantly, Kuperberg argued that the semantic P600 effect is not directly driven by the reversibility of thematic roles: in previous studies (Kuperberg et al., 2006, 2007), selection-restriction violations in nonreversible sentences (e.g., *The trumpets would *courtesy*...) evoked P600 effects of similar amplitude as those occurring in reversible sentences (e.g., *The eggs would *eat*...). This idea is supported by the present findings: the amplitude of the P600 effect to the violating (vs. nonviolating) direct objects was not modulated by their semantic or thematic reversibility.

EXPERIMENT 2

Introduction

In Experiment 1, we showed that animacy affected the processing of direct object arguments in simple English sentences. However, as noted in the above

discussion, this experiment could not differentiate between two potential mechanisms by which animacy impacted this processing: (1) through its association with specific thematic roles, or (2) through a direct mapping between the animacy hierarchy and the linear ordering of arguments. In both cases, animate direct object arguments were less expected because, in the former case, inanimate nouns are more Patient-like, and in the latter case, less animate nouns are expected at later sentence locations.

In Experiment 2, we attempted to disentangle these two accounts by manipulating the specific thematic role assigned to the direct object argument while keeping the animacy-based selection restrictions of the verb constant. To do this, we retained the sentences that selected for animate direct objects from Experiment 1 (e.g., *penalised*), all of which assigned the Patient role to the direct object argument. We then constructed a second set of sentences, based on these, which used object-experiencer verbs, such as *pleased, frightened, and astonished,* which assign the Experiencer role (i.e., someone who experiences an emotion or cognitive state) to the direct object argument (see Table 4, conditions 1 and 2 for example sentences). Note that all normal sentences used animate direct objects.

As already discussed, the Patient role is most closely associated with inanimate, rather than animate nouns. In contrast, the Experiencer role can plausibly be assigned only to animate nouns. Indeed, the restrictions on animacy for the Experiencer role are constrained to higher levels of the animacy hierarchy (e.g., *flabbergasted the ant* can only be understood metaphorically). Thus, if there is a direct mapping from animacy features to specific thematic roles and if this influences processing (e.g., Bornkessel & Schlesewsky, 2006; Traxler et al., 2002; Weckerly & Kutas, 1999), then in normal sentences it should be easier to process animate direct objects assigned the Experiencer role than those assigned the Patient role: in the former case, the animacy of the direct argument matches the thematic role assigned by the verb, but in the latter case it mismatches. This difference would lead to a smaller N400 amplitude to normal animate Experiencers than to normal animate Patients. If animacy instead influences processing of verb arguments through a direct mapping between the animacy hierarchy and linear order, we would expect the N400 amplitude not to be modulated by the thematic roles assigned to the direct object argument.

An additional goal of Experiment 2 was to examine the effects of the specific thematic role assigned on the processing of direct object arguments in implausible sentences. Therefore, as in Experiment 1, we introduced animacy-based selection-restriction violations between the verb and the direct object. Note that this meant that all the violated sentences had inanimate direct objects (see Table 4, conditions 3 and 4). Of note, these two types of violated sentences differed in their thematic reversibility. The sentences that introduced

TABLE 4
Example sentences in Experiment 2, including semantic similarity value (SSV) based on Latent Semantic Analysis, and plausibility ratings

Condition	*Example*	*SSV (LSA)*	*Plausibility ratings*
Nonviolating animate direct object Patient	At the homestead the farmer penalized the **laborer** for laziness	0.22	5.36
Nonviolating animate direct object Experiencer	At the homestead the farmer interested the **laborer** in some work	0.22	5.28
Selection-restriction violating, inanimate direct object Patient	At the homestead the farmer penalized the ***meadow** for laziness	0.20	2.23
Selection-restriction violating, inanimate direct object Experiencer	At the homestead the farmer interested the ***meadow** in some work	0.06	2.15

Critical direct object arguments, to which ERP responses were measured, are bolded in the example sentences.

selection-restriction violations on inanimate Patients were irreversible (e.g., *. . .*the farmer penalised the meadow*. . ./*. . .*the farmer was penalised by the meadow*. . .). The sentences that introduced selection-restriction violations on inanimate Experiencers, however, were fully repairable through a thematic role reversal (e.g., *. . .*the farmer interested the meadow*. . ./. . .*the farmer was interested by the meadow*. . .).

The Error Monitoring (van de Meerendonk et al., 2009), semantic attraction (Kim & Osterhout, 2005), and Hagoort et al.'s (2009) frameworks all predict that semantic reversibility should modulate the magnitude of the N400 effect to selection-restriction violated (vs. nonviolated) arguments: the N400 effect to these fully reversible anomalous Experiencers should be smaller than the N400 effect to irreversible anomalous Patients. The Error Monitoring framework predicts that both types of selection-restriction violations should evoke a P600 effect (as both yield highly implausible propositions) but that this effect should be larger to reversible than irreversible anomalies. Kim and Osterhout's (2005) and Hagoort et al.'s (2009) frameworks predict a P600 effect only on reversible anomalies.

The eADM predicts that selection-restriction violations on both Patient and Experiencer direct objects should evoke an N400 effect, although this would reflect different processes. For selection-restriction violating inanimate Patients, no costs would be expected during *compute prominence*, as Patients inanimate nouns are low in prominence. Instead, difficulties occur during the initial noncombinatorial *plausibility* step, as the selection-restriction violating

inanimate Patients cannot play any alternate role about the verb. For selection-restriction violating inanimate Experiencers, processing costs would be predicted to occur during *compute prominence*, as Experiencers are of higher prominence than Patients, and thus poorer fits for inanimate nouns. Importantly, as demonstrated in Experiment 1, for direct object arguments in simple English sentences, the processing cost of a mismatch in animacy during the *compute prominence* step is significantly smaller than the cost of processing irreversible selection-restriction violations during the *plausibility* step. Thus, in this experiment, the eADM would predict a significantly smaller N400 effect to selection-restriction violating (vs. nonviolating) Experiencers than to selection-restriction violating (vs. nonviolating) Patients. Note that this prediction holds true even if costs during *compute prominence* are not sufficient to block the *plausibility* step, as selection-restriction violating inanimate nouns in experiment 2 *could* serve a plausible alternative role about the verb as already discussed above. The eADM also predicts that both types of violations would result in a P600 effect due to costs during *well-formedness*, which would not be expected to be modulated by thematic role reversibility.

Kuperberg (2007) emphasises the roles of both animacy and semantic association in modulating the N400. If animacy information is used to guide thematic role assignment, this would predict a smaller N400 effect to inanimate selection-restriction violating Experiencers than Patients, due to blocking of subsequent finer-grained semantic memory-based processing (see Experiment 1 discussion). If, however, animacy exerts its influence directly through a direct mapping between the animacy hierarchy and linear order, an N400 effect would be seen to selection-restriction violations on inanimate direct objects following animate subjects, regardless of whether the direct objects were assigned the role of Patient or Experiencer. In addition, Kuperberg (2007) predicts a P600 effect to both types of violations as they both yield highly implausible propositions that conflict with matches between the input and associations stored within semantic memory. The P600 should not be modulated by thematic reversibility (see Kuperberg et al., 2006, 2007; Stroud and Phillips, 2009). Predictions made by all these frameworks are summarised in Table 5.

Methods

Development and pretesting of materials

A new set of scenarios was developed, each with four conditions: (1) normal, Patient direct object; (2) normal, Experiencer direct object; (3) selection-restriction violating, Patient direct object; (4) selection-restriction violating, Experiencer direct object.

TABLE 5
Experiment 2. Predictions made by different proposals regarding the modulation of the N400 and P600 by animacy and selection-restriction violations

Proposal	*N400*	*P600*
Nonviolating Experiencer and Patient arguments		
Animacy as a proxy for Thematic Role	Experiencer < Patient	
Animacy Hierarchy/Linear Position	Experiencer = Patient	
Violating versus Nonviolating Experiencer and Patient arguments		
Kuperberg et al.	*If animacy acts as a proxy to Thematic Role:* Experiencer: No N400 effect due to "switching off" of additional semantic analysis when animacy mismatches expectations based on selection restrictions of the verb and thematic role Patient: N400 effect *If animacy acts directly through semantic memory (due to animacy hierarchy-based linear mapping):* Experiencer: N400 effect Patient: N400 effect	Experiencer: P600 effect Patient: P600 effect Effect driven by implausibility/ impossibility of final interpretation in conflict with some match in semantic memory-based analysis, with no effect of thematic reversibility
Kolk et al.	Experiencer: No N400 effect due to heuristic mechanisms leading to fully plausible interpretation (full thematic reversibility) Patient: N400 effect	Experiencer: P600 effect (larger) Patient: P600 effect (smaller) Effect driven by reanalysis triggered by detection of highly implausible interpretation (error) Effect larger for Experiencer arguments driven by greater difficulty in resolving error due heuristic mechanisms leading to fully plausible interpretation (full thematic reversibility)
Kim & Osterhout	Experiencer: No N400 effect due to semantic attraction (reversibility) between argument and verb Patient: N400 effect	Experiencer: P600 effect driven by semantic attraction (reversibility) between argument and verb Patient: No P600 effect

(*Continued*)

Table 5 (*Continued*)

Proposal	*N400*	*P600*
eADM	*If Experiencer higher than Patient in prominence:* Experiencer: N400 effect (smaller) Patient: N400 effect (larger) Larger effect for Patient due greater costs incurred during *plausibility* than during *compute prominence*	*If Experiencer higher than Patient in prominence:* Experiencer: P600 effect Patient: P600 effect Effect driven by real-world impossibility detection during *well-formedness* step
	If Experiencer equal to Patient in prominence: Experiencer: No N400 effect due to lack of difficulties during *compute prominence* step or initial *plausibility* step (due to thematic reversibility) Patient: N400 effect	*If Experiencer equal to Patient in prominence:* Experiencer: P600 effect (larger) Patient: P600 effect (smaller Effect driven by real-world impossibility detection during *well-formedness* step Effect larger for *Experiencers* due to additional processing during *generalized-mapping* step
Hagoort et al.	Experiencer: No N400 effect due to semantic cues being stronger than syntactic cues (full thematic reversibility) Patient: N400 effect	Experiencer: P600 effect driven by semantic cues being stronger than syntactic cues (full thematic reversibility) Patient: No P600 effect

The normal and violated sentences with Patient direct objects were the same as the normal and violated sentences with animate-selecting verbs used in Experiment 1. To generate the normal sentences with Experiencer direct objects, we replaced the main Agent–Patient verbs with Object–Experiencer verbs, such as *pleased* or *frightened* that were plausible both with regards to the preceding sentence context and the animate direct object argument. All verbs were passivisable, with the subject argument being associated with the Stimulus thematic role. No nonpassivisable verbs such as *mattered to* were used in order to be able to test the hypothesis that thematic role reversibility modulates P600 amplitude. Where necessary, sentence endings following Experiencer direct objects were altered to maintain whole sentence plausibility. These normal sentences with Experiencer direct objects were then used to create their selection-restriction violating counterparts by substituting the animate for the inanimate direct object associated with that scenario, see Table 4, conditions 3 and 4. Thus, all the normal sentences had animate direct objects and all the violated sentences had inanimate direct objects. A complete list of stimuli is available for download at the following URL: http://kuperberglab.nmr.mgh.harvard.edu/publications.htm

Semantic relatedness was once again assessed using LSA (Landauer & Dumais, 1997; Landauer et al., 1998; available on the internet at http://lsa.colorado.edu), using a term-to-term comparison between the critical word and its preceding context. Scenarios for which SSVs could not be obtained (14) were removed from the analysis. As can be seen in Table 4, mean SSVs for three of the sentence types were at or above 0.2, while selection-restriction violating Experiencer arguments had SSVs of 0.06. A 2 (Thematic Role) $\times$ 2 (Violation) analysis indicated a significant main effect of Thematic Role, $F(1, 129) = 29.80$, $p < .001$, and Violation, $F(1, 129) = 314.68$, $p < .001$, as well as a significant Thematic Role $\times$ Violation interaction, $F(1, 129) = 311.2$, $p < .001$. Follow-up pairwise comparisons indicated that the violating Experiencers had lower SSVs than nonviolating Experiencers, $F(1, 129) = 322.1$, $p < .001$, and violating Patients, $F(1, 29) = 93.160$, $p < .001$. However, there were no significant differences in SSVs between violating and nonviolating Patients, $F(1, 129) = 2.18$, $p = .14$, nor for nonviolating Patient versus Experiencer arguments, $F(1, 129) = 1.67$, $p = .20$.

Four counterbalanced lists were created, as for Experiment 1, each containing 144 experimental scenarios (36 sentences in each of the four sentence types) and the same 128 filler sentences as used in Experiment 1 (64 normal and 64 anomalous).

Plausibility ratings

As in Experiment 1, plausibility ratings were collected by presenting all sentences up until the point of the critical noun to 16 participants who did not participate in any other portion of the study. Results are shown in Table 3. A 2×2 (Thematic Role $\times$ Violation) ANOVA reveals no main effect of Thematic Role on either the subjects, $F(1, 15) = 1.75$, $p = .21$, or items, $F(1, 143) = 0.79$, $p = .38$, analysis. However, as expected, a significant main effect of Violation was found in both the subjects, $F(1, 15) = 281.22$, $p < .0001$, and items, $F(1, 143) = 661.4$, $p < .0001$, analyses. There was no interaction between Thematic Role and Violation on either the subjects, $F(1, 15) = 0.002$, $p = .96$, or the items, $F(1, 143) = 1.03$, $p = .33$, analysis.

ERP experiment

Twenty-four right-handed undergraduate native English speakers from Tufts University were recruited who did not participate in any other parts of Experiments 1 and 2. The procedures were exactly the same as in Experiment 1 except for the stimuli presented and the use of Thematic Role, rather than Animacy, as a factor in data analysis.

TABLE 6
Experiment 1. Percentage of trials for each type of sentence in which participants' acceptability judgments during the ERP experiment matched the originally defined conditions

Condition	*Mean (*SD*) % accuracy*
Nonviolating animate direct object Patient	84.8 (7.7)
Nonviolating animate direct object Experiencer	82.3 (9.4)
Selection-restriction violating, inanimate direct object Patient	91.2 (12.1)
Selection-restriction violating, inanimate direct object Experiencer	90.6 (11.4)

Results

Behavioural results

On average, participants' acceptability judgments during the ERP experiment matched a priori classifications 87% of the time (see Table 6). There was no significant main effect of Violation or Thematic Role, nor was there a Violation × Thematic Role interaction, all Fs <2.86, ps $>.12$.

ERP results: The critical direct object argument

Early effects. Within the 0–100 ms time window there were significant Thematic Role × AP Distribution and Thematic Role × Violation × AP Distribution interactions at the midline, $F1(4, 92) = 4.21$, $p < .05$, $F2(4, 92) = 3.93$, $p < .05$, medial, $F1(2, 46) = 7.58$, $p < .01$, $F2(2, 46) = 6.76$, $p < .05$, and lateral, $F1(3, 69) = 7.94$, $p < .01$, $F1(3, 69) = 5.16$, $p < .05$, electrode columns. The effect was driven by an anterior negativity for selection-restriction violating Experiencer arguments. The effect appeared to begin prior to stimulus onset and is likely to have been driven by artifact. We therefore used a 0–100 ms poststimulus onset baseline for the remainder of the analyses below. Using the poststimulus baseline, in the 100–250 ms time window (the P2), there was no main effect of Thematic Role or Violation, all Fs <1. No interactions involving the two main factors were significant, all Fs <1.79, ps $>.19$ (see Figure 4).

350–500 ms. There were no main effects of Thematic Role or interactions involving Thematic Role at any electrode column (all Fs <1.43, ps >0.24). There was, however, a main effect of Violation at the midline, $F(1, 23) = 27.87$, $p < .001$, medial, $F(1, 23) = 25.47$, $p < .001$, and lateral, $F(1, 23) = 25.87$, $p < .001$, electrode columns, due to a larger N400 to selection-restriction violating than to normal direct objects (all Fs >22.6, ps $<.0001$). For comparison of all four conditions at the midline see Figure 4. A significant Violation × AP Distribution interaction at the lateral column, $F(1, 23) = 4.22$, $p < .05$, and Violation × Hemisphere interactions at the

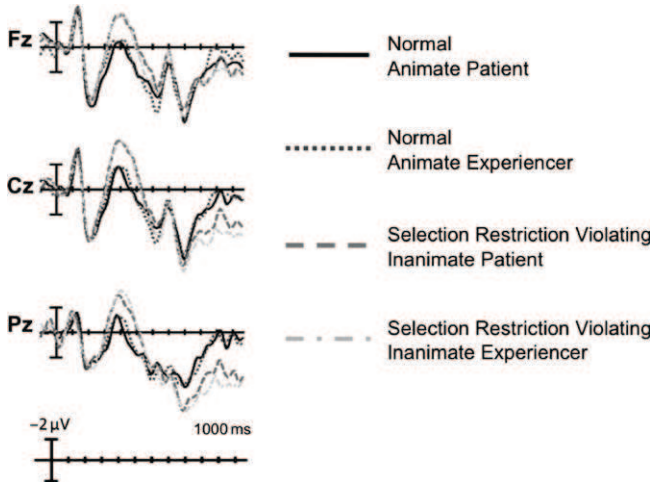

Figure 4. Experiment 2: ERPs evoked by direct object arguments in all four experimental conditions along the midline. The solid black line indicates normal animate Patients, the dotted blue line indicates normal animate Experiencers, the dashed red line indicates selection-violating inanimate Patients, and the dash-dotted green line indicates selection-restriction violating inanimate Experiencers. The plots are shown using a 0–100 ms poststimulus baseline (consistent with how the statistics were carried out). The modulation across the four conditions, however, was the same using a prestimulus −25 to 0 ms baseline, see http://www.nmr.mgh.harvard.edu/kuperberglab/materials.htm [To view this figure in colour, please visit the online version of this Journal.]

medial, $F(1, 23) = 9.29$, $p < .01$, and lateral columns, $F(1, 23) = 6.97$, $p < .05$, reflected the centro-parietal and right-lateralised distribution of this effect, see Figure 5.

500–700 ms. The N400 effect to the selection-restriction violating (vs. nonviolating) direct objects appeared to continue into the 500–700 ms time window, as reflected by a main effect of Violation that reached significance at the lateral, $F(1, 23) = 5.47$, $p < .05$, and approached significance at the midline column, $F(1, 23) = 4.23$, $p = .06$. This negativity was anteriorly distributed, as reflected by a significant Violation × AP Distribution interaction at the midline column, $F(4, 92) = 4.71$, $p < .05$.

700–900 ms. A main effect of Violation was significant at the lateral column, $F(1, 23) = 5.47$, $p < .05$, and approached significance at the midline column, $F(1, 23) = 4.23$, $p = .051$, due to selection-restriction violating direct objects evoking a larger P600 than normal direct objects, see Figure 4. Significant Violation × AP Distribution interactions were found at the midline, $F(4, 92) = 4.70$, $p < .05$, and lateral columns, $F(3, 69) = 7.83$, $p < .01$, due to the P600 being largest over centro-parietal sites. There was

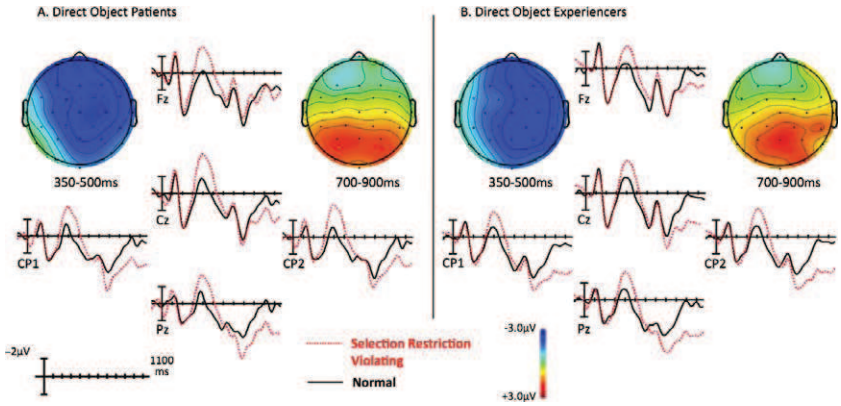

Figure 5. Experiment 2: ERPs evoked by direct object arguments assigned either the Patient role (A) or Experiencer role (B). ERPs to normal nonviolating animate direct object arguments are shown in a solid line, while those to selection-restriction violating inanimate direct object arguments are shown in a dotted line. Voltage maps show an average voltage difference between normal and selection-restriction violating arguments in the N400 (left) and P600 (right) time windows. [To view this figure in colour, please visit the online version of this Journal.]

no main effect of Thematic Role at any column (all Fs < 1.45, ps $> .24$), and the P600 effect to the violating (vs. normal) direct objects was not modulated by their Thematic Role (no Violation $\times$ Thematic Role interaction at any electrode columns, all Fs < 1, ps $> .38$).

Discussion

Experiment 2 examined ERPs to direct object arguments that were assigned either the Patient or Experiencer role by their preceding verb. In the plausible sentences, the amplitude of the N400 evoked by animate direct objects was not modulated by the thematic role they were assigned. In the implausible selection-restriction violating sentences, the violating (vs. nonviolating) inanimate direct object arguments evoked both an N400 and P600 effect. Again, neither of these effects was modulated by the thematic role they were assigned.

As in Experiment 1, the pattern of findings on the N400 is unlikely to have been driven by differences across conditions in the semantic relatedness across content words. Although semantic relatedness did vary across the four conditions, it did not pattern with N400 modulation. For example, selection-restriction violating inanimate Experiencer arguments had significantly lower semantic relatedness (SSV of 0.06) than the other three conditions. Yet the amplitude of the N400 evoked by these arguments was the same as that evoked by violating inanimate Patient arguments.

Effects of animacy on processing plausible sentences

As noted in the Introduction, several theorists have proposed that animacy impacts verb-argument processing through its association with particular thematic roles (e.g., Frazier & Rayner, 1982). On this account, a decreased N400 should be seen when there is a match between the animacy of an argument and the prototypical animacy of its assigned thematic role. For example, an Agent is prototypically animate; therefore, an animate Agent should be associated with a smaller N400 than an inanimate Agent (e.g., Nakano et al., 2010; Weckerly & Kutas, 1999). This link between animacy and thematic roles is explicitly articulated in Bornkessel and Schlesewsky's (2006) eADM in which animacy is proposed to influence the *compute prominence* step, including on postverbal direct object arguments (Figure 3 in Bornkessel & Schlesewsky, 2006). Importantly, for our study, within the eADM, animacy should impact the *compute prominence step* even in English (Bornkessel-Schlesewsky & Schlesewsky, 2008, p. 71). According to this framework, it should be easier to assign animate arguments to the more prominent Experiencer role than the less prominent Patient role, and this facilitation should manifest itself as a reduction in N400 amplitude.

The findings of the present experiment are, however, inconsistent with a direct mapping between animacy and specific thematic roles. The amplitude of the N400 evoked by plausible animate Experiencers was equal to that evoked by plausible animate Patients, even though Experiencers are required to be animate while Patients are more likely to be inanimate. Thus, at least for postverbal arguments in English, thematic role animacy entailments do not affect verb-argument processing.

Effects of animacy on processing selection-restriction violating sentences

As summarised in the Introduction, various frameworks have discussed the relationship between the N400 and P600 effects evoked by selection-restriction violating (vs. nonviolating) arguments. Below we discuss the present findings in relation to these frameworks.

Our results are inconsistent with both the "semantic-attraction" hypothesis (Kim & Osterhout, 2005), and the proposal by Hagoort and colleagues (2009). Both of these frameworks predicted an attenuation of the N400 effect to selection-restriction violations occurring on inanimate Experiencer arguments, as these anomalies were fully reversible (e.g., **. . .the farmer interested the meadow. . ./. . .the farmer was interested by the meadow. . .*). Instead, the N400 evoked by these anomalies was no different from that evoked by nonreversible anomalies (e.g., **. . .the farmer penalised the meadow. . ./*. . .the*

farmer was penalised by the meadow...). In addition, contrary to the predictions of both models, a robust P600 was observed to both types of anomalies.

The pattern of results is only partially compatible with Kolk's Error Monitoring Hypothesis (van de Meerendonk et al., 2009). Consistent with its predictions, both types of selection-restriction violations, which led to highly implausible propositions, evoked a semantic P600. However, the model also predicted that the N400 and P600 to these violations would be modulated by thematic role reversibility. Specifically, noncombinatorial heuristic processes would have initially evaluated the inanimate violated Experiencer sentences as plausible (e.g., ... *the farmer was interested by the meadow*...), leading to an attenuation of the N400 effect to these violations. In addition, this initial interpretation would lead to a greater conflict with full syntactic interpretation, thus leading to a larger P600 than to selection-restriction violating Patients. However, neither the N400 nor the P600 was modulated by the thematic role assigned to the violating direct object argument.

The findings are also only partially consistent with predictions of the eADM (Bornkessel & Schlesewsky, 2006). The eADM predicts that selection-restriction violations should incur processing costs during the *well-formedness* processing step, indexed by the P600, and that this processing step should be independent of thematic role reversibility—a prediction borne out by our results. However, the eADM predicts that the N400 is modulated by thematic role assignment, which is inconsistent with our results. Recall that the eADM proposes that anomalous inanimate Patients would incur costs during the initial noncombinatorial *plausibility* step, while anomalous inanimate Experiencers could only incur costs during the *compute prominence* step, as they could play a plausible alternative role about the verb, thereby no incurring costs in the *plausibility* step. Recall that in Experiment 1, the costs that could potentially be associated with the *compute prominence* step (i.e., difference in the N400 amplitude between nonviolating animate and inanimate direct objects assigned the Patient role) were significantly smaller than costs that could potentially be driven by the *plausibility* step (i.e., difference in the N400 amplitude evoked by violating vs. nonviolating inanimate direct objects). In order to be consistent with the results of Experiment 1, this would predict a larger N400 effect on selection-restriction violating inanimate arguments assigned the Patient role than on selection-restriction violating inanimate arguments assigned the Experiencer role. The N400 effect, however, was the same to both these violations.

The findings are most consistent with one version of the dynamic framework discussed by Kuperberg (2007), in which animacy acts directly through semantic memory, rather than by facilitating the assignment of

thematic roles. Such a framework predicts both the N400 and P600 effects observed to violations on both Patients and Experiencers: the N400 effect reflected the mismatch between the selection restrictions of the verb and the animacy features of the argument (a full semantic memory-based analysis ensued on both violations because the inanimate direct object argument matched verb-independent animacy hierarchy based expectations of linear ordering). The P600 effect was triggered primarily by the propositionally impossible arguments, particularly given the relatively high semantic constraint of the context and the plausibility judgment task performed by participants (Kuperberg, 2007). As predicted, neither effect was modulated by thematic or semantic reversibility (Kuperberg et al., 2006, 2007; Stroud & Phillips, 2009).

In sum, we find no support for the hypothesis that the animacy of a noun is used in the assignment of thematic roles during the processing of either plausible or selection-restriction violated direct object arguments in simple English sentences, as indicated by the lack of N400 modulation by the thematic role assigned to that argument. Taken together with the results of Experiment 1, our data rather suggest that any influence of animacy on the processing of direct object arguments is related to a direct mapping between the animacy hierarchy and the linear ordering of syntactic constituents. We return to this point in the General Discussion.

GENERAL DISCUSSION

We conducted two ERP experiments to determine how animacy influences the processing of selection-restriction violating and nonviolating direct object arguments in simple, active English sentences. In Experiment 1, we found a smaller N400 to inanimate than animate direct object NPs. We also found that selection-restriction violations on inanimate direct object arguments evoked a robust N400 effect, while selection-restriction violations on animate direct object arguments failed to impact the N400 amplitude. In Experiment 2, we found that selection-restriction violations on direct object arguments evoked a robust N400 effect, regardless of whether they were assigned the Patient or Experiencer thematic role. In both Experiments 1 and 2, selection-restriction violations evoked a robust P600 effect, which was not modulated by the animacy of the direct object (Experiment 1), or by the specific thematic role assigned (Experiment 2).

Below we discuss each of these findings in greater detail. First, we will provide interpretations of our findings in relation to what we understand about the N400 component. Next, we will relate our findings to recent frameworks that have discussed the relationships between the N400 and P600 components. We will then discuss how the use of an animacy hierarchy

during online processing can inform our understanding of previous linguistic and psycholinguistic research, and outline some open questions for future research. We conclude by discussing the more general implications of our findings.

Effects of animacy on the N400

There is general agreement that the amplitude of the N400 reflects lexico-semantic processing of an incoming word in relation to its preceding context and information stored within semantic memory. Here we examined N400 modulation to distinguish between three possible mechanisms by which animacy might influence semantic processing of direct object arguments in plausible sentences and sentences in which animacy-based selection restrictions of the verb were violated: (1) through links to syntactic ordering, (2) through inherent differences between animate and inanimate entities in their salience/lexico-semantic accessibility, and (3) through links to specific thematic roles.

The second mechanism—that animate entities are generally more accessible and/or salient than inanimate ones (e.g., Prat-Sala & Branigan, 2000)—was ruled out by Experiment 1. If animate and inanimate nouns differ generally in their accessibility and/or salience, regardless of syntactic context, this would predict that the N400 evoked by animate nouns should be smaller than that evoked by inanimate ones. No such significant main effect of animacy was observed for N400 amplitude; indeed, we showed that the N400 amplitude was *reduced* over centro-parietal sites to inanimate, relative to animate, direct object arguments in the nonviolated sentences. In addition, the accessibility/salience hypothesis offers no explanation for why an N400 effect to selection-restriction violating (vs. nonviolating) arguments should only be present for inanimate but not animate direct object arguments.

The third mechanism—that animacy serves as a proxy or indicator of specific thematic roles (e.g., Bornkessel & Schlesewsky, 2006; Traxler et al., 2002; Weckerly & Kutas, 1999)—was ruled out by Experiment 2. If animacy acts as a proxy for particular thematic roles, this would predict an attenuation of the N400 to arguments whose animacy matches the thematic role assigned to that argument. Specifically, it would predict that the N400 evoked by animate direct object arguments assigned the Experiencer role (strongly associated with animate entities) would be smaller than that evoked by animate direct object arguments assigned the Patient role (more closely associated with inanimate entities). We found no support for this hypothesis: the amplitude of the N400 was not modulated by thematic role assignment for either plausible or selection-restriction violating direct object arguments.

Taken together, the results seem most compatible with the first hypothesis—that animacy influences online argument processing through a linear mapping of the animacy hierarchy onto syntactic constituents, with more animate noun arguments being placed at earlier syntactic positions and less animate nouns placed at later positions (e.g., McDonald et al., 1993). The direct object argument in canonical English sentences occurs at a later sentential position, and thus would be expected to take a less animate noun: this can therefore account for the reduced N400 amplitude at centro-posterior midline sites in Experiment 1 to inanimate versus animate plausible direct object arguments.

More generally, our study adds to growing evidence that the amplitude of the N400 does not necessarily pattern with the implausibility of a word within a sentence. Despite the fact that animacy violated sentences such as "*At the homestead the farmer penalised the *labourer..*" in Experiment 1 were rated as highly implausible, no N400 effect was generated to these anomalies. This mirrors several previous findings that also demonstrate dissociations between the N400 and degree of plausibility (Baggio, Choma, van Lambalgen, & Hagoort, 2010; Geyer, Holcomb, Kuperberg, & Pearlmutter, 2006; Kolk et al., 2003; Kuperberg et al., 2003, Kuperberg et al., 2010).

Effects of animacy on the P600

The component that did pattern with plausibility in the present study was the P600. Consistent with previous findings by our group (Kuperberg et al., 2003, 2006) and others (Hoeks et al., 2004; Kim & Osterhout, 2005; Kolk et al., 2003; van Herten, Kolk, & Chwilla, 2005) reporting a P600 effect to selection-restriction violations on verbs, we found that selection-restriction violations on highly implausible direct object arguments evoked a significant P600 effect, relative to plausible direct objects.

Of note, the P600 observed in both studies had an onset at 700 ms, approximately 100 ms later than we have previously observed on verbs. We have observed a similar delay in previous studies in response to animacy selection-restriction violations occurring on postverbal NP arguments (Kuperberg et al., 2010; Paczynski, Kreher, Ditman, Holcomb, & Kuperberg, 2006). Taken together, these findings suggest that the timing of the semantic P600 onset may vary with word class. One reason for this may be that nouns can serve as modifiers of subsequent nouns, potentially leading to a plausible interpretation (e.g., *. . .penalised the meadow labourer. . .*), in a way that verbs cannot (e.g., *. . .eggs would eat break. . .*). Thus any continued analysis or reanalysis reflected by the P600 may not be triggered until the word class

of the subsequent word is determined and the semantic error becomes irrecoverable.[2]

Although there is some controversy about the precise neurocognitive processes indexed by the P600, there is general agreement that it reflects prolonged analysis or reanalysis necessary for coming up with a final representation of meaning. Several different factors have been hypothesised to trigger such prolonged neural processing reflected by the "semantic P600", none of which are likely to act in isolation (see review by Kuperberg, 2007). This study allowed us to examine the role of several of these factors: animacy, the specific thematic role assigned, semantic reversibility, and the plausibility of the final (syntactically determined) proposition.

In Experiment 1, we found that the P600 effect was not modulated by the animacy of the direct object: both animate and inanimate selection-restriction violating direct object arguments evoked P600 effects of similar size, time course and distribution. In Experiment 2, we found that the amplitude of the P600 did not differ between selection-restriction violating direct object arguments assigned the Patient role and those assigned the Experiencer role. Finally, we found that the P600 was not influenced by whether or not selection-restriction violating direct object arguments could plausibly play an alternative thematic role for the preceding verb (Experiments 1 and 2) or whether the arguments were fully reversible (Experiment 2). Taken together, these findings suggest that the primary trigger for the P600 effect in the present study was the highly implausible or impossible interpretation determined by full syntactically driven combinatorial analysis. However, as discussed further below, we suggest that additional factors played a role in triggering the P600 effect in these sentences.

Relationship between these findings and recent frameworks discussing the N400 and P600 effects

As outlined in the General Introduction, several frameworks have been proposed to explain the relationship between the N400 and P600 effects evoked by semantic violations of verb-argument structure. Here we discuss each of these proposals in relation to the present findings.

Kolk's Error Monitoring model proposes that the P600 reflects general monitoring and reanalysis processes which, in the case of semantic violations, are triggered when the full propositional interpretation is highly implausible (see van de Meerendonk et al., 2009). Thus the Error Monitoring model can account for the P600 effect to selection-restriction violations seen in both Experiments 1 and 2. However, it predicts that the P600 effect should be larger when there is more conflict with the output of the semantic

[2] In the current study, critical direct object arguments were followed by function words.

heuristic, that is, when the heuristic-based process arrives at a plausible interpretation, as would be the case for partially and/or fully thematically reversible sentences, such as *. . .plowed the *labourer. . ./. . .plowed by the labourer. . .* (Experiment 1) or *. . .the farmer interested the *meadow. . ./. . .the farmer was interested by the meadow. . .* (Experiment 2). In addition, this model fails to account for the pattern of N400 modulation seen in Experiment 2: a semantic heuristic attempting to come up with a plausible interpretation would predict a smaller N400 effect to selection-restriction violating (vs. nonviolating) reversible Experiencers than to selection-restriction violating (vs. nonviolating) irreversible Patients.

Kim and Osterhout's (2005) semantic attraction hypothesis suggests that the plausibility heuristic reflects a truly combinatorial semantic stream of processing that serves not only to attenuate the N400, but also to trigger the semantic P600 effect. The N400 is attenuated *and* a P600 is elicited when an implausible argument is semantically attracted to a specific verb and can therefore be assigned an alternative thematic role around that verb through semantic combination. Although the semantic attraction hypothesis explains the P600 effect observed in Experiment 1 to selection-restriction violating (vs. nonviolating) animate direct object arguments, which were partially reversible, it fails to account for the P600 effects observed to selection-restriction violating (vs. nonviolating) inanimate direct object Patient argument in Experiments 1 and 2, in which the anomalous noun could not plausibly occupy an alternate thematic role around the preceding verb. It also cannot account for the presence of an N400 effect prior to the P600 effect to selection-restriction violating inanimate Experiencers that could plausibly be reassigned the Stimulus thematic role. Hagoort's account of the semantic P600 effect (2009) encounters similar problems in explaining these patterns of results.

Bornkessel and Schlesewsky's (2006) eADM can account for why a P600 effect was observed to all selection-restriction violations in Experiments 1 and 2. Within this framework, the P600 effect observed to these violations was mediated by the *well-formedness* processing step; because impossible propositions are, by definition, not well-formed, they incur additional processing cost. Unlike the Error Monitoring model, the eADM does not necessarily predict that a semantic P600 effect is larger to reversible violations. Also, unlike the Error Monitoring model, the eADM allows for the possibility that an N400 effect may nonetheless be present even under conditions of full thematic role reversibility if additional processing is incurred during the *compute prominence* step. However, similarly to previously mentioned frameworks it cannot fully account for the pattern of N400 effects observed across the two experiments. In particular, while in Experiment 1 the cost of animacy-based mismatch in *compute prominence* was significantly smaller than that

evoked by difficulties during the *plausibility* step, in Experiment 2 the cost associated with both types of processing were the same. The eADM offers no a priori reason to expect that the cost of animacy mismatch during *compute prominence* should differ for animate and inanimate arguments within identical syntactic contexts. In addition, the model would predict a larger N400 to nonviolated animate Patients than nonviolated animate Experiencers in Experiment 2 because of costs incurred during the *compute prominence* step, yet no such modulation of the N400 was observed. Thus the eADM cannot account for the pattern of N400 effects observed in the current study.

We suggest that the pattern of current findings can be reconciled with one version of the dynamic framework proposed by Kuperberg (2007). In this framework, the N400 is modulated by activity within a semantic memory-based stream of processing in which incoming words are continually compared with semantic relationships within the context and relationships stored within long-term semantic memory (see also Kutas & Federmeier, 2000). The P600 is triggered in the presence of conflict between matches in the semantic memory-based analysis and an output of a syntactically driven combinatorial analysis that is evaluated as highly implausible or impossible with respect to our real-world knowledge. Conflict is most likely to be detected in the presence of a semantically constraining discourse context and when comprehenders are asked to pay attention to plausibility or acceptability.

We suggested that the semantic memory-based stream of processing simply detects *matches* between incoming and stored semantic relationships, rather than necessarily attempt to come up with a *plausible* representation through the assignment of thematic roles. This is consistent with our previous observations showing that the N400 was not modulated by degree of semantic reversibility: the N400 amplitude evoked by verbs in semantically reversible sentences like *Every morning at breakfast the eggs would *eat* was the same as that observed to verbs in irreversible sentences such as *In front of the queen of England, the trumpets would *curtsey*, even though these differed in their reversibility. Lexico-semantic co-occurrence in these two types of sentences, however, was matched (Kuperberg et al., 2006). Similarly, in the current study, the N400 was not modulated by either partial (Experiment 1) or full (Experiment 2) semantic reversibility.

Importantly, we see such semantic memory-based matching as occurring at multiple grains of representation: not only at the level of fine-grained semantic associations, but at the level of more coarse semantic features and categories, such as animacy. In our original 2003 study, we suggested that different types of semantic memory-based expectations might interact with one another, such that a violation of animacy-based expectations may have "switched off" further semantic analysis. In that study, we argued that, in the

sentence like "*. . .the eggs would* *eat. . .", the most likely animacy of the first argument was violated (*eggs* is inanimate instead of animate), and this blocked further semantic processing between verb and argument, leading to the absence of an N400 effect to these selection-restriction violations. Similarly, in the present study, we also suggest that the reader had course-grained expectation, this time for the direct object to be inanimate (rather than animate); when such expectations were violated and the argument also violated the animacy-based selection restrictions of the verb, further finer-grained semantic memory-based analysis between the argument, the verb and its preceding context was again aborted.

More specifically, we suggest that the semantic analyzer runs an initial feature check when it encounters a postverbal direct object, asking: "Does the animacy of the direct object match expectations based on its syntactic position? and (b) does the animacy of the direct object match expectations based the animacy-based selection restrictions of the verb?". If the answer to either of these questions is "yes", then the system proceeds with a fuller semantic memory-based analysis of the semantic features of the argument in relation to other semantic restrictions of the verb and the preceding context, leading to modulation of the N400. If the answer to both these questions is "no", then no further attempts are made to match the semantic features of the argument with its preceding context. Importantly, this account does not imply that argument violating animacy-based expectations are not processed at all; rather, processing within the N400 time window is more superficial than that when animacy expectations are met.

Note that in our original paper (Kuperberg et al., 2003), we speculated that animacy expectations might be based both on linear position and thematic role expectations, animate nouns at the beginning of an active sentence being more likely Agents than Patients. On the basis of the results of the current study, we suggest that such expectations of animacy were not mediated through thematic roles, but were primarily based on a direct mapping between linear order and the animacy hierarchy. Evidence for this comes from Experiment 2, where selection-restriction violating inanimate arguments, assigned the Experiencer role, evoked a normal N400 effect. These arguments failed to meet animacy expectations based on thematic role, but they did meet expectations based on the animacy hierarchy (inanimate argument after animate argument).

Kuperberg (2007) suggested that semantic memory-based processing operated in parallel with a syntactic-based combinatorial stream of processing that assigns thematic roles on the basis of syntactic constraints and evaluates the real-world plausibility of these syntactically assigned roles. When this combinatorial stream outputs propositions that are highly implausible/impossible, but the semantic memory-based analysis yields a match between

the input and stored semantic relationships, additional analysis or reanalysis is triggered, reflected by the P600. In the present study, the propositions output by the syntactic assignment of thematic roles were equally implausible, the semantic contexts of the sentences were all constraining, and in all cases, participants explicitly judged the plausibility of the sentences (see Kuperberg, 2007, for a discussion of possible mechanisms by which these factors may exert their effects). Kuperberg (2007) also considered the possibility that animacy, functioning as part of a "thematic" stream of processing, might, together with the output of the semantic memory-based analysis, conflict with the implausibility of the final proposition, enhancing the P600 effect. The results of this experiment do not support this hypothesis. Rather, based on the results of the current study, the second possibility proposed by Kuperberg (2007) is supported: that animacy exerts its effects more directly, as part of the semantic memory-based mechanism of analysis which functions to match semantic relationships in the input and stored relationships in semantic memory. As discussed further below, we suggest that this direct impact of animacy may occur through our representation of the animacy hierarchy within semantic memory.

The role of the animacy hierarchy during language processing

As reviewed in the Introduction, there is extensive evidence that the animacy hierarchy impacts the structure and development of language. Cross-linguistically, there is a strong preference for placing animate noun before inanimate ones (Aissen, 2003), with several languages encoding this constraint within syntax. Adult competency for using the animacy hierarchy is achieved by age 4, compared with use of thematic role information, for which adult competency is not achieved until age 12 (Demuth et al., 2005). The animacy hierarchy may also play a role during speech production: studies have reported that a tendency to order nouns on the basis of animacy is independent of thematic role assignment (McDonald et al., 1993; Tanaka et al., 2005), or the ordering of syntactic arguments (e.g., SOV vs. OSV, Feleki & Branigan, 1997).

Although it is important to recognise that neurocognitive processes engaged during production and comprehension do not necessarily translate on to one another (e.g., syntactic priming appears to more consistently aid in production than comprehension, see Branigan, Pickering, Liversedge, Stewart, & Urbach, 1995, for a review), we interpret our findings as suggesting that the animacy hierarchy may also act as a constraint during online language *comprehension*, and that, at least in processing the direct objects of English sentences, this constraint can operate independently of any association between animacy and specific thematic roles. As discussed below, we further suggest that the use of animacy hierarchy biases can also provide

alternative accounts for the results of previous comprehension studies in which animacy was assumed to aid thematic role assignment.

In ERP studies, there is evidence that inanimate (vs. animate) sentence initial arguments evoke an N400 effect (Nakano et al., 2010; Paczynski & Kuperberg, 2009; Weckerly & Kutas, 1999). These results have previously been interpreted as being due to a violation of the expectation that the initial argument is an Agent/Actor and therefore more likely to be animate (Bornkessel & Schlesewsky, 2006; Weckerly & Kutas, 1999). We agree with Nakano et al. (2010) who argue that readers (at least those with high reading spans) are sensitive to the frequency with which animate nouns serve as subjects. However, we propose that rather than this sensitivity being driven by the link between animacy and Agenthood, it is driven primarily by animacy hierarchy-based preferences of placing animate arguments early in a sentence and inanimate ones later. This expectation is violated when the sentence initial NP is inanimate, thus evoking an N400 effect on the normal sentences.

As previously discussed, the reduced or absent N400 effect sometimes seen to semantic verb-argument violations during comprehension has either been attributed to heuristic plausibility operations (Bornkessel & Schlesewsky, 2006; Kolk et al., 2003) or semantic attraction (Kim & Osterhout, 2005). However, in the majority of previous studies in which the N400 was attenuated, not only were the verb's selection restrictions violated, but so were the animacy hierarchy-based biases on linear order. For example, in Kuperberg et al. (2003, 2006); **For breakfast the eggs would eat*...), and Kim and Osterhout (2005); **The hearty meals were devouring*...), the inanimate noun violated an expectation that sentence initial nouns should be animate and no N400 effect was seen on the selection-restriction violated verb. In Hoeks et al. (2004); **The javelin has the athletes thrown*...), *javelin* (inanimate) and *athletes* (animate) violate expectations that animate entities should be encountered first and inanimate entities encountered second in Dutch. This is not, however, the case for all the stimuli used by Kolk et al. (2003) and van Herten et al. (2005). It is therefore important to note that the attenuation of the N400 by a mismatch of animacy-based expectations is most likely dependent on other factors including lexico-semantic association, and amount and type of context (for discussion see Kuperberg, 2007).

Conversely, in situations where a semantic P600 effect is observed but the N400 effect is *not* attenuated, animacy hierarchy-based expectations were not violated. For example, Paczynski et al. (2006) examined postverbal Agent arguments that violated the selection restrictions of their preceding verb (e.g., *In church the baptism was performed by the *bible*...). In this case, the inanimate argument appeared at a later sentential position, and hence did not violate animacy hierarchy-based biases on linear order. Similarly,

Kuperberg et al. (2010) found an N400 effect prior to a P600 effect for anomalous inanimate direct object arguments in sentences, similar to those used in Experiment 2 of the current study (e.g., *The journalist astonished the* **article*...). However, this does not always appear to be the case. A recent study in Polish (Szewczyk & Schriefers, 2011) did not find any effect of animacy on animacy-violating direct object arguments. There are two important differences between the current study and that of Szewczyk and Schriefers. First, Szewczyk and Schriefers used high Cloze words for nonviolating direct objects, whereas in the current study we specifically chose nonviolating direct object nouns to be low Cloze. Second, Szewczyk and Schriefers specifically chose animacy violating direct object nouns to be semantically *un*related to their preceding context, whereas we chose selection-restriction violating direct object nouns to be semantically related to the preceding context to a similar degree as the nonviolating direct object nouns. Thus, the different pattern of N400 modulation observed in the present experiment and in that by Szewczyk and Schriefers may be due to a greater impact of animacy on processing when other factors known to strongly impact N400 amplitude are held constant across experimental conditions.

Animacy hierarchy-based biases on linear ordering may also provide an alternative explanation for effects previously reported in several behavioural and eye-movement studies. As reviewed in the General Introduction, noncanonical syntactic structures, such as reduced relative clauses and object relative clauses, in which the initial verbal argument is assigned the Patient role, rather than an Agent role, incur increased processing costs (Clifton, 1993; Ferreira & Clifton, 1986; McRae, Ferretti, & Amyote, 1997; Rayner et al., 1983; Traxler et al., 2002; Trueswell et al., 1994). However, these groups also found that when the initial argument is inanimate (e.g., *The evidence examined by the witness*...), these processing penalties were reduced. The results have been taken as evidence that animacy information facilitates either the reassignment of thematic roles after an initial stage of parsing (Ferreira & Clifton, 1986; Frazier & Rayner, 1982), or an initial assignment of thematic roles during a single stage of parsing that takes all sources of information into account (MacDonald et al., 1994; Trueswell et al., 1994). Specifically, both these accounts suggest that processing penalties are reduced because inanimate nouns are more closely associated with the Patient role than are animate nouns. An alternative explanation for these findings is that sentence initial inanimate noun arguments violate animacy hierarchy-based expectation, thereby increasing the argument's salience. This increased salience of an initial inanimate argument may lead to its increased accessibility in working memory, facilitating processing of noncanonical syntactic structures (see Johnson and Gordon, 2009, for a similar interpretation when

the salience of the initial, Patient, argument was increased through an adjectival modifier in object relative clauses).

Another open question is whether use of animacy hierarchy information in online language processing is based on absolute or relative animacy. In the current experiment, the N400 to plausible direct object arguments was only modestly modulated by argument animacy, at least in comparison to N400 modulation by animacy of subject arguments in previous studies (Paczynski & Kuperberg, 2009; Weckerly & Kutas, 1999). If the impact of animacy hierarchy information is absolute, this would suggest that the "inanimate second" bias is less strong than the "animate first" bias. In other words, the expectation of an inanimate noun coming later in the sentences may be generally weaker than the expectation that an animate noun will come first. Conversely, if the use of the animacy hierarchy is relative, and dependent on the animacy of syntactic constituents earlier in the sentences, this would predict that, when the initial argument is inanimate, an "inanimate second" bias is as strong as the "animate first" bias. Future studies will need to explore how animacy of sentence initial verb arguments impacts the use of animacy hierarchy on subsequent arguments.

Finally, it is important to emphasise that our failure to find an effect of an association between animacy and Thematic Role in the present study using simple English sentences may not necessarily generalise to all types of structures and all languages. For example, in verb final languages such as German, comprehenders may rely more heavily on animacy information to make initial thematic role assignments on arguments encountered prior to the verb.

A multilayered and dynamic language processing system

In sum, the present study provides evidence that, at least in simple English sentences, animacy impacts the semantic processing of direct objects, as indexed by the N400 component. Animacy, however, did not serve as a proxy for thematic role assignment. Rather, we hypothesise that it may have impacted processing more directly via animacy hierarchy-based biases on the linear ordering of arguments within a sentence.

More generally, these findings add to growing evidence that the N400 is influenced by many different types of meaningful information, stored at various grains of representation within semantic memory. In addition to animacy-based relationships discussed in this study, previous studies have described the N400 as being modulated by associative relationships between individual words (Van Petten, 1993), categorical relationships between entities sharing common features (Ditman, Holcomb, & Kuperberg, 2008; Federmeier & Kutas, 1999), violations of the semantic category of verb arguments (i.e., objects vs. events, Baggio et al., 2010; Kuperberg et al., 2010), pragmatic expectations (Nieuwland & Kuperberg, 2008; van Berkum,

Koornneef, Otten, & Nieuwland, 2007), and situation-level information (Ditman, Holcomb, & Kuperberg, 2008; Kuperberg, Paczynski, & Ditman, 2011). Taken together, these findings support the idea that multiple processing streams, each dealing with different levels of linguistic representation, interact dynamically during online language comprehension, influencing lexico-semantic processing of each upcoming word.

Our findings also corroborate previous research, which has shown that, at least when the semantic context is constraining, highly implausible propositions, derived from a full combinatorial syntactic-based analysis, incur an additional and sustained processing cost beyond the N400 time window, regardless of their semantic–thematic reversibility. The challenge for future studies will be to more fully define the nature of the various processing streams and to explore the nature of the interactivity between them.

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