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Multiple Influences of Semantic Memory on Sentence Processing: Distinct Effects of Semantic Relatedness on Violations of Real-World Event/State Knowledge and Animacy Selection Restrictions

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Abstract

We aimed to determine whether semantic relatedness between an incoming word and its preceding context can override expectations based on two types of stored knowledge: real-world knowledge about the specific events and states conveyed by a verb, and the verb's broader selection restrictions on the animacy of its argument. We recorded event-related potentials on post-verbal Agent arguments as participants read and made plausibility judgments about passive English sentences. The N400 evoked by incoming animate Agent arguments that violated expectations based on real-world event/state knowledge, was strongly attenuated when they were semantically related to the context. In contrast, semantic relatedness did not modulate the N400 evoked by inanimate Agent arguments that violated the preceding verb's animacy selection restrictions. These findings suggest that, under these task and experimental conditions, semantic relatedness can facilitate processing of post-verbal animate arguments that violate specific expectations based on real-world event/state knowledge, but only when the semantic features of these arguments match the coarser-grained animacy restrictions of the verb. Animacy selection restriction violations also evoked a P600 effect, which was not modulated by semantic relatedness, suggesting that it was triggered by propositional impossibility. Together, these data indicate that the brain distinguishes between real-world event/state knowledge and animacy-based selection restrictions during online processing.

Keywords

animacy; ERP; event; language; latent semantic analysis; N400; P600; real-world knowledge; selection restriction; semantics; semantic association; semantic attraction; semantic illusion; semantic relatedness; sentence; prediction; syntax

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Introduction

In order to rapidly and proficiently understand sentences, comprehenders use different types of stored semantic information. These include: 1) knowledge about the *semantic relatedness* between groups of concepts (e.g. *music, bass* and *guitarist* are semantically related to each other by sharing a common general schema), 2) more structured *real-world knowledge* about the likely Agents, Themes and Instruments around particular events and states, conveyed by the verb (e.g. knowing that a *bass* is more likely to be *strummed* by a *guitarist* than by a *drummer*), and 3) animacy-based selection restrictions of a verb on its argument(s) (e.g. the verb *strum* requires that that its Agent argument be animate, like a *guitarist*, rather than inanimate, like *drum*). Each of these different types of stored semantic knowledge can influence online sentence and discourse comprehension, as indicated by behavioral studies as well as electrophysiological studies that focus on the N400—an event-related potential (ERP) thought to reflect lexico-semantic processing of a word in relation to its preceding context (Kutas & Federmeier, 2011). What is currently less clear is how they interact with one another as meaning is built incrementally during word-by-word comprehension. In this ERP study, we explore these interactions by determining whether, when and how semantic relatedness influences the processing of post-verbal Agent arguments that violate either our real-world knowledge about events and states, or the animacy selection restrictions of their preceding verbs.

We first review behavioral and ERP evidence that each of these three types of stored semantic knowledge can individually influence online sentence and discourse processing. We then consider previous studies that speak to the question of how they interact during sentence and discourse processing, before describing how the present study was designed to address this question.

Semantic relatedness networks

From the earliest descriptions of the ‘semantic priming effect’ (Meyer 1971; Becker 1979), it has been known that lexico-semantic processing of one word can be facilitated by a preceding semantically related word. Electrophysiologically, semantic priming manifests as an attenuation of the N400 (Bentin, 1985; Rugg, 1984). N400 attenuation is seen to target words that are related to prime words along a variety of semantic dimensions, including category membership (e.g. *tulip-ROSE*) (Grose-Fifer & Deacon, 2004), semantic features (e.g. *wig-MOP*) (Deacon, Grose-Fifer, Yang, Stanick, Hewitt, & Dynowska, 2004), through an indirectly related mediator (e.g. *lion*-[tiger]-*STRIPES*) (Chwilla, Kolk, & Mulder, 2000; Kreher, Holcomb, & Kuperberg, 2006; Silva-Pereyra, Harmony, Villanueva, Fernandez, Rodriguez, Galan, et al., 1999), and through common schema membership, e.g. scalpel-SURGEON (Deacon et al., 2004) or director-bribe-DISMISSAL (Chwilla & Kolk. 2005).

Semantic priming is usually explained by appealing to the activation of stored networks that encode various types of semantic relationships, including associative (Collins & Loftus, 1975), featural (e.g. Smith, Shoben & Rips, 1974) and categorical (e.g. Collins & Quillian, 1969) relationships. Stored networks may also encode more general script or schema-based knowledge (Schank & Abelson, 1977), e.g. knowing that the concepts of *waiter*, *chair*, *wine* and *menu* are all linked to a *restaurant* theme. In this manuscript, we collectively refer to these types of networks as *semantic relatedness networks*. When a prime word interacts with and activates a semantic relatedness network, processing of a related target is facilitated through various different mechanisms, including passive spreading activation (Neely, 1977), active prediction (Becker, 1980), and semantic matching (Neely et al, 1989), see Neely (1991) for a review.

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A single prime word can also facilitate processing of a related target in lists of words (e.g. Foss, 1982; Foss & Ross, 1983), Jabberworky sentences (Van Petten, 1993), and incongruous sentences (Camblin, Gordon, and Swaab, 2007; Coulson, Federmeier & Kutas, 2005). However, these types of pure *lexical* priming effects (i.e. facilitation driven by a single prime word, in isolation of its broader context) tend to be fairly small (e.g. Coulson, Federmeier & Kutas, 2005), short-lived (Foss & Ross, 1983), and, in some cases, absent altogether (e.g. Morris, 1994, Experiment 2; Traxler et al., 2000). In contrast, when a prime is congruous and focused within its surrounding sentence or discourse context, facilitation of a subsequent related target is more robust (Duffy, Henderson & Morris, 1989; Foss & Ross, 1983; Carroll & Slowiaczek, 1986; Morris & Folk, 1998). This suggests that, during sentence and discourse processing, relatedness networks are primarily activated not by individual words, but rather by a higher-level representation of the preceding context. We will henceforth refer to this higher-level representation as the ‘contextual representation’. This type of top-down interaction between the contextual representation and relatedness networks is central to several memory models of text comprehension, which argue that such ‘resonance’ initiates a passive spread of activation across relatedness networks, leading to facilitated processing of semantically related upcoming targets (e.g., Myers & O’Brien, 1998; Gerrig & McKoon, 1998).

Real-World Event/State Knowledge

We are faster to detect (Marslen-Wilson, Brown & Tyler, 1988) and read (Rayner, Warren, Juhasz, and Liversedge, 2004; Warren and McConnell, 2007; Camblin, Gordon and Swaab, 2007) words that are plausible and congruous than words that are incongruous and implausible with our real-world knowledge. This type of facilitation also manifests as an attenuation of the N400 (Kuperberg, Sitnikova, Caplan, & Holcomb, 2003; Hagoort, Hald, Bastiaansen, Marcel, & Petersson, 2004; Ferretti, Kutas and McRae, 2007; Filik & Leuthold, 2008; Bicknell, Elman, Hare, McRae, & Kutas, 2010; van de Meerendonk, Kolk, Vissers, and Chwilla, 2010).

The activation of relatedness networks, particularly those encoding schema-based relationships, goes some way in explaining these effects of real-world knowledge on sentence and discourse comprehension. Importantly, however, they cannot fully explain all such effects: facilitation is also seen to real-world congruous (versus incongruous) targets, even when content words are matched across conditions. For example, behavioral facilitation is seen to *crook* (versus *cop*) in sentences describing likely events, e.g. “She arrested the *crook/cop*”, but not unlikely events, “She was arrested by the *crook/cop*” (Ferretti et al., 2001). Similarly, we have shown that the N400 is attenuated to critical words in pragmatically licensed congruous affirmative versus incongruous negated sentences, which had exactly the same content words (Nieuwland & Kuperberg, 2008). We also reported an attenuation of the N400 evoked by critical words in causally related versus unrelated short discourse scenarios, where semantic relatedness of the target to the preceding context was matched across conditions (Kuperberg, Paczynski, & Ditman, 2010).

These observations suggest that, in addition to storing general schema-based relationships between words and concepts within memory, we also encode more structured event/state representations that capture more specific information about the Agents, Themes and Instruments that are most likely to participate in familiar and repeatable events or states described by the verb (see McRae, Ferretti, and Amyote, 1997, for discussion). In this manuscript, we will refer to this type of more structured real-world knowledge as *real-world event/state knowledge.* The activation of such event/state knowledge by the contextual representation can, at least under some circumstances, facilitate the processing of congruous upcoming words, leading to an attenuation of the N400 (Ferretti, Kutas, & McRae, 2007). There is also evidence that such facilitation can be driven by active predictions, whereby the contextual representation, held within working memory, is updated and some commitment is made to the expected item or set of semantic features, in advance of the actual input (e.g. DeLong, Urbach & Kutas, 2005; Van Berkum et al., 2005; Lau, Holcomb and Kuperberg, under review).

Selection Restrictions on Verb Arguments

A third way in which stored semantic information can influence lexico-semantic processing of incoming words is through a verb's selection restrictions — the coarser semantic constraints that a verb places on its argument(s). By far the most common type of selection restriction explored in psycholinguistics is that of animacy. For example, in the sentence, "The farmer penalized the *meadow…", *meadow* is anomalous because *penalized* selects for an animate rather than an inanimate direct object. This knowledge about a verb's selection restrictions can be dissociated from semantic relatedness between individual words. For example, in "The pillow *slept," the word *pillow* violates the restrictions of *sleep* for an animate Agent, despite the two words being highly semantically related.

By definition, animacy selection restriction form part of real-world event/state knowledge. However, the two types of knowledge are at least partially dissociable: it is possible to violate real-world event/state knowledge without violating the broader animacy selection restrictions of a verb. For example, in the sentence, "In front of the crowd, the guitarist *slept", the verb, *slept* violates our real-world knowledge about what a guitarist is most likely to do in this situation, but its animacy selection restrictions are not violated. This distinction between real-world event/state knowledge and selection restrictions was reflected in early versions of generative grammar in which selection restrictions were conceptualized as being lexically encoded, independent from real-world knowledge (Chomsky, 1965; Katz, 1963; but see Jackendoff, 2002 and Elman, 2009).

Consistent with there being at least some distinction between real-world event/state knowledge and animacy-based selection restrictions, behavioral studies report differences in processing sentences that violate these two types of knowledge (Marslen-Wilson, Brown, & Tyler, 1988; Warren & McConnell, 2007). These differences are not only quantitative, but also qualitative. For example, in an eye-tracking study, Warren and McConnell (2007) reported longer regression time durations on words that violated real-world knowledge such as "The man used a blow-dryer to dry (*versus* a strainer to drain) ?the thin spaghetti yesterday evening.". In contrast, they reported longer first fixation durations to selection restriction violations, such as "The man used a photo to blackmail (*versus* a strainer to drain) *the thin spaghetti yesterday evening." The authors suggested that the verbs' selection restrictions might have a privileged status during processing, either because they are accessed earlier than more general real-world knowledge, or because their coarse-grained animacy constraints are prioritized over finer-grained semantic representations, as proposed by Sanford and Garrod (1998). They also noted that the selection restriction violations, but not the real-world knowledge violations, were associated with additional downstream effects past the critical noun-phrase region (see also Rayner et al., 2004).

In ERP studies, the effects of violating selection restrictions can once again manifest on the N400. Animacy selection restrictions violations evoke a larger N400 than non-violated words, regardless of whether such violations occur on the verb itself, e.g. "The honey was *murdered." (Rösler, Pütz, Friederici & Hahne, 1993; see also Friederici & Frisch, 2000; Hahne & Friederici, 2002; Bornkessel-Schlesewsky, Kretzschmar et al. 2010) or on one of its arguments, e.g. "The businessman knew whether the secretary called the *article at home." (Garnsey, Tanenhaus et al. 1989; see also Ainsworth-Darnell, Shulman et al. 1998; Friederici & Frisch, 2000; Nieuwland & Van Berkum 2005; Li, Shu et al. 2006; Paczynski & Kuperberg, 2011).

This N400 effect evoked by selection restriction violations has sometimes been interpreted as reflecting the *implausibility* of the proposition that is generated once full semantic-syntactic integration (including thematic role assignment) of the target word into its preceding context has occurred (Friederici & Frisch, 2000; Garnsey, Tanenhaus, & Chapman, 1989). However, N400 amplitude does not necessarily pattern with ratings of propositional plausibility (e.g. Kuperberg et al., 2003; Kuperberg, Choi et al., 2010; van de Meerendonk et al., 2010; Paczynski & Kuperberg, 2011). Instead, we have suggested that the N400 effect to selection restriction violations reflects a mismatch between the verb's selection restrictions and its argument's coarse semantic properties, e.g. animacy (Kuperberg et al., 2010; Paczynski & Kuperberg, 2011). On this view, the contextual representation interacts with the verb's lexical representation, facilitating processing of arguments that match its selection restrictions. This may once again occur through active predictive mechanisms or semantic matching. When an argument mismatches the verb's lexical representation, no facilitation occurs and the N400 is not attenuated.

Semantic memory-based processing: semantic 'expectations' are based on multiple types of stored semantic information

In sum, during online comprehension, a contextual representation can interact with different types of stored semantic information to influence the semantic processing of an incoming word. We will broadly refer to this three-way interaction between the contextual representation, multiple types of stored information at different grains of representation, and the semantic features of an incoming word as 'semantic memory-based processing' (Kuperberg, 2007). For convenience, we distinguish between two 'phases' of semantic memory-based processing. The first phase constitutes the interaction between the contextual representation and stored information to generate expectations for a particular lexical item, or a group of lexical items sharing common semantic features. These expectations can be generated through a passive spread of activation, as well as through more active predictions. We will refer to this phase as *expectancy generation* and we refer to any representations that are activated as *expected representations*. The second phase of semantic memory-based processing constitutes the matching of expected representations to the semantic features of the incoming target word. We will refer to this phase as *semantic matching*. Of note, the processes of expectancy generation and semantic matching may not always be temporally distinct. For example, expectancy generation can be further constrained by interactions with bottom-up perceptual information of the incoming word during semantic matching (e.g. Marslen-Wilson, 1987; Van Petten et al., 1999)[1]. In this paper, however, we are less concerned with exactly when an expected representation is generated. Rather, we ask how expectations, based on these multiple types of stored information, interact to impact semantic matching at the point of encountering an incoming word.

During normal language processing, an incoming word will often be consistent with expectations based on *all* these different types of stored semantic knowledge. They will act synergistically to facilitate the processing of incoming words. This is because, during

[1]A note about terminology. Some groups have referred to the three-way interaction between the contextual representation, stored information in semantic memory, and the semantic features of the critical word as *semantic integration*. This has been distinguished from *prediction*, which implies an interaction between the contextual representation and stored information *before* any bottom-up input from the critical word (e.g. Van Petten & Luka, 2012). Other researchers, however, have used the term *semantic integration* in a different sense: to refer specifically to a process by which a critical word is *combined* with its contextual representation to form a new higher-order representation of meaning. This has been distinguished from *lexical access*, which does *not* assume a combination between the contextual representation and an incoming word (e.g. Lau, Phillips, & Poeppel, 2008). *Lexical access* to a particular word is said to be facilitated when its representation matches an expected representation, leading to an attenuation of the N400. We conceive of both phases of semantic memory-based processing as being non-combinatorial. However, we prefer not to use the term *lexical access* as it implies a fixed stage of lexical processing, with combinatorial analysis ensuing only after it is over. Rather, we think of semantic memory-based processing and full combinatorial semantic-syntactic analysis as proceeding, at least partially, in parallel.

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everyday communication, these different types of semantic information tend to co-occur. As noted above, selection restrictions of verbs are a component of event/state real-world knowledge. And words used to describe likely events will tend to be (or become) stored within semantic relatedness networks. Thus, upon encountering the context, "The pianist played his music while the bass was strummed by the…," the contextual representation may interact with more general schema-based relatedness networks about what words are related to a band. It may also interact with the stored lexical representation of *strum* that encodes its restrictions for an animate Agent. Finally, it may interact with more fine-grained structured event real-world knowledge about who, in particular, is likely to carry out the action of *strumming* a *bass*. If the incoming word is *guitarist*, it conforms to all these different types of expectations (a *guitarist* is semantically related, through schema-membership, to the band schema, it is an animate Agent, and it is a likely strummer of a bass). Thus, the N400 to *guitarist* will be attenuated.

However, as discussed above, these different types of stored information are not all simply reducible to one another. An incoming argument can mismatch expectations based on specific event/state knowledge, but it may not necessarily violate the selection restrictions of a given verb. Similarly, an incoming word can be semantically related to its contextual representation through shared schema membership, association or by sharing common semantic features, but it can still violate more specific real-world event/state knowledge, or a verb's coarser selection restrictions. This raises the question of which types of stored information take precedence in influencing the semantic processing of this incoming word?

There is some behavioral evidence that semantic relatedness between a target and its preceding context can lead to facilitated processing of that target, even when it violates more specific real-world knowledge event/state expectations set up by the context (Duffy, Henderson and Morris, 1989; Morris, 1994, Experiment 1). Similarly, a partial attenuation of the N400 has been reported to incoming words that violate real-world expectations when they share semantic features (Federmeier & Kutas, 1999), categorical relationships (Ditman & Kuperberg, 2007) or schema-based relationships (Otten & Van Berkum, 2007; Metusalem et al., In press) with the expected word or the preceding context. Indeed, sometimes this N400 attenuation can even be complete. For example, Kolk et al. (2003) and van Herten et al. (2005) saw no N400 effect at all to words that violated real-world knowledge, but that shared close semantic and thematic relationships with their context, see also Sanford et al. (2011)[2].

It is less clear whether semantic relatedness can impact the processing of selection restriction violations. Results from an initial set of ERP studies examining selection restriction violated verbs, seemed to suggest that it did. For example, Kuperberg et al. (2003) showed that selection restriction violated verbs that were semantically related to their preceding context failed to produce any N400 effect (relative to non-violated verbs), e.g. "Every morning at breakfast the boys/*eggs would eat…" (see also Hoeks et al., 2004, and Kim & Osterhout, 2005, Experiment 1). However, later studies, showed that the N400 was attenuated not only to *related*, but also to *unrelated* selection restriction violated verbs, e.g. "Every morning at breakfast the eggs would *plant…" (e.g. Kuperberg et al., 2007, Hoeks et al., 2004), and direct comparisons between the amplitude of the N400 produced by related and unrelated selection restriction violated verbs have yielded mixed findings[3]. It is also

[2]This complete attenuation of the N400 to semantic violations has sometimes been termed a temporary 'semantic illusion'. This follows the use of the term to describe behavioral phenomena such as 'The Moses Illusion' (Erickson, 1981; Barton and Sanford, 1993). However, this account assumes that the attenuated N400 reflects the integration of the critical word to form an intermediate *plausible* representation of meaning, through semantic heuristic (van Herten et al., 2005) or combinatorial (Kim & Osterhout, 2005) mechanisms. Also, note that the use of the term 'temporary semantic illusion' was first used to describe the attenuation of the N400 effect produced by certain types of selection restriction violations (Hoeks et al., 2004, Nieuwland and Van Berkum, 2005).

unclear whether semantic relatedness can facilitate the processing of target nouns that violate the selection restrictions of their preceding verbs, with some studies showing facilitation (e.g. Nieuwland & Van Berkum, 2005), and others showing no facilitation (e.g. Traxler et al., 2000 Experiments 1 and 3; Paczynski & Kuperberg, 2011).

The P600 and propositional implausibility

In sum, we take the amplitude of the N400 of an incoming word to reflect the degree to which its semantic features match expectations that are based on the interaction between its preceding contextual representation and stored semantic knowledge. Above, we have emphasized the idea that such expectations can be based on multiple types of stored semantic knowledge, and that some of these may take precedence over others. However, all these types of stored semantic knowledge can have a *direct* influence on semantically processing these words — hence our grouping them together as a *'semantic memory-based analysis'* (Kuperberg, 2007).

We distinguish this type of semantic memory-based analysis from a set of processes that act to fully semantically and syntactically integrate the meaning of an incoming word into its context through combinatorial mechanisms. By semantic-syntactic integration, we refer to a full assignment of thematic roles around a verb (determining who does what to whom), based on both semantic and syntactic constraints. We will refer to this type of analysis broadly as constituting a full 'combinatorial analysis' (Kuperberg, 2007). At least when a participant is deeply engaged in comprehension, a combinatorial analysis will output a full propositional, message-level representation of meaning. This representation constitutes the 'contextual representation' that then interacts with stored material to produce expectations for the subsequent word (expectation generation). Thus, we conceive of the interplay between semantic memory-based and combinatorial processing as being highly dynamic, with the two mechanisms running in parallel during word-by-word comprehension (see Discussion for further elaboration).

It has been known for some time that disrupting a combinatorial analysis by violating syntactic constraints can trigger a posteriorly-distributed late positivity effect, known as the P600. This waveform is thought to reflect a continued analysis or reanalysis in a further attempt to integrate the violated word into its context (Osterhout & Holcomb, 1992; Hagoort, Brown & Groothusen, 1993). More recently, however, it has become clear that, under some circumstances, a P600 effect is evoked by certain semantic violations (Kuperberg et al. 2003, Kolk et al., 2003; Hoeks et al., 2004, see Kuperberg, 2007 for a review), where it has been descriptively termed a 'semantic P600'. There has been much debate about what exactly triggers a semantic P600, and several frameworks have been proposed to explain this phenomenon. For the purposes of this study, we divide them into two broad categories.

The first category of accounts subdivides combinatorial analyses into semantic and syntactic components, and proposes that the semantic P600 is triggered by a conflict between the

[3]Kuperberg et al. (2007) showed no significant difference in the N400 time window for this contrast. Hoeks et al. (2004) do not report statistics for this contrast; while examination of their waveforms does suggest a smaller N400 to related than unrelated animacy selection restriction violated verbs, this pattern can be explained by the larger P600 effect produced by the related than the unrelated violations. The N400 and P600 both have a posterior scalp distribution and have opposite polarities. Thus, when the P600 starts within the N400 time window, it can mask the appearance of an N400 on the surface of the scalp. This means that it is often unclear whether the reduced N400 on the scalp surface is an artifact of this component overlap, or whether it reflects a true absence of neural modulation within this time window (see Kuperberg et al. 2007 for a discussion). Kim & Osterhout (2005, Experiment 2) report a larger N400 to unrelated than related selection restriction violating verbs, but the unrelated selection restriction violations did not produce a P600 effect at all. In fact, a replication study using Kim and Osterhout's (2005) materials did reveal a P600 effect to unrelated selection restriction violations, and here the difference in the N400 amplitude between the related and unrelated selection restriction violations was smaller and did not reach significance (Stroud, 2008).

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outputs of competing semantic and syntactic interpretational mechanisms. Kim and Osterhout (2005) proposed that a strong ‘semantic attraction’ between a verb and its argument(s), e.g. “The hearty meals were *devouring…” would lead the parser to arrive at an incorrect semantically-derived plausible interpretation, e.g. “The hearty meals were devoured…,” which conflicts with the full syntactic interpretation of the phrase. More recently, Hagoort, Baggio and Willems (2009) proposed a more general version of this account in which they suggest that strong semantic cues, encompassing strong semantic relatedness between words, are sufficient to bias the initial interpretation towards one which conflicts with a full syntactic interpretation, triggering a P600.

The second set of accounts places more emphasis on overall *implausibility* or incoherence of the proposition produced by a full combinatorial analysis, as a critical factor that triggers the semantic P600 effect (Kuperberg, 2007; van de Meerendonk et al., 2009; Bornkessel-Schlesewsky & Schlesewsky, 2008). According to all three accounts, severely implausible-and-impossible propositions can evoke a P600, even when the critical word is not semantically attracted to its preceding arguments (Kuperberg et al., 2006, Stroud & Philips, 2012), and even when it is completely unrelated to the preceding context (Kuperberg et al., 2007; Hoeks et al. 2004; Stroud, 2008), e.g. “…every morning at breakfast the eggs would *plant…”[4]. What appears to be critical to whether or not a P600 is generated is whether this implausibility is actually detected (Sanford et al., 2011). This sensitivity of the P600 to the detection of implausibility also explains why task plays an important role in modulating this effect. For example, in a recent study we demonstrated that, during passive reading, a P600 effect was observed to animacy selection restriction violations, but this effect was smaller than when participants were asked to make explicit plausibility judgments (Wang et al., 2010), see Kuperberg (2007) for a more in-depth discussion of how propositional implausibility, contextual constraint and task may interact to modulate the P600.

It is important to note that there are important differences between these three frameworks, particularly in the type of intermediate representations that are computed, and whether conflict between these intermediate representations and the implausible overall proposition contributes to triggering a P600 (see Discussion for further elaboration). However, the present study was not designed to distinguish between them.

The present study

In this study, we examined the processing of passive English sentences (see Table 1) as participants carried out an active plausibility judgment task. We measured ERPs on Agentive arguments that appeared after the verb. We explored the influence of relatedness networks on processing by manipulating the semantic relatedness between the target word and its preceding contextual representation, as operationalized by Semantic Similarity Values (SSVs), generated by Latent Semantic Analysis (LSA). LSA uses a large training corpus to create representations of words and relationships between them within a multidimensional semantic space (see Methods). In addition to using the co-occurrence of words within the training document itself, LSA generates inferences about semantic relationships. It therefore captures knowledge about multiple different semantic relationships between words and concepts, including schema-based relationships. Importantly for our purposes, LSA is insensitive to word order, syntax or overall propositional meaning. For example, “the chef cooked the pasta” is plausible, while “the pasta cooked the *chef” is highly implausible. However, both sentence contexts are equally related to the general schema of *kitchen*—a judgment that is accurately modeled by LSA.

[4]Kim & Osterhout (2005, Experiment 2) reported no P600 effect to verbs that were unrelated to the context (e.g. “The dusty tabletops were *devouring…”). However, consistent with the results of Kuperberg et al. (2007) and Hoeks et al. (2004), a replication using the same stimuli did show a robust P600 effect to unrelated selection restriction violations (Stroud, 2008).

We studied the effects of one type of real-world event/state knowledge—our knowledge about *who* is likely to carry out or participate in a particular event or state described by the verb. For example, given an introductory context like “At the estate sale, prices are announced by the…”, this type of real-world event knowledge tells us that it is more likely that an *auctioneer* would make such an announcement than a *bidder*, despite both Agents being highly semantically related, through schema membership, to the preceding context, and both Agents being equally able to *announce* something. Thus, violating this type of real-world event/state knowledge produces propositions that are implausible, but still possible.

Finally, we examined one type of selection restriction: a verb’s broad restrictions for animate Agent arguments (the same restriction that we examined in several of our previous studies, e.g. Kuperberg et al., 2003, 2006, 2007). As noted above, these selection restrictions describe the relationship between the verb and its Agent argument, independent of the preceding context. Thus, when they are violated, they yield implausible-and-impossible propositions (rather than implausible-but-possible propositions).

We fully crossed semantic relatedness with type of violation (real-world event/state knowledge versus verb-based animacy selection restrictions), giving rise to five conditions: 1) plausible control, 2) semantically related violations of real-world event/state knowledge, 3) semantically unrelated violations of real-world event/state knowledge, 4) semantically related violations of animacy selection restrictions, and 5) semantically unrelated violations of animacy selection restrictions; see Table 1 for example sentences in each of the five conditions.

Based on previous studies (e.g. Federmeier & Kutas, 1999; Ditman et al., 2007, Otten & Van Berkum, 2007), we predicted at least some attenuation of the N400 to related (versus unrelated) animate Agent NPs real-world violations. As noted above, previous studies examining the effects of semantic relatedness on selection restriction violations have yielded contradictory results. If, under these task and experimental conditions, selection restriction violations are processed like real-world violations, this would predict a similar attenuation of the N400 by close semantic relatedness. If, however, the two types of knowledge are functionally distinct, with coarse-grained animacy restrictions prioritized above finer-grained semantic information (Sanford and Garrod, 1998; Warren & McConnell, 2007), selection restriction violations might be relatively impervious to the influence of semantic relatedness networks. This would predict no modulation by semantic relatedness.

We also examined activity in the P600 time window. The two broad categories of frameworks highlighted above make different predictions about when this effect should be elicited in this study. According to the frameworks proposed by Kim & Osterhout (2005) and Hagoort et al. (2009), a semantic P600 effect should only be observed when semantic cues are stronger than syntactic cues. This would be the case for semantically related (or attracted) violating nouns (both related real-world violations and related selection restriction violations), but not semantically unrelated violating nouns. On the other hand, the proposals of Kuperberg (2007), Kolk and colleagues (van den Meerendonk, 2009), and Bornkessel-Schlesewsky and Schlesewsky (2010) predict a P600 effect to both types of selection restriction violations, as in both cases the overall propositional meaning is implausible-and-impossible, and, given their requirement to make explicit judgments, participants were likely to detect this incoherence.

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Methods

Construction and ratings of materials

Five types of sentences were constructed (see Table 1 for explanation and examples of each type of sentence; see http://www.nmr.mgh.harvard.edu/kuperberglab/materials.htm. for the full list of stimuli). We selected 120 verbs that required animate Agents (e.g. *strummed*). For each verb, we created a fairly constraining introductory context (e.g. "The pianist played his music while the bass was strummed by…"). Plausible Control sentences were created by adding an animate noun—the critical word—that was semantically related to the content words in the preceding context to serve as a plausible Agent of the verb (e.g. *guitarist*). Related Real-World Knowledge Violation sentences were created in a similar fashion, with the exception that the semantically related animate noun was an unlikely Agent within the context (e.g. *drummer*). No animate critical nouns were repeated and critical nouns in the Control and Real-World Knowledge Violation sentences did not differ significantly on either length ($t(239)=0.13$, $p = 0.89$) or frequency ($t(239)=0.76$, $p=0.45$), see Table 2. Related Animacy Selection Restriction Violations were created by selecting an inanimate noun that was related to the preceding sentential context (e.g. *drum*). No inanimate critical nouns were repeated. Compared with animate critical nouns in the Control and Related Real-World Knowledge Violation sentences, inanimate critical nouns were, on average, one letter shorter ($ts > 4.82$, $ps < 0.00001$), and more frequent ($ts > 2.74$, $ps < 0.01$), see Table 2.

To create the Unrelated Real-World Knowledge Violation and Unrelated Animacy Selection Restriction Violation sentences, scenarios that were not semantically related to each other were paired up. Unrelated Real-World Knowledge Violation sentences were created by substituting animate critical nouns from the Control sentences (50% of scenarios) or Related Real-World Knowledge Violation sentences (50% of scenarios) of the paired scenario (e.g. "The pianist played his music while the bass was strummed by the gravedigger…"). Unrelated Animacy Selection Restriction Violations were created by substituting the critical noun from the Related Animacy Selection Restriction Violation sentences of the paired scenario (e.g. "The pianist played his music while the bass was strummed by the coffin…").

To confirm that the semantic relatedness between the critical nouns and their preceding content words in the related sentence types was indeed closer than in the unrelated sentence types, we determined their Semantic Similarity Values (SSVs) using LSA (Landauer and Dumais 1997; Landauer et al. 1998; available on the internet at http://lsa.colorado.edu). LSA has been shown to reliably model and predict human performance in various linguistics tasks, including word categorization (Laham, 1997; see also Landauer, McNamara, Dennis, & Kintsch, 2007 for additional discussion of the relationships between LSA driven analysis and human performance). As noted in the Introduction, LSA uses a large training corpus to develop a multidimensional representation in which each word is represented by a single vector. The Semantic Similarity Value (SSV) between two words (or texts) is computed by finding the cosine of the two vectors representing the words (or texts)[5].

We calculated SSV for each sentence by averaging the SSVs, based on term-by-term pair-wise comparisons, between the critical noun and the content words that preceded it using the tasaALL space corresponding to a 1st year college student reading level, using all 300 factors. Mean SSV values and standard deviations for the five sentence types are shown in

[5]One criticism of LSA is that it is insensitive lexical ambiguity (e.g. *bass* referring to a type of musical instrument and to a type of fish are treated as instances of the same token). However, the impact of this confound is relatively minimal in a large analysis, such as in the current experiment where several hundred stimuli were generated and SSVs were examined between the critical word and *multiple* words in the preceding context. For example, within the original corpus on which the LSA algorithm was trained, *bass* is used to refer to a type of fish. Nonetheless, LSA yields a high SSV when *guitarist* is compared to *music* and *bass*, and this is value is higher than that the SSV for *guitarist*, *music* and *cod* (*cod* being the nearest neighbor of *bass).*

Table 2. A 5-way ANOVA revealed a significant effect of Sentence Type, $F(4,476) = 51.51$, $p < 0.0001$. Planned pair-wise comparisons were carried out between the Control sentences and each of the Violation sentences. There was no difference in semantic relatedness between the Control sentences and either the Related Real-World Knowledge Violation sentences or the Related Animacy Selection Restriction Violation sentences. As expected, SSV values in the Control sentences were significantly higher than in the Unrelated Real-World Knowledge Violation sentences ($t(119)=9.759$, $p < 0.0001$) and the Unrelated Animacy Selection Restriction Violation sentences ($t(119)=9.877$, $p<0.0001$). A 2 (Relatedness) × 2 (Violation Type) ANOVA revealed a main effect of Relatedness ($F(1,119)=124.789$, $p < 0.00001$), owing to the Unrelated sentences types having significantly lower SSVs than the Related sentence types. There was no main effect of Violation Type and no Relatedness by Violation Type interaction.

The experimental sentences were then assigned to ten lists such that each scenario appeared twice within each list in two out of the five conditions. An equal number of each possible combination of condition pairs appeared within each list and, across all lists, each scenario appeared in each of the five conditions the same number of times.

To each list, 144 plausible filler sentence were then added so that participants would have an equal likelihood of encountering a plausible or implausible sentence. These filler sentences had the same construction as the experimental sentences, but used verbs that did not impose animacy selection restrictions on the critical nouns. In 96 of these fillers, the critical noun was inanimate (e.g. "After the injury his leg was supported by the pillow to reduce swelling.") and in 48 fillers, the critical noun was animate (e.g. "At the circus the kids were entertained by the clown who was extremely funny.").

Fillers and experimental sentences were then pesudorandomized in each list. Because each scenario appeared twice in each list, in two different conditions, constraints were imposed during randomization. First, no two sentence types of the same scenario occurred within forty sentences of each other. This was done to minimize potential repetition priming effects. It also reduced the potential for participants being able to remember the plausibility of the first presentation of the scenario and use it to predict the plausibility of the second presentation. Second, for a given scenario, the Control sentence was never presented before the Related Violation sentence. This was done in order to prevent the prior presentation of a congruous critical word from interfering with the processing of a semantically related violated critical word the second time a scenario was presented.

To summarize, in each list, there were 240 experimental sentences (48 sentences in each of the five sentence types) and 144 filler sentences. In total, each list consisted of 192 plausible sentences (96 with animate and 96 with inanimate critical nouns) and 192 implausible sentences (96 with animate and 96 with inanimate critical nouns).

Because, at the point of the critical word, passive sentences are ambiguous as to whether the *by*-phrase is Agentive, as intended for our critical manipulation, or Locative (e.g. "… the bass was strummed by the drummer/drum…" can potentially be interpreted as "… the bass was strummed next to the drummer/drum…"), we conducted a rating study. All sentences (experimental and fillers) were presented up to the point of the critical noun to 20 Tufts student volunteers who did not participate in the ERP study. Three periods after the critical nouns were used to indicate that the sentences could continue after this point. Each of the ten lists was presented to two participants. 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 described something that would be very unlikely to occur in the real world and 7 indicating that the sentence described something that would be very likely to occur in

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the real world. Several examples were given but participants were told to go with their first instincts and that there were no right or wrong answers.

As can been seen in Table 2, results of our plausibility rating study clearly indicate that the critical nouns in our stimuli were interpreted as Agentive, rather than Locative. An overall ANOVA indicated a significant main effect of Sentence Type on both subjects ($F(4,76)=655.71$, $p < 0.0001$) and items ($F(4,476)=830.36$, $p < 0.0001$) analyses. Planned pair-wise comparisons indicated that, at the point of the critical noun, each of the Violation sentences was rated as significantly less plausible than the Control sentences (subject analyses, $ts > 28.66$, $ps < 0.0001$; items analyses, $ts > 36.27$, $ps < 0.0001$). A 2x2 ANOVA crossing Relatedness and Violation Type revealed main effects of Relatedness ($F1(1,19)=25.43$, $p < 0.0001$, $F2(1,119)=16.38$, $p < 0.0001$) and Violation Type ($F1(1,19)=65.57$, $p < 0.0001$, $F2(1,119)=101.61$, $p < 0.0001$). The effects were due to the Unrelated Violation sentences being rated as slightly more implausible than the Related Violation sentences, and Animacy Selection Restriction Violation sentences being rated as slightly more implausible than Real-World Knowledge Violation sentences. Additionally, the Relatedness by Violation interaction was significant ($F1(1,19)=7.01$, $p < 0.05$, $F2(1,119)=4.24$, $p < 0.05$). Follow-up pair-wise comparisons indicated a significant difference in plausibility between the Related and Unrelated Animacy Selection Restriction Violation sentences in both the subjects analysis ($t(19)=7.34$, $p < 0.0001$) and the items analysis ($t(119)=9.56$, $p < 0.0001$), while the difference in plausibility between Related and Unrelated Real-World Knowledge Violation sentences was smaller, reaching significance on the subjects analysis ($t(19)=2.44$, $p < 0.05$), but only approaching significance on the items analysis ($t(119)=1.83$, $p=0.07$).

Event-related potentials

ERP recording—Twenty-nine tin electrodes were held in place on the scalp by an elastic cap (Electro-Cap International, Inc., Eaton, OH), see Figure 1 for montage. Electrodes were placed below the left eye and at the outer canthus of the right eye to monitor vertical and horizontal eye movements, and also over the left mastoid (reference) and right mastoid (recorded actively to monitor for differential mastoid activity). All EEG electrode impedances were maintained below 5 kΩ (impedance for eye electrodes was less than 10 kΩ).

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 to 40 Hz and was continuously sampled at 200 Hz by an analogue-to-digital converter. The stimuli and participants' behavioral responses were simultaneously monitored by a digitizing computer.

ERP Procedure—Twenty participants (12 female; mean age 19.75 (2.75)) were recruited by advertisement and were paid to participate. All were right-handed native speakers of English, who had not learned any other language before the age of five, and who had normal or corrected-to-normal vision.

Each participant was given 15 practice trials at the start of the experiment and was then assigned to one of the ten experimental lists (i.e. each list was viewed by two different participants). Participants sat in a comfortable chair in a dimly lit room, separate from the experimenter and computers. Sentences were presented word-by-word on a computer monitor located 47 inches in front of participants. Text was centered and displayed in white on a black background. Text subtended approximately 1° visual angle vertically and 1–3° visual angle horizontally. Each trial (one sentence) began with the presentation of a fixation point at the center of the screen for 450ms, followed by a 100ms blank screen, followed by

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the first word of the sentence. Each word appeared on the screen for 450ms with an interstimulus interval (ISI) of 100ms separating words. The final word of each sentence appeared with a period. A 750ms blank-screen interval followed the final word in each sentence, followed by a "?". This cue remained on the screen until the participant made his/her response at which point the next trial started. Participants' task was to decide whether or not each sentence made sense by pressing one of two buttons on a response box with their left or right thumb (counterbalanced across participants). They were told that sentences may not make sense in different ways and that if a sentence seemed at all odd or unlikely, they should indicate that it did not make sense. They were instructed to wait until the "?" cue before responding. This delayed response was designed to reduce any contamination of the ERP waveform by response sensitive components such as the P300 (Donchin & Coles, 1988).

ERP Analysis—ERPs were averaged offline from trials that were free of both ocular and muscular artifacts, and were time-locked to the onset of the words of interest. The averaged ERPs were quantified by calculating the mean amplitude, relative to 100ms prestimulus baseline, in selected time windows that were each analyzed with four repeated-measures analyses of variance (ANOVAs), one for each electrode column (see Figure 1 for our columnar approach to analysis). Each ANOVA included Sentence Type (Control, Related Real-World Knowledge Violation, Unrelated Real-World Knowledge Violation, Related Animacy Selection Restriction Violation, and Unrelated Animacy Selection Restriction Violation) and Anterior-Posterior (AP) Distribution as factors. ANOVAs at the three lateral electrode columns also included Hemisphere (left, right) as a factor.

Effects of Sentence Type in the omnibus ANOVAs were followed up in two ways. First, we carried out pair-wise ANOVAs comparing the ERPs evoked by each type of Violation with the ERPs to non-violated critical nouns in the Control sentences. Second, we carried out 2 × 2 ANOVAs to determine the effects and interactions between Violation Type and Relatedness on the ERPs in the four Violation conditions. The Geisser-Greenhouse correction (Greenhouse & Geisser, 1959) was applied when evaluating effects with more then one degree of freedom to protect against Type 1 errors resulting from violations of sphericity. In these cases we report original degrees of freedom and the corrected probability levels.

Linearly interpolated voltage maps showing the scalp distribution of differences in ERPs elicited by critical nouns were produced using EEGLAB v4.512 for MatLab software.

Results

Participant Responses

Overall, participants' judgments matched our prior categorizations 90% of the time (see Table 3 for the judgments of each type of sentence). An ANOVA revealed significant differences across the five sentence types in how well participants' judgments matched our prior categorizations ($F(4,76) = 15.33$, $p < 0.001$). Post-hoc t-tests indicated that, in comparison with the other violation-containing sentence types, Related Real-World Knowledge Violation sentences were least likely to be judged as implausible (all $ts > 3.06$, $ps < 0.01$), and the Unrelated Animacy Selection Restriction Violation sentences were most likely to be judged as implausible (all $ts > 3.36$, $ps < 0.01$). There were no differences in judgments of the Unrelated Real-World Knowledge Violation and Related Animacy Selection Restriction Violation sentences.

ERP data—Approximately 5% of the trials were rejected for artifact (Control: 5.0% (3.1); Related Real-World Knowledge Violations: 4.4% (2.9); Unrelated Real-World Knowledge

Violations: 5.8% (2.6); Related Animacy Selection Restriction Violations: 5.9% (3.0); Unrelated Animacy Selection Restriction Violations: 5.5% (2.9)). An overall ANOVA indicated there was no significant effect of sentence type on rejection rates, $F(4,76) < 1$, $p > 0.87$. ERP analyses only included trials in which participants' judgments matched our prior categorizations of the five sentence types.

ERPs on critical nouns—Voltage maps and grand-average ERPs elicited by the critical nouns at selected electrode sites are presented in Figure 2 (Control versus Real-World Knowledge Violations) and Figure 3 (Control versus Animacy Selection Restriction Violations).

Early Time Windows—Within the first 100ms post stimulus onset there were no significant main effects or interactions involving Sentence Type at any electrode column (all ps > 0.1).

Visual inspection of the waveforms indicated a modulation of ERPs prior to the N400 time window (see Figure 2). We therefore carried out additional analyses within the 150–250ms time window, which captured this early effect. Omnibus ANOVAs that included all five sentence types revealed main effects of Sentence Type, but no further interactions involving Sentence Type, at all electrode columns (see Table 4).

Follow-up pair-wise ANOVAs, comparing each Violation sentence type with the Control sentences, revealed a smaller early positivity to critical nouns in the Unrelated Real-World Knowledge Violation sentences than the Control sentences at all electrode columns (Table 5). This was qualified by an interaction with AP Distribution at the midline and medial columns, reflecting an anterior distribution of the effect. Critical words in the Unrelated Animacy Selection Restriction Violation sentences likewise evoked a small attenuation of this early positivity, though the effect was only significant at the midline electrode column. No other pair-wise contrasts were significant at any electrode column.

Additional 2 (Violation Type) × 2 (Relatedness) ANOVAs revealed a significant main effect of Relatedness as well as significant Violation Type by Relatedness interaction at all electrode columns (Table 6). This interaction was driven by the smaller positivity/larger negativity to the Unrelated than the Related Real-World Knowledge Violations, with no effect of Relatedness on the Animacy Selection Restriction Violations.

The N400 (300–500ms)—Omnibus ANOVAs including all five sentence types revealed main effects of Sentence Type at all electrode columns as well as Sentence Type by AP Distribution interactions at the midline and peripheral columns (see Table 4), reflecting larger N400 effects at posterior than anterior scalp locations (see Figures 2 and 3). There were no differences in the hemisphere distribution of N400 modulation by critical nouns across the five sentence types, as indicated by the lack of Sentence Type by Hemisphere or Sentence Type by Hemisphere by AP Distribution interactions.

Pair-wise ANOVAs contrasting the N400 to critical nouns in Control sentences and Unrelated Real-World Knowledge Violations (Table 5B), Related Animacy Selection Restriction Violations (Table 5C), and Unrelated Animacy Selection Restriction Violations (Table 5D) all revealed significant main effects of Sentence Type at all electrode columns, and Sentence Type by AP Distribution interactions at some electrode columns, indicating significant N400 effects to these violations, particularly over cento-parietal sites. However, the comparison between critical nouns in the Control sentences and those in the Related Real-World Knowledge Violation sentences did not show robust N400 modulation, as reflected by the absence of a main effect of Sentence Type at any electrode column, with

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only the midline column showing a significant Sentence Type by AP Distribution interaction (Table 5A).

2 (Violation Type) × 2 (Relatedness) ANOVAs revealed significant main effects of both Violation Type and Relatedness at most electrode columns and significant Violation Type by Relatedness interactions at all electrode columns (Table 6). No interactions involving Hemisphere and/or AP Distribution reached significance. The Violation Type by Relatedness interactions arose because of a significantly smaller N400 to the Related than the Unrelated Real World Violations (Fs > 13.34, ps < 0.01), but no difference in the N400 evoked by the Related and Unrelated Animacy Selection Restriction Violations (Fs < 1, ps > 0.84).

***The P600* (700–900ms)—**Omnibus ANOVAs showed highly significant main effects of Sentence Type at all electrode columns and significant Sentence Type by AP Distribution interactions at the midline, medial and lateral electrode columns (see Table 4).

Pair-wise ANOVAs comparing critical nouns in Control sentences and those in the Related and Unrelated Real-World Knowledge Violation sentences showed no main effects of Sentence Type or Sentence Type by AP Distribution interactions at any electrode columns (see Table 5). On the other hand, ANOVAs comparing the Control sentences with the Related and Unrelated Animacy Selection Restriction Violation sentences revealed a clear posteriorly-distributed P600 effect, as reflected by main effects of Sentence Type at all columns and Sentence Type by AP Distribution interactions at several electrode columns (see Table 5).

2 (Violation Type) × 2 (Relatedness) ANOVAs confirmed highly significant main effects of Violation Type at all electrode columns (Table 6), as well as interactions between Violation Type and AP Distribution at all columns (Fs > 5.11, ps < 0.05) except the peripheral column ($F(4,76)=2.16$, $p=0.24$). This was due to a larger posteriorly-distributed P600 to both types of Animacy Selection Restriction Violations than to both types of Real-World Knowledge Violations. There were, however, no significant main effects of Relatedness and no interactions involving Violation Type and Relatedness (Table 6).

ERPs on sentence-final words—Grand-average ERPs elicited by sentence-final words at select midline electrode sites are shown in Figure 4. A negativity starting at approximately 300ms and persisting until 500ms is apparent on sentence-final words following all four types of Violation sentences compared to Control sentences, i.e. an N400 effect. Omnibus ANOVAs within this epoch comparing all five sentence types confirmed highly significant main effects of Sentence Type (all Fs > 6.92, ps < 0.001) and Sentence Type by AP Distribution interactions (all Fs > 3.88, ps < 0.01) at all electrode columns. Follow-up simple effects ANOVAs confirmed more negative N400s on sentence-final words in all four Violation sentences than in Control sentences, with significant main effects of Sentence Type (all Fs > 6.01, ps < 0.05) and significant Sentence Type by AP Distribution interactions at all electrode columns (all Fs > 6.63, ps < 0.05). 2 × 2 ANOVAs examining the effects of Violation Type and Relatedness on N400 amplitude revealed no significant main effects or interactions between these two variables at any electrode column (all Fs < 1, all ps > 0.4).

Discussion

We used ERPs to investigate the online use of three types semantic information: 1) semantic relatedness (including relatedness through shared schema membership) between content words, 2) knowledge about who is likely to take part in familiar real-world events or states,

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and 3) a verb's selection restrictions for animate Agentive arguments. We examined how and when these types of information interact in passive English sentences by contrasting plausible post-verbal Agent arguments with arguments that either violated real-world event/state knowledge expectations or the animacy selection restrictions of their preceding verbs. Consistent with our pre-rating plausibility studies, we found that sentences which violated real-world event/state knowledge as well as sentences which violated animacy selection restrictions were generally classified as unacceptable. This indicates that the critical nouns were indeed interpreted as implausible Agents, rather than plausible Locatives. Both types of violations evoked robust N400 effects, relative to non-violated arguments. However, the two types of violations differed with regards to how they were modulated by semantic relatedness. While the N400 effect on the real-world knowledge violations was almost completely attenuated when the critical noun was semantically related to the context, semantic relatedness failed to modulate the N400 evoked by selection restriction violations. Additionally, we found that selection restriction violations, but not real-world knowledge violations, evoked a robust P600 effect, regardless of semantic relatedness. On the sentence-final word, all four types of violations produced an N400 effect, which was not modulated by either violation type or by semantic relatedness.

Below we will discuss our findings in greater detail before considering their general implications and some open questions.

The N400

Effects of semantic relatedness on violations of real-world event/state knowledge—Our finding that the semantically unrelated violations of real-world knowledge evoked a significant N400 effect (relative to non-violated nouns) is consistent with previous work from our group (Kuperberg et al., 2003; Kuperberg et al., 2006, Kuperberg et al., 2007) as well as others (Camblin et al., 2007; Federmeier & Kutas, 1999; Hagoort et al., 2004). As noted in the Introduction, the N400 effect evoked by semantic violations has sometimes been interpreted as reflecting the *implausibility* of the proposition formed by full semantic-syntactic integration of a critical word into its context. Although this type of explanation can account for the N400 effect evoked by unrelated real-world knowledge violations, it does not easily account for the near-complete attenuation of the N400 effect evoked by *related* real-world knowledge violations. Related real-world knowledge violations were rated as significantly more implausible than the control sentences (a difference of 3.9 on a seven-point scale), while the N400 amplitude difference between these two conditions was almost non-existent. On the other hand, the difference in plausibility between the related and unrelated real-world knowledge violations was very small (0.2 on a seven-point scale), while the difference in N400 amplitude was substantial and significant. Indeed, because we only used trials that matched our prior classifications of sentence types in the ERP analysis, any differences in plausibility between the control and related real-world knowledge violation sentence types were likely exaggerated.

Rather than being driven by sentence-level plausibility that was assessed once the critical Agent NP had been fully semantically-syntactically integrated with its preceding context, we take the N400 to reflect the results of a semantic memory-based analysis (Kuperberg, 2007; Kutas & Federmeier, 2011) that matched its semantic features with expected representations that were generated by the interaction between the context and semantic information stored within semantic memory.

As noted in the Introduction, an attenuation of the N400 to incoming words that violate real-world expectations when they are semantically related to either an expected critical word or the contextual representation, has been reported before. Federmeier & Kutas (1999) proposed that the reduced N400 in their study reflected the activation of feature-based semantic networks, while Ditman et al. (2007) discussed the role of categorical semantic relationships. In many of our related real-world knowledge violation sentences, however, the Agent shared few semantic features, and was not categorically related, to either the expected critical word or the contextual representation. For example, in "The wreckage of the sunken ship was salvaged by the victims…," *victims* shares few semantic features with the expected critical word, *divers*, and the two words do not share an obvious superordinate category. To explain the attenuation of the N400, we suggest that the context activated *schema-based* relatedness networks, which encode general script-level relationships between words and concepts (although not necessarily finer-grained relationships about who is likely to carry out specific actions, in a given situation), perhaps through top-down passive resonance mechanisms (Myers & O'Brien, 1998; Gerrig & McKoon, 1998). According to this idea, the contextual representation of the stem, "The pianist played his music while the bass was strummed by the…," interacted with general schema-based relatedness networks, activating words related to a band scenario. The contextual representation also interacted with the stored lexical representation of *strum*, which specifies that the subsequent Agent should be animate. Finally, it interacted with more fine-grained real-world knowledge encoding information about who, in particular, would be likely to carry out the action of *strumming* a *bass*. In the normal, plausible sentences, the critical word, *guitarist*, matched expectations based on all three types of information, and the N400 was attenuated. In the unrelated real-world violated sentences, a critical word such as *gravedigger* matched the verb's selection restrictions, but it mismatched both schema-based as well as event/state real-world expectations, and the N400 was *not* attenuated. In the related real-world violated sentences, however, the critical word, *drummer*, matched expectations based on general schema-based relatedness networks. We suggest that this match is what drove the attenuation of the N400 (relative to the unrelated real-world violations). Similar interpretations have been offered by Otten & Van Berkum (2007) and Metusalem et al. (In press) to explain the attenuation of the N400 to words that were related to the schema established by the preceding context, even when these words violated more specific real-world event/state knowledge.

The effects of schema-based activation appeared to be evident quite early: the waveform evoked by the unrelated real-world violations started to diverge (becoming less positive/ more negative) from that evoked by critical words in the control and the related real-world violation sentences at around 150ms. This early effect appeared too early to be part of the N400 itself. It also had a more anterior distribution than the subsequent N400 effect, and, as discussed below, it did not pattern with N400 modulation to the animacy violations[6]. Speculatively, it may have reflected an early detection of a mismatch between schema-related representations that were activated by the context, and the semantic features of the target word. This would be consistent with emerging evidence that certain types of semantic expectations can influence processing of a target word quite quickly (e.g. Dikker et al., 2009; Federmeier, Mai, and Kutas, 2005), or even before it appears (see DeLong, Urbach, & Kutas, 2005; Federmeier, 2007; Van Berkum, Brown, Zwitserlood, Kooijman, & Hagoort, 2005), although, in the present study, we do not think that such expectations were necessarily generated through active prediction mechanisms.

In the ERP studies described above (Federmeier & Kutas, 1999; Ditman et al., 2007; Otten & Van Berkum, 2007; Metusalem et al., in press), the N400 evoked by related real-world violations was partial--smaller than the N400 evoked by unrelated real-world violations, but still larger than the N400 evoked by highly expected words. In this study, however,

[6]This early effect is unlikely to reflect artifact that artificially drove the N400 effect to the unrelated real-world knowledge violations. First, there were no significant effects in the first 100ms post-stimulus onset. Second, its distribution was distinct from that of the N400. Indeed, when we rebaselined to a post-stimulus baseline of 100–250ms, the N400 effect to the unrelated real-world violations was still present, but this rebaselining artificially induced a prolonged anterior positivity effect to both types of real-world violations.

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attenuation of the N400 to the related real-world violations was near-complete: at almost all sites its amplitude was the same as the N400 evoked by the plausible non-violated, expected Agents. This complete attenuation of the N400 to real-world violations has been reported before by Kolk et al., (2003), van Herten et al. (2005) and Sanford et al., (2011). It has sometimes conceptualized as reflecting a ‘semantic illusion’. This interpretation assumes that the critical word is integrated with the context, by heuristically or semantic combinatorial mechanisms to form an intermediate plausible (or partially plausible, van Herten et al., 2005) representation of meaning (e.g. van Herten et al., 2005, van den Meerendonk, see also Kim & Osterhout, 2005, and Bornekssel-Schlesewsky & Schlesewsky, 2008). In this study, however, the thematic roles were not easily reversible. For example, in the related real-world violated sentence, “The wreckage of the sunken ship was salvaged by the victims…,” *victims* are unlikely to either *salvage* or to *be salvaged*. (There was also no evidence of a behavioral illusion; by the end of the sentences, participants had registered the implausibility of the related real-world knowledge violations, as indicated by both their judgments, and a clear N400 effect on the sentence-final words, which did not differ significantly from that evoked on sentence-final words in any of the three other violation conditions.)

We suggest that the reason why there was no further attenuation of the N400 to non-violated critical words, was because more specific expectations based on specific real-world event/state knowledge were relatively weak. Thus, these types of specific real-world event/state expectations did not confer any additional faciliatory advantage over and above more general expectations generated by activating schema-based relatedness networks. This, of course, raises the question of why, in some studies, expectations based on schema-based relatedness networks are sufficient to attenuate the N400 completely (the present study; Sanford et al., 2011; Kolk et al., 2003), whereas in other studies, more specific real-world event/state knowledge confers an additional faciliatory advantage on processing incoming words, leading to further reduction in the N400 (Otten & Van Berkum, 2007; Metusalem et al., In press; see also Federmeier & Kutas, 1999; Ditman & Kuperberg, 2007). We suggest that this may hinge on the degree to which the parser uses real-world event/state knowledge to actively predict an upcoming word. Such active predictive mechanisms contrast with the type of resonance and passive spreading activation that may have driven the facilitation in the present study. We will return to this idea below under Open Questions.

Effects of semantic relatedness on violations of animacy selection restrictions—Inanimate nouns that violated the selection restrictions of their preceding verb evoked a robust N400 effect, consistent with numerous previous studies (Ainsworth-Darnell, Shulman, & Boland, 1998; Bornkessel-Schlesewsky et al., 2010; Friederici, Pfeifer, & Hahne, 1993; Garnsey et al., 1989; Li, Shu, Liu, & Li, 2006; Nieuwland & Van Berkum, 2005; Rösler et al., 1993). Once again, the larger N400 to selection restriction violations than non-violated words is unlikely to reflect the implausibility of the proposition formed by integrating the critical word with its preceding context (see Kuperberg, Choi et al., 2010 and Paczynski & Kuperberg, 2011, for discussion). Rather, we have suggested that it more directly reflects the mismatch between the verb’s selection restrictions and the argument’s semantic features. Thus, the contextual representation of the stem, “The pianist played his music while the bass was strummed by the…,” might interact with the stored lexical representation of *strum* that specifies that the Agent should be animate. Upon encountering an inanimate Agent, this expectation is not met, and there is no attenuation of the N400.

Unlike violations of real-world knowledge, however, the N400 effect to the selection restriction violations was not modulated by semantic relatedness between the critical noun and the preceding content words. This is consistent with a previous behavioral study by Traxler et al. (2000) who also reported no facilitation on selection restriction violating direct

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objects that were associated (versus non-associated) with a single preceding Agent NP. It is also consistent with our finding of a large N400 effect on inanimate direct object nouns that violated (versus did not violate) the selection restrictions of their preceding verbs, even when these nouns were semantically related to the preceding context, e.g. "At the homestead the farmer *penalized/plowed the meadow…" (Paczynski & Kuperberg, 2011). It is, however, inconsistent with findings by Nieuwland and Van Berkum (2005) who did report a reduced N400 on selection restriction violating inanimate nouns that were related to the general discourse context. However, in that study, the target noun was repeated several times in the context, which is likely to have attenuated the N400 through repetition priming (see Traxler et al., 2000, Experiment 2 for evidence that repetition priming can facilitate processing of nouns that violate the selection restrictions of their preceding verb).

The failure of semantic relatedness to impact N400 amplitude to the animacy selection restriction violations in the current study cannot be attributed to our relatedness manipulation being ineffective. As noted in the Methods, the difference in SSVs between the related and unrelated selection restriction violations was highly significant and the same as the difference in SSVs between the related and unrelated real-world knowledge violations which, as discussed above, did lead to marked N400 modulation. We offer two potential explanations for why semantic relatedness had different effects on the real-world event/state knowledge violations and the animacy selection restriction violations.

The first is that, during expectancy generation, the verb's broad animacy selection restrictions were inherently more constraining or predictive than real-world event/state knowledge. On this account, the verb's animacy selection restrictions were used to predictively constrain the activation of potential candidates only to animate items. For example, the contextual representation of "The pianist played his music while the bass…," might resonate with relatedness networks, spreading activity to several potential schema-related items, including *guitarist*, *guitar*, *drummer*, *drum* etc. However, the interaction between the contextual representation and the lexical selection restrictions of *strum* would constrain the potential set of candidates to include only *guitarist* and *drummer*. Thus, when the related selection restriction violation, *drum*, was encountered, it did not match expectations and the N400 was not attenuated. This predictive, constraining effect of the verb's broad animacy selection restrictions contrasts with the effects of stored real-world event/state knowledge, which, as we have argued above, was less strongly constraining and less predictive in this study.

The second possibility is that animacy was prioritized over real-world event/state knowledge during semantic matching. According to this idea, once the inanimate argument was encountered, the parser registered its broad mismatch with the animacy restrictions of the preceding verb, and, as a result, failed to pursue any further matching between the finer-grained semantic features of the target and any schema related representations activated by the context.

It is difficult to distinguish between these two accounts, but one observation is consistent with the first: there was no influence of semantic relatedness on the selection restriction violations within the 150–250ms time window. This differs from what we observed on the real-world violations where, as noted above, there was an early effect of semantic relatedness. It implies that inanimate items may have been excluded from the expectancy set quite early. Thus, as soon as an inanimate critical word was encountered, the parser registered only the mismatch of animacy and did not distinguish between words that were related and unrelated with the context.

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It is important to note that our interpretation does not contradict previous proposals arguing that verbs can encode additional event-specific information which can be used to facilitate verb argument processing, as shown by McRae, Ferretti, and Amyote (1997), McRae, Ferretti, and Hatherell (2001), Matsuki et al. (2011), and others. As described above, it is likely that both coarse-grained as well as fine-grained semantic information associated with a verb can be utilized by the parser to facilitate online processing of normal, non-violated sentences. What our data rather suggest is that, at least under these task and experimental conditions, the verb's broad animacy selection restrictions on its argument was privileged, either because it acted as a stronger predictive cue than finer-grained event-specific information, or because it was prioritized over finer-grained feature matching at the point of encountering the argument. This type of functional distinction between violations of animacy selection restrictions, and violations of real-world event/state knowledge, during online sentence processing, is consistent with previous eye-tracking results by Warren and McConnell (2007).

The P600: Effects of severe implausibility

As outlined in the Introduction, there has been debate about exactly what triggers a P600 to semantic violations. One set of accounts interprets the two components as being functionally related to one another. For example, Kim and Osterhout's (2005)'s 'semantic attraction' hypothesis suggests that, when a selection restriction violating verb argument can plausibly occupy an alterative thematic role around the verb, the N400 is attenuated and instead a P600 is triggered. More recently, Hagoort, Baggio and Willems (2009) proposed a more general version of this theory, suggesting that linguistic errors trigger an N400 when syntactic cues are strong but semantic cues are weak, while a P600 is triggered if semantic cues are strong but syntactic cues are weak. Within this model, violations involving 'semantic attraction' between a verb and its argument(s) constitute a subset of circumstance under which a P600 is evoked.

The present findings are inconsistent with these semantic attraction/semantic relatedness types of accounts. We found that selection restriction violations evoked a P600 effect, regardless of whether the critical noun was semantically related or unrelated to the preceding verb or other words in the context. This is in line with several previous studies that have also reported clear P600 effects to unrelated selection restriction violations on verbs that were not attracted to their preceding argument(s), i.e. irreversible (Kuperberg et al., 2006, Stroud & Philips, 2012), or that were completely unrelated to the preceding contextual representation (Hoeks et al., 2004; Kuperberg et al. 2007; Kuperberg et al. 2010, Stroud, 2008; but see Kim & Osterhout, 2005, Experiment 2). Indeed, in a post-hoc analysis (data not reported here), we found that the P600 evoked by related selection restriction violating critical nouns was not modulated by whether or not the critical noun could act as a plausible Theme for the preceding verb (see also Kuperberg et al., 2006, and Paczynski & Kuperberg, 2011).

Our results are more consistent with frameworks which emphasize that the P600 effect is triggered by the detection of overall *implausibility/impossibility* of the proposition that is derived by combinatorially syntactically and semantically integrating the critical word with its preceding context (Kuperberg, 2007; van de Meerendonk, 2009; Bornkessel-Schlesewsky & Schlesewsky, 2008). According to all these accounts, a P600 effect, reflecting continued analysis or reanalysis, was evoked by the selection restriction violations because they resulted in implausible-and-impossible propositions that were detected by the parser. Consistent with this idea, eye-movement studies have shown that violations resulting in implausible-and-impossible, but not implausible-but-possible, propositions are associated with downstream effects (Rayner, Warren, Juhasz, and Liversedge, 2004; Warren and McConnell, 2007). These three frameworks do differ in some important ways, and we

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discuss some of these differences under 'Open Questions' below. However, this study was not designed to distinguish between them.

Of note, in the present study, the sentences with inanimate critical nouns resulted in implausible-and-impossible interpretations by virtue of their being assigned an Agent role. In fact, the constructions were structurally ambiguous and, in theory, participants could have assigned these nouns a Locative role, resulting in either plausible or implausible-but-possible interpretations (e.g. interpreting "… the bass was strummed by the drum…" to mean that the bass was strummed next to the drum). Our norming studies, however, suggest that this did not happen: participants consistently rated the sentences with inanimate critical nouns as being more implausible than those with animate critical nouns, indicating that they did assign these nouns an Agent role. It also seems unlikely that the P600 was triggered directly by the structural ambiguity of our materials, as this would have predicted a P600 effect to *both* animate and inanimate nouns, which can each serve as equally plausible Locations. Rather, we suggest that the P600 to the inanimate NPs in this study was triggered by propositional implausibility/impossibility resulting from their initial thematic role assignment to the Agent role, and that it reflected an attempt to recover discourse meaning, regardless of whether this attempt was successful or not (for a discussion, see Kuperberg et al. 2006). This is analogous to the well-established finding that the syntactic P600 is triggered not only by syntactic anomalies, but also by syntactically ambiguous structures, when the initial syntactic analysis yields an 'impossible' initial interpretation (e.g. "The banker persuaded to sell…" (Holcomb & Osterhout, 1992).

Relevant to the idea that the P600 reflects an attempt to recover a coherent discourse meaning, its onset in this study was somewhat later (by approximately 100ms) than the P600 evoked by selection restriction violations falling on verbs (e.g. Kuperberg et al., 2003, 2006, 2007; Kim & Osterhout, 2005, Hoeks et al. 2004). This later onset of the P600 on selection restriction violating nouns is consistent with our previous findings (e.g. Paczynski & Kuperberg, 2011; Kuperberg, Choi, Cohn, Paczynski & Jackendoff, 2010). We have speculated that it reflects a greater likelihood that semantic violations on nouns (as opposed to verbs) can be recovered on the subsequent word. Comprehenders may delay reanalysis on nouns in case a subsequent word disambiguates a highly implausible interpretation (see Paczynski & Kuperberg, 2011 for discussion). In contrast, selection restriction violations falling on verbs will hardly ever be recoverable as this is where thematic roles are (usually) unambiguously assigned.

Implications and Open questions

Under these task conditions, real-world event/state violations on post-verbal animate Agents, were much more susceptible to faciliatory effects of semantic relatedness than selection restriction violations on inanimate Agents, as reflected by differences in N400 modulation. We have suggested that this is because the coarse-grained selection restrictions of these verbs were prioritized over real-world event/state knowledge, perhaps because they were used in a predictive fashion to select potential animate candidates, and exclude potential inanimate candidates, even those that were semantically related to the preceding context (activated through passive resonance with relatedness networks). We also showed that animacy selection restriction violations, but not real-world knowledge violations, evoked a P600 effect, and that this P600 was not modulated by semantic relatedness. We have suggested that this P600 effect was triggered by the implausibility/incoherence of the propositional representation (produced by a full combinatorial analysis), and that it reflected attempts to recover a coherent discourse meaning. These interpretations raise many important questions for future investigation.

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N400 modulation: A balance between predictive processing and passive resonance—In this study, we suggested that any expectations based on specific real-world knowledge about the people who were likely to take part in the particular events/states described by the verb, were relatively weak and did not confer any faciliatory advantage over and above the activation of semantic relatedness networks through more passive resonance mechanisms. This, however, does not imply that specific real-world knowledge about events and states can never be used in a more predictive fashion. The degree to which the parser makes active predictions about upcoming words will depend on many factors. These include the degree of semantic constraint of the context itself (Kutas & Hillyard, 1984), which is, in turn, influenced by many semantic and syntactic variables. There is also evidence that pragmatic informativeness (e.g. Nieuwland & Kuperberg, 2008) and discourse focus (e.g. Sanford & Garrod, 1998; Morris & Folk, 1998) play important roles, perhaps by encouraging the parser to adopt a 'predictive mode' of comprehension. It is also possible that some types of stored real-world knowledge are inherently more predictive than others, and so future studies should distinguish between events and states, as well as between the knowledge we have about people, objects and locations.

What we have argued is that, under the same task conditions, using similar contexts, the same participants used the verb's coarser-grained selection restrictions for animate arguments to constrain activity across semantic relatedness networks: the processing of inanimate selection restriction violating Agents was not facilitated, even when such Agents were semantically related to the context. It is important to recognize, however, that this relative impermeability to semantic relatedness may not necessarily generalize to other types of selection restriction violations. For example, in a recent study, we showed that animate direct object noun-phrases that violated the restrictions of their preceding inanimate-selecting verbs (e.g. "…plowed the *laborer…") evoked a smaller N400 than inanimate direct object noun-phrases that violated the restrictions of their preceding animate-selecting verbs (e.g. "…penalized the *meadow…) (Paczynski & Kuperberg, 2011). In contrast to animate-selecting verbs, inanimate-selecting verbs tend to select not only for a broad inanimate semantic features, but also for finer-grained semantic features: whereas one can *penalize* most (animate) humans, one can only *plow* specific inanimate items. Thus, inanimate-selecting verbs may not necessarily exclude semantically related animate candidates, activated through resonance mechanisms, from the expectancy set. Moreover, encountering an animate direct object also violates even more general verb-independent expectations, based on the animacy hierarchy--that inanimate arguments canonically follow animate arguments (for discussion see Paczynski & Kuperberg, 2011). We speculated that this may have reduced the detection of the verb-argument semantic mismatch, again leaving selection restriction violations falling on animate noun-phrases relatively vulnerable to the effects of semantic relatedness. Interactions between word order and the animacy hierarchy might also contribute to the reduced N400 effect on selection restriction violations falling on verbs that follow inanimate NP arguments. For example, encountering an inanimate NP at the beginning of a clause may reduce semantic matching between the verb and its preceding subject, once again leaving these types of violations more vulnerable to the effects of semantic relatedness networks, and leading to an attenuation of the N400 in sentences like, "…the eggs would *eat…".

It will also be important for future studies to determine whether semantic relatedness can override a verb's selection restrictions for properties other than animacy, such as concreteness (e.g. "The pirates buried the treasure/*mutiny…"), or finer-grained features (e.g. "The man drank the *sandwich."). Addressing these issues has important theoretical implications. Early versions of generative grammar proposed a mental lexicon with verb-argument selection restrictions that were separate and independent from real-world knowledge (Chomsky, 1965; Katz, 1963). Others, however, have argued that the selection restrictions and real-world knowledge associated with a given verb are very difficult to disentangle (e.g. Jackendoff, 2002; Matsuki, Chow, Hare, Elman, Scheepers, & McRae, 2011; Elman, 2009). On the other hand, there is evidence that animacy may be somewhat privileged as a semantic feature: in some languages, animacy is formally encoded within syntactic structure (Craig, 1977; Hale, 1972; Minkoff, 2000; Van Valin, 1997) as well as word morphology (Aristar, 1997; Malchukov, 2008; Wiese, 2003). Even in languages where it does not formally constrain syntactic structure, such as English, animacy information can influence noun ordering (Rosenbach, 2008; Snider & Zaenen 2006). Thus, the differences between real-world knowledge and animacy-based selection restrictions in the present study may reflect a privileged property of animacy, rather than a more general distinction between selection restrictions and real-world event/state knowledge.

Finally, it will also be important to isolate the effects of different types of semantic relatedness on sentence processing. In this study, we defined ‘semantic relatedness’ between the target word and its preceding context quite broadly, operationalizing it through LSA, which has been shown to closely mirror human judgments of semantic relatedness (Laham, 1997). However, as outlined in the Introduction, semantic relatedness can encompass semantic associations, category membership, shared semantic features, as well as schema knowledge. Although each of these have shown to have similar impact on N400 modulation in single word priming studies (Grose-Fifer & Deacon, 2004, Deacon et al., 2004), it is as yet unclear how they each interact with real-world event/state knowledge and/or animacy selection restrictions during sentence and discourse comprehension.

The semantic P600: conflict between semantic memory-based predictions and the detection of propositional incoherence—A second question left unresolved by the current study is under what circumstances semantic violations elicit a P600 effect. Our study adds to a growing literature indicating that semantic relatedness between the incoming word and its preceding context is *not* necessary for a P600 to be evoked by that word (e.g. Kuperberg et al, 2007; Kuperberg et al., 2010; Paczynski & Kuperberg, 2011; Stroud, 2008). It favors accounts that emphasize the detection of propositional implausibility/impossibility as a particularly important trigger of this effect (Kuperberg, 2007; van de Meerendonk et al., 2009; Bornkessel-Schlesewsky & Schlesewsky, 2008). This study, however, was not designed to distinguish between these three accounts, which differ in the emphasis placed on conflict between propositional incoherence and alternative representations computed during online processing. We consider some of these distinctions below.

Bornkessel-Schlesewsky et al. suggest that the P600 reflects “a domain-general, binary categorization of well-formedness… [and] not the conflict between alternative interpretations” (Bornkessel-Schlesewsky, Kretzschmara, Tune, Wang, Genç, Philipp, Roehm, Schlesewsky, 2011, p. 149). This can explain why a P600 effect is often evoked by impossible violations, even when the critical word is semantically unrelated to preceding content words, as in the present study and previous studies (Kuperberg et al., 2007, Kuperberg et al. 2010, Stroud, 2008). However, it does not easily explain why a P600 effect is sometimes present (e.g. Kolk et al. 2003; van Herten et al., 2005) and sometimes absent (e.g. Kuperberg et al., 2003, 2006 and 2007, the present study) to real-world violations, even when they are explicitly classified as implausible during dichotomous judgment tasks and during pre-rating studies.

The error-monitoring framework discussed by Kolk and colleagues (van de Meerendonk et al. 2009) and the dynamic framework proposed by Kuperberg (2007) emphasize *both* the detection of an implausible proposition, and a competing intermediate semantic representation as being critical to the production of a semantic P600. The main difference between these two frameworks is in the nature of this intermediate semantic representation,

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and when it is computed. Within the monitoring framework, the competing alternative semantic interpretation is a plausible, or partially plausible, representation of meaning that is computed by integrating the critical word itself into its context through asyntactic ‘plausibility heuristic’ mechanisms (similar to Kim & Osterhout, 2005; see also Bornkessel-Schlesewsky & Schlesewsky, 2008). This account can explain the findings of Kolk (2003), van Herten et al. (2005) and Sanford et al. (2011). However, it less easily explains why a P600 effect can be produced by critical words that are *completely* unrelated to any of the preceding content words (Hoeks et al., 2004; Kuperberg et al., 2007; Stroud, 2008) when such a plausibility heuristic would fail to come up with a plausible or even a partially plausible alternative representation.

In contrast, we see the alternative competing semantic representation as being generated by a semantic memory-based analysis (Kuperberg, 2007) which does *not* necessarily integrate the critical word to come up with a plausible, or semi-plausible, representation of meaning Kuperberg et al., 2010; Paczynski & Kuperberg, 2011)[7]. More specifically, we suggest that the competing representation is generated through *semantic expectancy generation,* which is, in principle, independent of the semantic features of the critical word itself. The competing intermediate representation may be the semantic expectations themselves (specific words or groups of words sharing common semantic features, category or schema), or it may constitute a higher-order representation that is computed by integrating these expected representations into the contextual representation, held within working memory, ahead of any bottom-up input.

According to this framework, language processing is highly dynamic: a linguistic context interacts with *multiple* types of stored semantic information to generate semantic expectations. Whether or not the N400 is attenuated to an incoming word will depend on the degree to which this word’s semantic features match these expectations. In parallel, this incoming word is syntactically-semantically integrated with its contextual representation (combinatorial analysis) to generate a new proposition. This proposition forms the new contextual representation, which, in turn, again interacts with semantic memory (as described above) to generate expectations for the next word, thus beginning a new cycle. Our view is that that a P600 effect is most likely to be triggered when there is a conflict between (a) an expected representation that is predicted based on the interaction between the contextual representation and stored semantic material, regardless of the critical word, and (b) detected incoherence of the new semantically-syntactically determined proposition, formed by combinatorially (semantically-syntactically) integrating the incoming critical word into its preceding context[8].

As discussed by Kuperberg (2007), this type of framework is quite flexible and dynamic, because both (a) and (b) can vary. If participants fail to make strong semantic predictions (for whatever reason), a P600 effect can still sometimes be produced by a highly implausible/impossible or syntactically ill-formed proposition, particularly if the task encourages the detection of incoherence. And if participants make strong semantic predictions, it is possible for a P600 effect to be triggered by a less implausible (not

[7]In addition to proposing a semantic memory-based mechanism, Kuperberg (2007) also discussed the possibility that animacy can be used to assign thematic roles, independent of syntax. However, based on the results of our recent study (Paczynski & Kuperberg, 2011), we now believe that the animacy of arguments within a context can directly influence semantic memory-based predictions, independent of a verb’s thematic structure.

[8]This sensitivity to both prediction and the detection of an anomaly puts the P600 effect squarely into the P300 family of components (see Coulson, King, & Kutas, 1998). We also think that the semantic P600 effect may be functionally related to a more anteriorly-distributed positivity effect which is also seen when a semantic memory-based analysis yields a close match between context and stored material (strong semantic memory-based predictions) that are disconfirmed by a critical word. Anterior positivities, however, are usually seen when the syntactic-semantic integration of the critical word yields a plausible, rather than implausible interpretation (Federmeier, Wlotko, De Ochoa-Dewald, & Kutas, 2007; for a review see Van Petten & Luka, 2012).

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impossible) proposition, as there is still some conflict between (a) and (b), as in Sanford et al. (2011) but not in the present study. The advantage of this type of highly dynamic framework is that it can accommodate many of the current findings. Its challenge is to determine exactly how much context, and what degree of contextual constraint, are necessary to trigger a P600 effect for a given degree of implausibility and given task, and it would therefore benefit from being modeled computationally to determine how these variables interact with one another.

Effects of task—Finally, there is the question of what our findings mean for more naturalistic language comprehension. As is common in many psycholinguistic studies, we explored how the language system behaves when pushed against limits, by asking participants to carry out an explicit judgment task. This is likely to have influenced both N400 and P600 modulation. It may have influenced the N400 by encouraging predictive processing, making it more likely that participants used the selection restrictions of the verbs to anticipate the semantic features of upcoming words. It may have influenced P600 modulation by encouraging predictive processing *and* by making it more likely that the parser detected propositional implausibility/impossibility (for a discussion, see Kuperberg, 2007; see also Sanford et al. 2011 for evidence that the detection of incoherence plays an important role in triggering a P600 effect, even during more passive reading). Our results clearly demonstrate that, under these conditions, the real-world and animacy selection restrictions violations engendered different patterns of processing. This tells us that these types of animacy selection restriction violations are not necessarily treated as a “more severe” type of real-world knowledge violation, but rather that the two types of knowledge can be treated distinctly by the parser. However, it remains an open question whether, and to what extent, such functional distinctness impacts more natural language comprehension, both during auditory comprehension and more passive reading, in which demands vary depending on the comprehender’s attention and motivation.

Conclusions

In the present study, we have drawn a distinction between semantic memory-based processes, which modulate the N400, and the implausibility/impossibility of the proposition formed by semantic-syntactic integration, which modulates the P600. Semantic memory-based mechanisms refer to the generation of expectations, through the interaction between representations of the context (prior to the critical word) and stored semantic relationships of various types, about the semantic features of an incoming critical word. They also encompass the degree to which such expectations match or mismatch the semantic features of upcoming words, which influences N400 modulation to such words. We showed that strong semantic relatedness between content words in a context can, at least under these task and experimental conditions, override expectations based on real-world event/state knowledge, but not necessarily expectations based on a verb’s selection restrictions on argument animacy. Combinatorial mechanisms refer to the integration of a critical word with its preceding context using both syntactic and semantic constraints to produce a propositional interpretation. We showed that when the resulting proposition is implausible-and-impossible, but not implausible-but-possible, additional analysis/reanalysis ensues, reflected by a P600 effect, at least under these task and experimental conditions. Finally, we demonstrated that this continued combinatorial analysis was not modulated by semantic relatedness, supporting our previous findings that the semantic P600 is not dependent on semantic relatedness or attraction between the critical word and its context. Taken together, our findings suggest a complex and dynamic interplay between different types of semantic information that can influence early and later stages of online word-by-word sentence comprehension.

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Acknowledgments

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Highlights

- We examined how semantic relatedness impacts the processing of two violation types.
- Real-world knowledge violations evoked an N400 but no P600 effect.
- Animacy selection restriction violations evoked an N400 and P600 effect.
- Semantic relatedness only modulated processing of real-world knowledge violations.
- The brain recognizes a distinction between real-world and animacy selection restriction violations.

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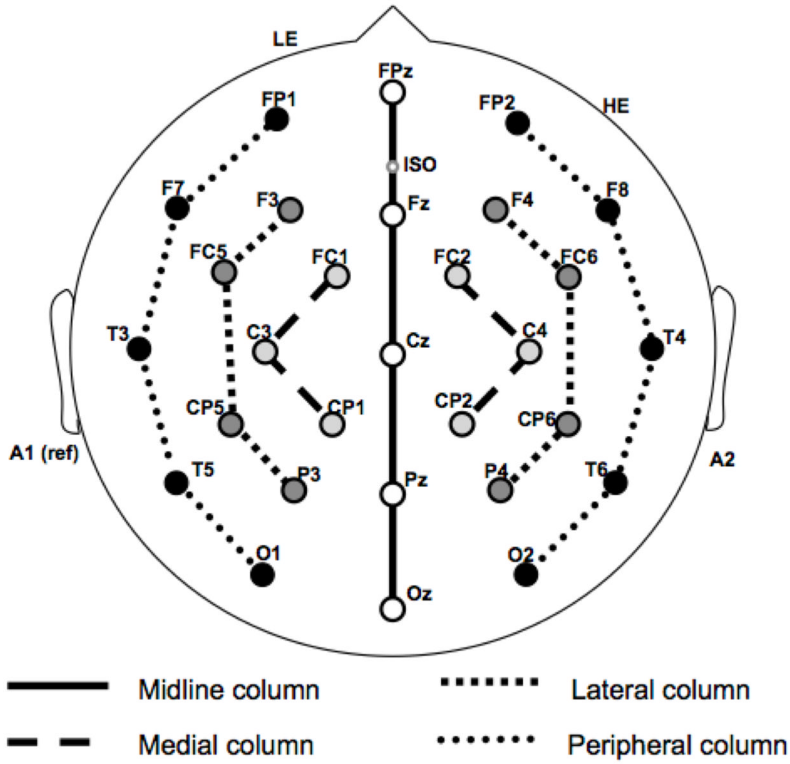

Figure 1.

Electrode montage. Analyses of variance were conducted at midline, medial, lateral and peripheral electrode columns shown (see Methods).

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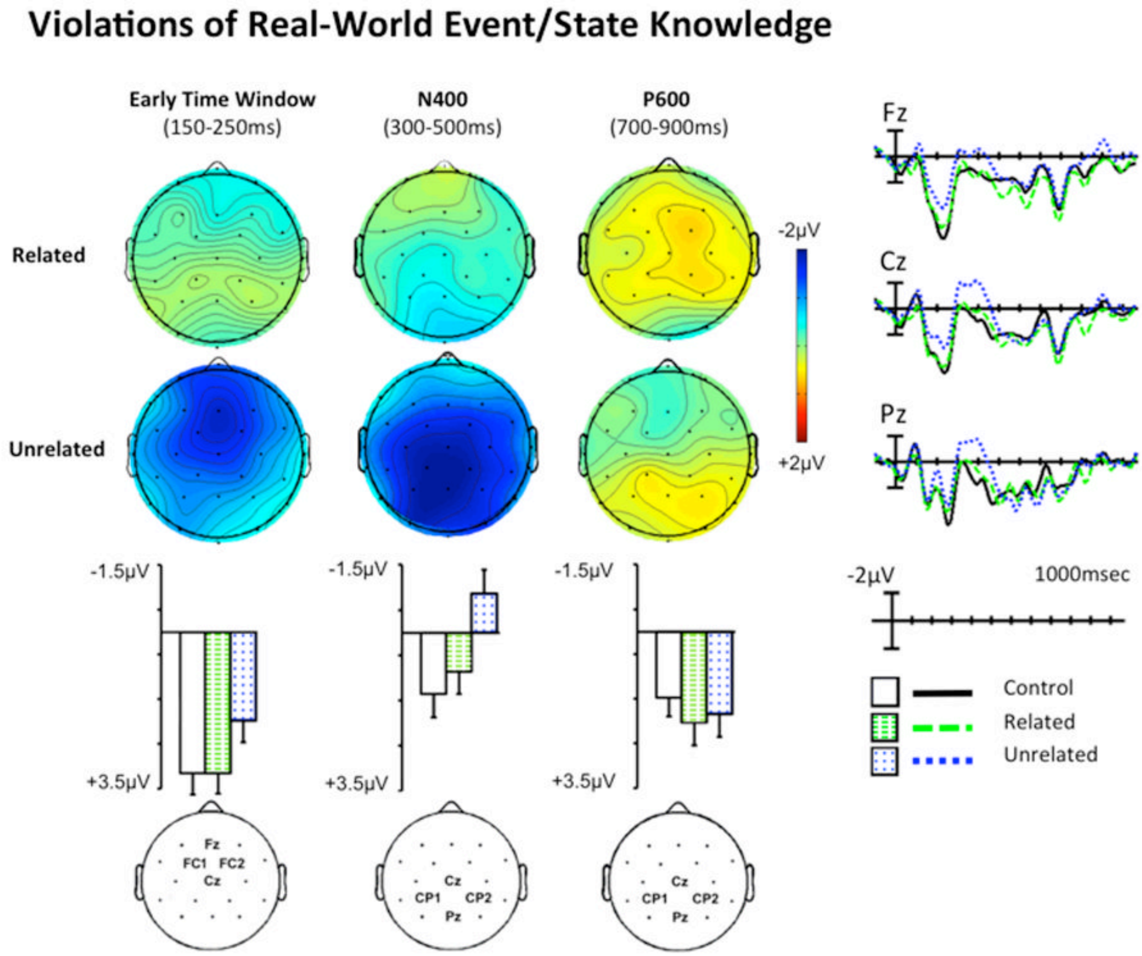

Figure 2.
ERPs evoked by critical nouns in Control, semantically Related and Unrelated Real-World Knowledge violation sentences along midline electrode sites, as well as voltage maps in the 150–250ms, N400 (300–500ms) and P600 (700–900ms) time windows. Solid black lines and white bars indicate Control condition; dashed green line and bar indicate Related Real-World Knowledge Violation condition; dotted blue line and bar indicate Unrelated Real-World Knowledge Violation condition. The plots are shown using a -100-0ms pre-stimulus baseline. All voltage maps show differences between ERPs to the violations and control critical words, averaged across each time window. Bar graphs show the amplitude of ERPs to each condition averaged across each time window, across the four electrode sites where the effects were maximal (indicated below each bar graph). Error bars show standard errors.

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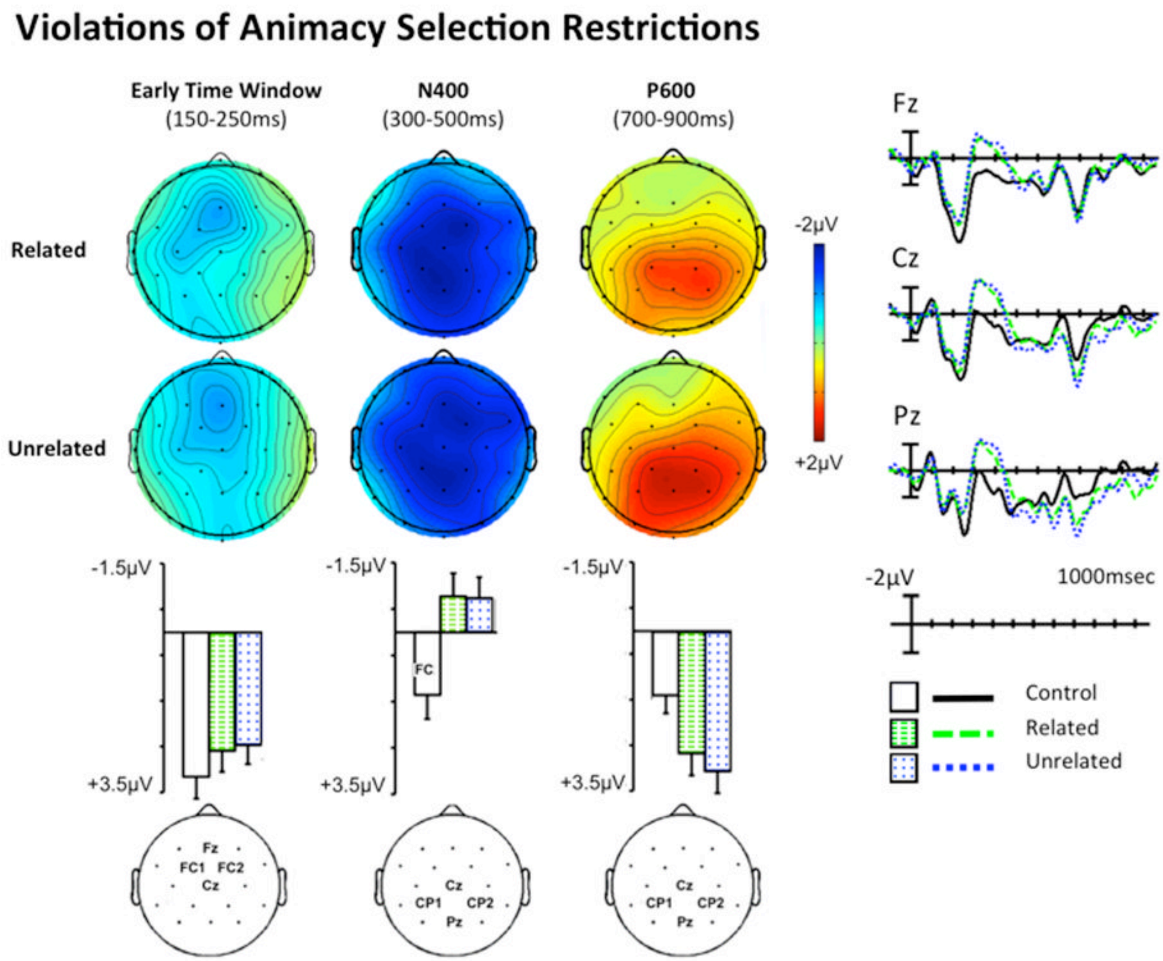

Figure 3.
ERPs evoked by critical nouns in Control, semantically Related and Unrelated Animacy Selection Restriction Violation sentences along midline electrode sites, as well as voltage maps in the 150–250ms, N400 (300–500ms) and P600 (700–900ms) time windows. Solid black lines and white bars indicate Control condition; dashed green line and bar indicate Related Animacy Selection restriction Violation condition; dotted blue line and bar indicate Unrelated Animacy Selection restriction Violation. The plots are shown using a -100-0ms pre-stimulus baseline. All voltage maps show differences between ERPs to the violations and control critical words, averaged across each time window. Bar graphs show the amplitude of ERPs to each condition averaged across each time window, across the four electrode sites where the effects were maximal (indicated below each bar graph). Error bars show standard errors.

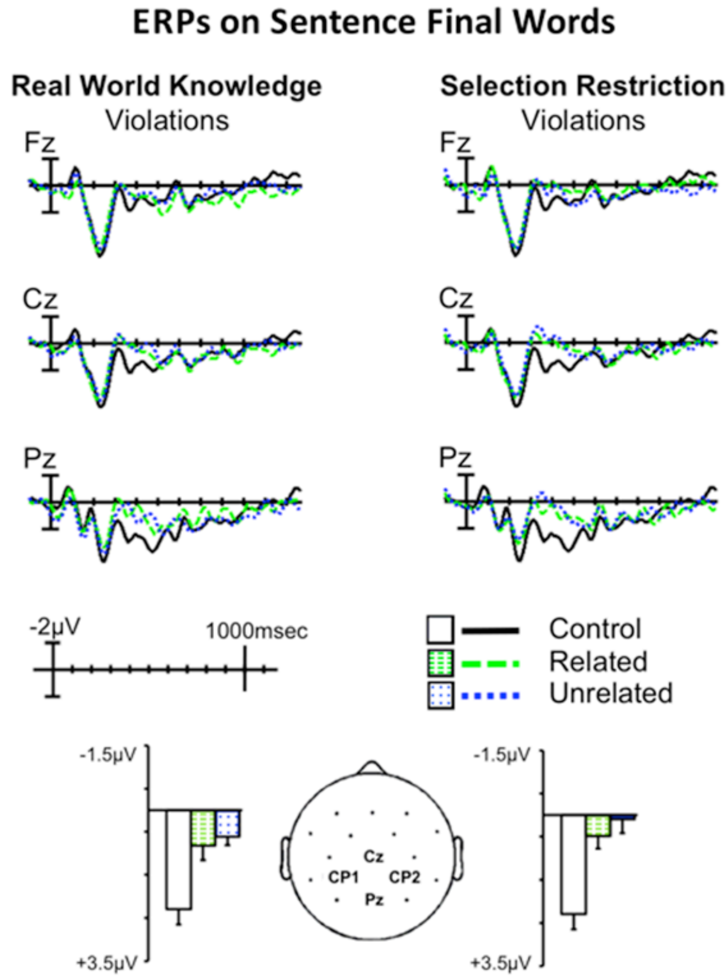

Figure 4.
ERPs evoked by sentence-final words in all conditions along midline electrode sites. Solid black lines and white bars indicate control Condition, dashed green lines and bar indicate Related Violation conditions, dotted blue lines indicate Unrealted Violation conditions. The plots are shown using a -100-0ms pre-stimulus baseline. Bar graphs show the amplitude of ERPs to each condition averaged across the 300–500ms time window and across Cz, Pz, CP1 and CP2 where the effects were maximal. Error bars show standard errors.

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Table 1

Types of linguistic violations and example sentences.

Sentence Type	Example
1. Control	
The critical animate noun (e.g. *guitarist*) is semantically related to the general message conveyed by the group of content words in the preceding context (*pianist, played, music, bass, strummed*), *and* it conforms to expectations based on real-world knowledge about how likely it is for the Agent to be carrying out this action in this particular context.	The pianist played his music while the bass was strummed by the guitarist during the song.
2. Related Real-World Knowledge Violations	
The critical animate noun (e.g. *drummer*) is semantically related to the general message conveyed by the group of content words in the preceding context (*pianist, played, music, bass, strummed*), *but* it violates expectations based on real-world knowledge about how likely it is for the Agent to be carrying out this action in this particular context (a bass is unlikely to be strummed by a drummer in this situation). Note that this event is implausible but not impossible. Note also that the Agent is animate and therefore matches the animacy selection restrictions of the verb.	The pianist played his music while the bass was strummed by the drummer during the song.
3. Unrelated Real-World Knowledge Violations	
The critical animate NP (e.g. *gravedigger*) is not related to the general message conveyed by the group of content words in the preceding context (*pianist, played, music, bass, strummed*) *and* it violates expectations based on real-world knowledge about how likely it is for the Agent to be carrying out this action in this particular context (a bass is unlikely to be strummed by a gravedigger in this situation). Note that this event is implausible but not impossible. Note also that the Agent is animate and therefore matches the animacy selection restrictions of the verb.	The pianist played his music while the bass was strummed by the gravedigger during the song.
4. Related Animacy Selection Restriction Violations	
The critical inanimate noun (e.g. *drum*) is semantically related to the general message conveyed by the group of content words in the preceding context (*pianist, played, music, bass, strummed*), *but* it violates the animacy-based selection restrictions of the verb for an animate Agent (drums are inanimate and therefore cannot carry out the action of strumming). Note that this event is impossible, rather than simply implausible.	The pianist played his music while the bass was strummed by the drum during the song.
5. Unrelated Animacy Selection Restriction Violations	
The critical inanimate noun (e.g. *coffin*) is not semantically related to the general message conveyed by the group of content words in the preceding context (*pianist, played, music, bass, strummed*) *and* it also violates the animacy-based selection restrictions of the verb for an animate Agent (coffins are inanimate and therefore cannot carry out the action of strumming). Note that this event is impossible, rather than simply implausible.	The pianist played his music while the bass was strummed by the coffin during the song.

Critical Agent nouns are underlined in the examples.

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Table 2

Sentence Type	Critical Noun Length		Critical Noun Frequency		SSV		Plausibility ratings*	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
1. Control	7.54	2.08	2.45	0.89	0.22	0.02	6.3	0.3
2. Related Real-World Knowledge Violation	7.58	1.92	2.37	0.80	0.18	0.02	2.4	0.4
3. Unrelated Real-World Knowledge Violation	7.56	1.98	2.31	0.81	0.00	0.01	2.2	0.5
4. Related Animacy Selection Restriction Violation	6.23	1.98	2.74	0.74	0.18	0.02	1.8	0.5
5. Unrelated Animacy Selection Restriction Violation	6.23	1.98	2.74	0.74	0.01	0.01	1.3	0.3

SD: Standard Deviation.

Length: number of letters.

Frequency based on the SUBTLEXus Corpus' log of word form frequency per million, $LgSUBTL_{WF}$ (Brysbaert and New 2009); available on the Internet through the English Lexicon Project http://elexicon.wustl.edu/

SSV: Semantic Similarity Values, as determined using Latent Semantic Analysis (LSA; Landauer and Dumais 1997; Landauer et al. 1998; available on the internet at http://lsa.colorado.edu) between critical noun and preceding sentence context.

* Plausibility ratings on a 7-point Likert scale up until and including the critical noun. Plausibility ratings of the fillers: Mean: 6.2, SD: 0.4.

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Table 3

Percentage of participants' 'make sense' and 'does not make sense' judgments for each experimental condition, and filler sentences, during the ERP experiment.

Sentence Type	**'Makes sense' judgment**	**'Does not make sense' judgment**
Control	89% (5.7)	
Related Real-World Knowledge Violations		79% (11.4)
Unrelated Real-World Knowledge Violations		89% (7.8)
Related Animacy Selection Restriction Violations		93% (4.9)
Unrelated Animacy Selection Restriction Violations		97% (4.3)
Plausible Fillers	93% (5.2)	

Mean percentages are shown with standard deviations in brackets.

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Table 4

Omnibus ANOVAs in the 150–250ms, N400 (300–500ms), and P600 (700–900ms) time windows, comparing ERPs to critical nouns across all five sentence types.

	Main effect of Sentence Type		Interactions between Sentence Type and AP Distribution	
	DoF	F value	DoF	F value
150–250ms				
Midline	4, 76	5.15**	16, 304	1.61
Medial	4, 76	5.44**	8, 152	1.15
Lateral	4, 76	5.15**	12, 228	0.75
Peripheral	4, 76	4.99**	16, 304	1.05
N400 (300–500ms)				
Midline	4, 76	8.53***	16, 304	2.93*
Medial	4, 76	10.10****	8, 152	1.18
Lateral	4, 76	9.10***	12, 228	1.78
Peripheral	4, 76	7.09***	16, 304	2.54**
P600 (700–900ms)				
Midline	4, 76	7.91***	16, 304	2.89*
Medial	4, 76	9.26****	8, 152	6.07***
Lateral	4, 76	7.69***	12, 228	3.20*
Peripheral	4, 76	6.00**	16, 304	1.66

DoF: Degrees of Freedom.

* $p < .05$

** $p < .01$.

*** $p < .001$.

**** $p < .0001$.

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Table 5

Simple effects ANOVA comparing ERPs to each type of violated noun with the control critical nouns in the 150–250ms, N400 (300–500ms) and P600 (700–900ms) time windows

	150–250ms				N400 (300–500ms)				P600 (700–900ms)			
	Sentence Type		Sentence Type x AP Distribution		Sentence Type		Sentence Type x AP Distribution		Sentence Type		Sentence Type x AP Distribution	
	DoF	F value	DoF	F value	DoF	F value	DoF	F value	DoF	F value	DoF	F value
A. Related Real-World Knowledge Violations vs. Control												
Midline	1,19	0.859	4,76	0.511	1,19	2.47	4,76	4.40*	1,19	0.06	4,76	1.46
Medial	1,19	0.078	2,38	0.7	1,19	3.24	2,38	0.46	1,19	0.51	2,38	0.31
Lateral	1,19	0.274	3,57	0.562	1,19	1.81	3,57	0.82	1,19	1.38	3,57	0.08
Peripheral	1,19	1.039	4,76	0.815	1,19	0.82	4,76	2.48	1,19	0.35	4,76	0.57
B. Unrelated Real-World Knowledge Violations vs. Control												
Midline	1,19	14.461**	4,76	3.686*	1,19	10.69**	4,76	7.95****	1,19	0.79	4,76	1.77
Medial	1,19	16.301**	2,38	3.098*	1,19	14.37**	2,38	1.79	1,19	0.9	2,38	2.19
Lateral	1,19	13.554**	3,57	1.106	1,19	13.23**	3,57	3.31	1,19	1.54	3,57	2.46
Peripheral	1,19	13.516**	4,76	1.746	1,19	10.74**	4,76	6.69**	1,19	1.64	4,76	0.72
C. Related Animacy Selection Restriction Violations vs. Control												
Midline	1,19	3.357	4,76	0.866	1,19	19.36***	4,76	4.50**	1,19	5.93*	4,76	1.43
Medial	1,19	3.029	2,38	1.37	1,19	24.93****	2,38	2.26	1,19	11.14**	2,38	7.45**
Lateral	1,19	2.088	3,57	0.368	1,19	17.91***	3,57	2.44	1,19	8.80**	3,57	3.28
Peripheral	1,19	1.121	4,76	0.333	1,19	12.76**	4,76	2.55	1,19	4.86*	4,76	0.71
D. Unrelated Animacy Selection Restriction Violations vs. Control												
Midline	1,19	5.052*	4,76	0.567	1,19	11.90**	4,76	1.61	1,19	23.27***	1.61	6.31**
Medial	1,19	3.392	2,38	0.409	1,19	12.33**	2,38	1.07	1,19	23.68***	1.07	15.39***
Lateral	1,19	2.634	3,57	1.041	1,19	12.08**	3,57	0.41	1,19	34.88****	0.41	6.70**
Peripheral	1,19	1.823	4,76	2.058	1,19	11.36**	4,76	0.53	1,19	27.92****	0.53	3.13

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* $p < .05$

** $p < .01$.

*** $p < .001$.

**** $p < .0001$.

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Table 6

2 × 2 ANOVAs: 1effects of Violation Type and Relatedness on violated nouns within the 150–250ms, N400 (300–500ms) and P600 (700–900ms) time windows.

	Main effect of Violation Type		Main effect of Relatedness		Interaction between Violation Type and Relatedness	
	DoF	F value	DoF	F value	DoF	F value
150–250ms						
Midline	1, 19	0.01	1, 19	9.58**	1, 19	9.390**
Medial	1, 19	0.02	1, 19	7.47*	1, 19	16.671**
Lateral	1, 19	0.54	1, 19	8.30*	1, 19	11.792**
Peripheral	1, 19	.90	1, 19	7.81*	1, 19	9.74**
N400 (300–500ms)						
Midline	0.22	5.17*	1, 19	4.20	1, 19	2.34*
Medial	0.22	4.51*	1, 19	5.31*	1, 19	14.88**
Lateral	1, 19	4.39*	1, 19	6.22*	1, 19	16.39***
Peripheral	1, 19	3.78	1, 19	4.82*	1, 19	9.26**
P600 (700–900ms)						
Midline	1, 19	12.21**	1, 19	0.02	1, 19	1.46
Medial	1, 19	14.03**	1, 19	0.02	1, 19	2.21
Lateral	1, 19	10.06**	1, 19	0.00	1, 19	2.44
Peripheral	1, 19	11.01**	1, 19	0.20	1, 19	0.22

* $p < .05$

** $p < .01$.

*** $p < .001$.

**** $p < .0001$.