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Short Communication

Conflict and surrender during sentence processing: An ERP study of syntax-semantics interaction

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ABSTRACT

Recent ERP studies report that implausible verb-argument combinations can elicit a centro-parietal P600 effect (e.g., "The hearty meal was devouring ..."; Kim & Osterhout, 2005). Such eliciting conditions do not involve outright syntactic anomaly, deviating from previous reports of P600. Kim and Osterhout (2005) attributed such P600 effects to structural reprocessing that occurs when syntactic cues fail to support a semantically attractive interpretation ('meal' as the Agent of 'devouring') and the syntactic cues are overwhelmed; the sentence is therefore perceived as syntactically ill-formed. The current study replicated such findings and also found that altering the syntactic cues in such situations of syntax-semantics conflict (e.g., "The hearty meal would devour ...") affects the conflict's outcome. P600s were eliminated when sentences contained syntactic cues that required multiple morphosyntactic steps to "repair". These sentences elicited a broad, left-anterior negativity at 300–600 ms (LAN). We interpret the reduction in P600 amplitude in terms of "resistance" of syntactic cues to reprocessing. We speculate that the LAN may be generated by difficulty retrieving an analysis that satisfies both syntactic and semantic cues, which results when syntactic cues are strong enough to resist opposing semantic cues. This pattern of effects is consistent with partially independent but highly interactive syntactic and semantic processing streams, which often operate collaboratively but can compete for influence over interpretation.

1. Introduction

Human language comprehension requires the rapid extraction and coordination of grammatical (syntactic) and semantic cues from linguistic input. The investigation of how this signature human ability occurs "on-line" has been a fundamental and controversial challenge of psycholinguistic research for decades (Friederici, 2002; MacDonald, Pearlmutter, & Seidenberg, 1994; Ferreira & Clifton, 1986; Rayner, Carlson, & Frazier, 1983). A number of recent proposals have departed from an influential paradigm in which grammatical constraints strictly determine the range of possible interpretations (Frazier, 1987; MacDonald et al., 1994)[1] to parallel architectures in which syntactic and semantic analysis occur in partially independent, parallel processing streams, which interact in a potentially adversarial relationship (e.g., Bornkessel & Schlesewsky, 2006; Kim & Osterhout, 2005; Kolk & Chwilla, 2007; Kuperberg, 2007; Ferreira, 2003). One key source of data driving these parallel proposals is a set of findings that the P600 component of the event-related potential (ERP), which most studies have reported to be correlated with grammatical anomaly, is also elicited by sentences in which semantic cues signal interpretations that conflict with syntactic cues (e.g., Kolk, Chwilla, van Herten, & Oor, 2003; Kuperberg, Sitnikova, Caplan, & Holcomb, 2003). These findings have been interpreted as indicating that semantic cues can sometimes drive interpretative commitments, even in the face of direct opposition from unambiguous syntactic cues (Kim & Osterhout, 2005). Here we extend and clarify understanding of the brain's response to conflict between syntactic and semantic cues during sentence processing, finding evidence that syntactic cues vary in their ability to resist vs. "surrender" to opposition from semantic analyses.

ERP studies of sentence processing find a robust distinction between brain responses to syntactically and semantically anomalous stimuli. Sentence-embedded semantically anomalous words elicit a negative-going wave around 400 ms after onset of the anomalous word (N400; e.g., Kutas & Hillyard, 1984). In contrast, syntactic anomalies elicit a slightly later positive-going shift (P600; e.g., Hagoort, Brown, & Groothusen, 1993; Osterhout & Holcomb, 1992) and, in some studies, an anterior negativity (e.g.,

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[1] Constraint-based models have proposed parallel, interactive semantic and syntactic processing streams (e.g., MacDonald et al., 1994; Trueswell & Tanenhaus, 1994). However, the focus of these models on the process of syntactic ambiguity resolution entails an assumption that syntactically *unambiguous* cues will determine interpretation (Kim & Osterhout, 2005).

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Osterhout & Mobley, 1995; Gunter, Friederici, & Schriefers, 2000; Coulson, King, & Kutas, 1998). Such findings are consistent with a wide range of psycholinguistic models that distinguish between syntactic and semantic levels of analysis (cf. Osterhout, Kim, & Kuperberg, 2011).

In an apparent deviation from earlier findings, recent studies report that some semantically anomalous verb-argument combinations elicit P600 rather than N400 effects (Hoeks, Stowe, & Doedens, 2004; Kim & Osterhout, 2005; Kolk et al., 2003; Kuperberg et al., 2003; Nieuwland & Van Berkum, 2005). For instance, sentences like "The hearty meal was devouring . . .," elicit P600 effects at the verb, relative to well-formed controls (Kim & Osterhout, 2005), even though the syntactic cues are well-formed. Although the syntactic cues unambiguously signal a semantically anomalous interpretation ('meal' as Agent of 'devouring'; meals are incapable of devouring anything), no N400 enhancement occurs.

Kim and Osterhout (2005) interpret these P600 effects in terms of partially independent semantic and syntactic streams of combinatory processing, which can pursue conflicting analyses during sentence processing. In the example above, processing is dominated by strong "semantic attraction" between 'meal' and the Theme role of 'devour'; meals are highly plausible things to devour. This semantic attraction opposes and overwhelms syntactic cues, causing the well-formed syntactic cues to appear ill-formed ('devour**ing**' should be 'devour**ed**'). P600 effects are consistent with structural reprocessing in response to the perception of syntactic anomaly. A follow-up study found N400, not P600 effects, elicited by syntactically similar sentences that lacked semantic attraction, such as "The dusty tabletops were devouring . . .", where tabletops are not plausible Agents or Themes for 'devour' (Kim & Osterhout, 2005; but see Kuperberg, Kreher, Sitnikova, Caplan, & Holcomb, 2007). Thus, in the absence of semantic attraction to a particular interpretation, comprehenders appear to pursue the syntactically signaled but semantically implausible analysis. Kim and Osterhout (2005) conclude that semantic processing can sometimes dominate interpretation, even when opposed by unambiguous syntactic cues.

Other studies have shown that the eliciting conditions of so-called semantic P600s extend beyond cases of clear semantic attraction to an ungrammatical interpretation. In several situations, animacy violations elicit the P600, in the absence of clear attraction to an ungrammatical interpretation (Kuperberg et al., 2003, 2007). Kuperberg (2007) has offered a more general proposal that P600 reflects continued combinatory processing in response to conflict between the outputs of a semantically-driven and a morphosyntactically-driven combinatory stream. Within this view, semantic processing does not dominate syntactic processing but rather is sufficiently independent of syntactic control to generate analyses that challenge the syntactic stream, leading to continued combinatory analysis (see Kolk & Chwilla, 2007 for a related perspective).

Semantic P600 effects also appear consistent with the framework of Bornkessel-Schlesewsky & Schlesewsky (2008), in which an initial syntactic processing stage is followed by parallel processing within (1) a "compute prominence/linking" mechanism, which assigns thematic roles based on a restricted set of features, including linear order, case marking, animacy, and definiteness, and (2) a mechanism that selects the most plausible of the verb-argument combinations generated during the compute prominence/linking stage. These processes are integrated within a "generalized mapping" stage, where integration difficulty generates P600 effects. The P600 to "The hearty meal was devouring . . ." may reflect conflict during generalized mapping between the plausibility of "meal" as the Theme of "devouring" and output of compute prominence/linking, where strong linear order constraints in English drive an Agent assignment. Like other proposals described above, this model emphasizes the role of non-syntactic processing mechanisms in the combinatory analysis of sentences. Unlike other models, this proposal is guided by cross-linguistic variation in the influence of specific linguistic features, such as linear order (Bornkessel & Schlesewsky, 2006; Bornkessel-Schlesewsky & Schlesewsky, 2009).

Much remains unknown about the full range of conditions that elicit semantic P600s and their implications for the neurocognitive processes that serve sentence processing (Bornkessel-Schlesewsky & Schlesewsky, 2008; Kuperberg, 2007; Osterhout et al., 2011). A streams-based architecture raises fundamental questions about the nature of the streams and the interactions between them. Several recent studies focused on the ability of semantic processing to independently pursue analyses that challenge syntactic cues (Hoeks et al., 2004; Kim & Osterhout, 2005; Kolk et al., 2003; Kuperberg et al., 2003). A complementary issue is the role of syntactic cues in allowing challenges from other cue systems. Here, we investigated whether putatively unambiguous syntactic cues varied in their susceptibility to challenges from opposing semantic attraction. Specifically, we examined whether putatively unambiguous syntactic cues were more vulnerable to opposition from semantic attraction when the syntactic cues were *partially consistent* with the semantic attraction.

Kim and Osterhout (2005) speculated that the ability of semantic attraction to control interpretation of their stimuli (e.g., 1b below) was facilitated by the ease with which syntactic cues might be "repaired"—with a single morphosyntactic edit ("devour**ing**" → "devour**ed**")—to accommodate the opposing semantic attraction. In this situation, the semantically attractive "meal" = Theme analysis may be strengthened by its partial consistency with the syntactic cues (a single morphosyntactic edit away), generating a compelling challenge to the syntactically licensed analysis. In the current study, we examined whether syntactic cues would be more resistant to challenge from semantic attraction when such partial consistency was reduced. We compared brain responses to sentences like 1b and 1c, in which the former required a single morphosyntactic change to render plausible (1b; single-edit-repair) and the latter required two morphosyntactic changes to render plausible (1c; multiple-edit-repair). For single-edit-repair sentences, we predicted continued combinatory processing, reflected in P600 effects (replicating Kim & Osterhout, 2005). For multiple-edit-repair sentences, we predicted that syntactic cues would resist an alternative combinatory analysis, reducing the P600. We further predicted that multiple-edit-repair sentences would enhance N400, reflecting the ability of repair-resistant syntactic cues to support the syntactically licensed but implausible interpretation ('meal' = Agent), "winning" the conflict with opposing semantic cues.

1a	The hearty meal was devoured . . .	CONTROL
1b	The hearty meal was devouring . . .	SINGLE-EDIT-REPAIR
1c	The hearty meal would devour . . .	MULTIPLE-EDIT-REPAIR

Our prediction of reduced P600 for multiple-edit-repair sentences is potentially at odds with robust P600s reported for seemingly similar structures by Kuperberg et al. (2003, 2007). However, there are differences between the materials in the current study and these earlier studies, which may modulate the syntax-semantics interactions in the two situations. In the Kuperberg stimuli, the target verb appeared following a lead-in context clause (e.g., ""Every morning at breakfast, **the eggs would plant**. . .";

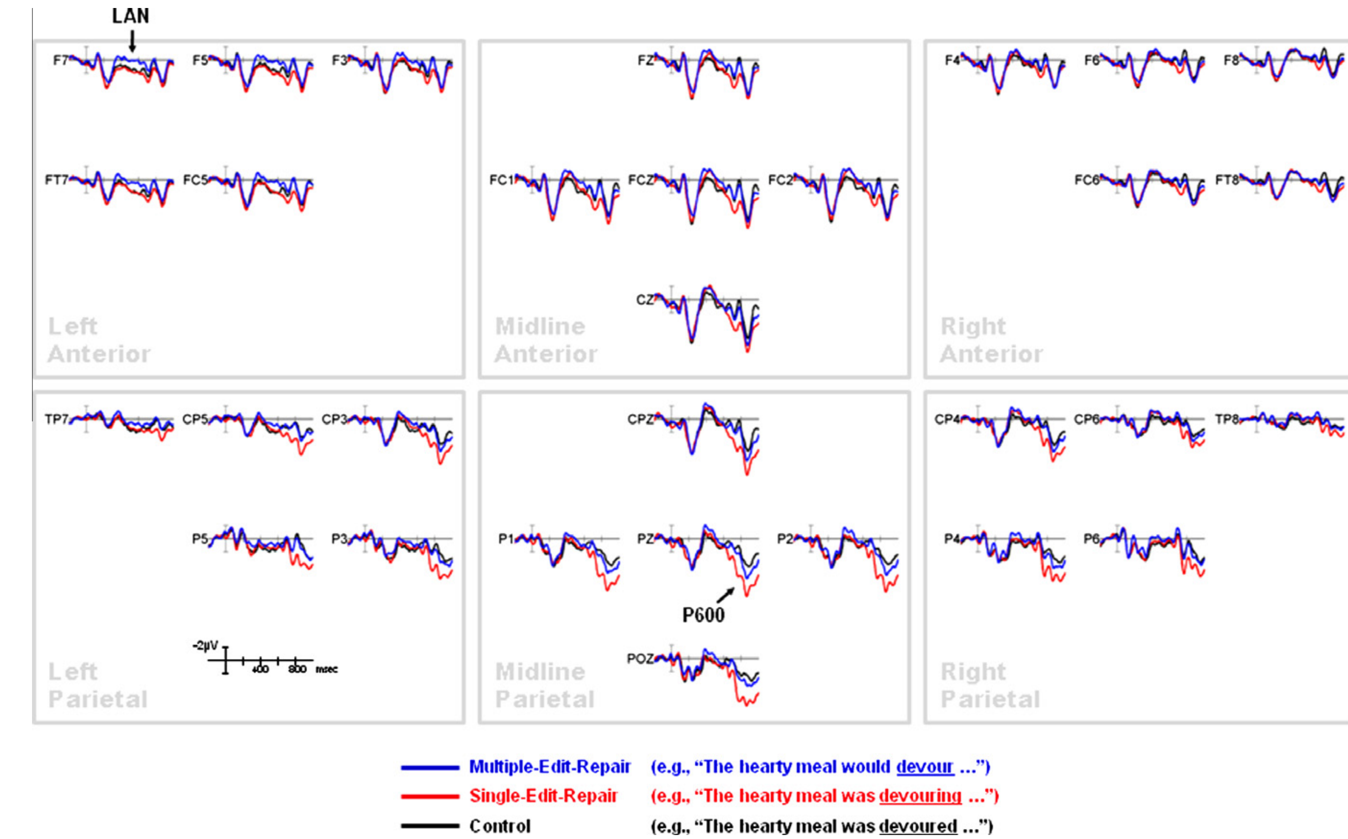

Fig. 1. Grand-average ERPs at 30 selected channel locations for control (black), single-edit-repair (red), and multiple-edit-repair sentences (blue). Onset of the critical verbs is indicated by the vertical bar. Positive voltage is plotted down.

Kuperberg et al., 2007). It is possible that the lead-in context within these sentences increases the likelihood that syntactically unlicensed analyses will be considered (Kuperberg, 2007; Kuperberg et al., 2007). The current study manipulated syntactic cues in a situation that lacked such lead-in contexts, and it leaves as an empirical issue the question of whether this potentially important difference between the current stimuli and those of Kuperberg et al. (2003, 2007) will result in distinct brain responses. The potential impact of context on P600 is discussed in more detail in Section 2.

We recorded ERPs as participants read plausible control sentences (1a), single-edit-repair sentences (1b), multiple-edit-repair sentences (1c). These sentences were pseudo-randomly ordered and intermixed with filler sentences and were presented one word at a time from a computer screen.

1.1. Results

1.1.1. Acceptability judgments

Participants' judgments of target sentence acceptability agreed with the intended judgments (controls are normal and single-edit-repair and multiple-edit-repair stimuli are unusual) at the following rates: 95%, 96%, and 97%, respectively, with ranges of 86–100%, 87–100%, and 88–100%, respectively.

1.1.2. ERPs

Grand-averaged ERPs are shown in Fig. 1 for 30 selected channels, which were used for data analysis. Fig. 2 shows the scalp topography of the single-edit-repair vs. control (Fig. 2A) and multiple-edit-repair vs. control (Fig. 2B) effects at six contiguous 100 ms time windows from 300–900 ms (voltages averaged within each window). All waveforms showed a clear negative-positive complex in the first 300 ms following word-onset (the "N1–P2" complex), followed by a negative-going component peaking around 400 ms (N400; Fig. 1). Single-edit-repair waveforms showed a large positive shift, relative to control, which was maximal at centro-parietal channels, began around 600 ms, and continued through the end of the epoch (P600; Figs. 1 and 2B). Multiple-edit-repair waveforms did not contain this positive shift and instead contained a widely distributed negativity at 300–600 ms, which was maximal at left-anterior channels but was visible over centro-parietal channels (Figs. 1 and 2A). We analyzed ERP effects at six five-channel-groups: including left-anterior, left-posterior, right-anterior, right-posterior, midline-anterior, midline-posterior electrodes, with separate analyses at midline channels and at lateral channels (left and right hemisphere), which included position (anterior/posterior) and hemisphere (left/right; only for the lateral channels) as factors. See Section 2.5 for further details.

ANOVAs in early latency windows (50–150; 150–300 ms) showed no significant effect of sentence-type.

1.1.3. Broad negativity (300–600 ms)

In the 300–600 ms window, voltages in the multiple-edit-repair condition were more negative than in the control condition, reflected in a main effect of sentence-type at all channel-groups [midline: $F(2, 78) = 3.48$, $p < 0.05$; lateral: $F(2, 78) = 4.35$, $p < 0.05$]. Pairwise comparisons showed that the multiple-edit-repair condition was more negative-going than the control [midline: $F(1, 39) = 9.78$, $p < 0.01$; lateral: $F(1, 39) = 11.83$, $p < 0.01$] but that the single-edit-repair condition did not differ from control [$Fs < 2$]. This effect was left-lateralized, reflected in an interaction between hemisphere (left/right) and sentence-type at the lateral channel-groups [$F(2, 78) = 3.35$, $p < 0.05$]. This interaction reflected an effect of sentence-type at left hemisphere channels

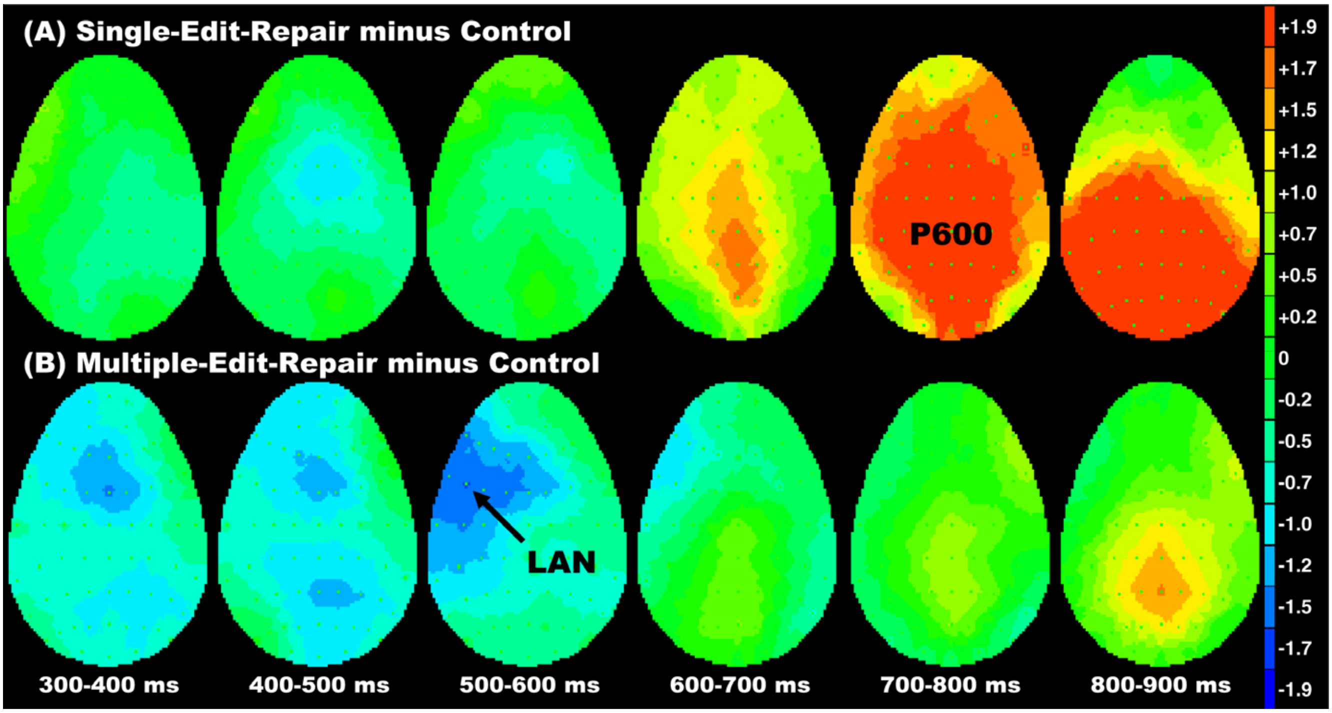

Fig. 2. Topographic maps of voltage-differences between single-edit-repair and control (A) and between multiple-edit-repair and control stimuli (B). Each plot shows average voltage difference at six consecutive 100 ms time windows, starting at 300 ms.

[$F(2, 78) = 6.2$, $p < 0.01$] but not right hemisphere channels ($F < 2$). The effect was furthermore focused at left-anterior channels, reflected in an interaction between position (anterior/posterior), hemisphere and sentence-type for the lateral channel-groups [$F(2, 78) = 7.23$, $p < 0.01$]. Examining each of the lateral channel-groups individually, the multiple-edit-repair condition was more negative than control at all lateral channel-groups except the right-anterior [left-anterior: $F(1, 39) = 12.05$; $p < 0.01$; left-posterior: $F(1, 39) = 10.00$, $p < 0.01$; right-posterior $F(1, 39) = 6.10$, $p < 0.05$]. The single-edit-repair condition did not differ from control at any channel-groups (Fs < 2).

1.1.4. P600 (650–900 ms)

In the 650–900 ms window, voltages in the single-edit-repair condition were more positive than in the control and multiple-edit-repair conditions, reflected in a main effect of sentence-type in all channel-groups [midline: $F(2, 78) = 19.93$, $p < 0.001$; lateral: $F(2, 78) = 13.66$, $p < 0.001$]. Pairwise comparisons showed that the single-edit-repair condition was more positive-going than both the control [midline: $F(1, 39) = 23.96$, $p < 0.001$; lateral: $F(1, 39) = 15.30$, $p < 0.001$] and the multiple-edit-repair condition [midline: $F(1, 39) = 22.76$, $p < 0.001$; lateral: $F(1, 39) = 17.6$, $p < 0.001$]. The multiple-edit-repair condition was marginally more positive than control at midline [$F(1, 39) = 3.5$, $p = 0.07$] but not lateral sites [$F < 1$]. The P600 effect was larger over posterior than anterior channels, reflected in an interaction between position (anterior/posterior) and sentence-type [midline: $F(2, 78) = 5.24$, $p < 0.01$; lateral: $F(2, 78) = 3.77$, $p < 0.05$].

2. General discussion

We recorded ERPs elicited by two types of sentences in which syntactic and semantic cues signaled incompatible analyses. Semantically anomalous sentences that could be rendered plausible by a single morphosyntactic edit (single-edit repair; e.g., 1b) elicited a robust P600 effect at the verb, replicating Kim and Osterhout (2005). Semantically anomalous sentences that required more than a single morphosyntactic edit to repair (multiple-edit repair; e.g., 1c) did not elicit reliable P600 effects and instead elicited a broad negativity, 300–600 ms post stimulus onset, which was maximal over left-anterior channels. The P600 effect observed for single-edit-repair sentences is consistent with the hypothesis that semantic processing can pursue interpretations that conflict with the syntactically licensed analysis of a sentence (Kim & Osterhout, 2005; see also Kolk et al., 2003; Kuperberg et al., 2003). The qualitative reduction of P600 in the multiple-edit repair condition is consistent with the additional conclusion that the outcome of conflict between syntactic and semantic analyses is modulated by the susceptibility of the syntactic cues to alternative analyses.

2.1. P600 and syntactic cues

The modulation of P600 found here can be understood in terms of varying syntactic consistency with an alternative analysis. When syntactic cues are nearly consistent with semantic attraction to an unlicensed analysis (single-edit-repair), the combination of strong semantic plausibility and partial syntactic support generates an analysis that challenges the syntactically licensed analysis, reflected in P600. When syntactic cues are more distinct from a configuration that would accommodate the semantic attraction (multiple-edit-repair), they can resist the alternative combinatory analysis, eliminating the P600 effect. In other words, in situations involving conflict between a semantically attractive interpretation and putatively unambiguous syntactic cues, the syntactic cues can vary in their ability to resist vs. "surrender" to challenge from semantics.

2.2. Negativity 300–600 ms

We originally predicted that multiple-edit-repair anomalies would enhance N400, reflecting the ability of syntactic cues to resist an alternative combinatory analysis *and* support the highly implausible 'meal' = Agent interpretation. However, the left-anterior focus of the negativity at 300–600 ms contrasts with the central-parietal distribution typical of semantic anomaly N400s. The absence of a typical N400 effect may reflect the strength of semantic attraction; even when the syntactic cues resist repair, they cannot force through the semantically unattractive 'meal' = Agent interpretation.

We offer here a speculative interpretation of the left-anterior negativity (LAN) effect elicited by the multiple-edit repair condition. It is possible that the LAN reflects participants' pursuit of an interpretation that simultaneously satisfies the syntactic and semantic cues, with "meal" serving as Theme of "devour" and as syntactic subject. This might resemble the middle-construction, in which a verb that typically takes a direct-object Theme occurs with a subject Theme (e.g., "This book reads well"). This analysis requires a thematic grid (Carlson & Tanenhaus, 1988),[2] which is not typically associated with the verb, and may engage controlled retrieval processes in order to access this grid. We do not know whether a functional relationship exists between the LAN effect here and similar ERP effects elicited by morphosyntactic violations (Osterhout & Mobley, 1995; Gunter et al., 2000; Coulson et al., 1998) and by syntactically complex sentences (Fiebach, Schlesewsky, & Friederici, 2001; King & Kutas, 1995). It is conceivable that LAN reflects working memory resources recruited in all of these situations: controlled retrieval of atypical lexical senses, syntactically complex sentences, and some types of morphosyntactic anomaly. Further work is needed to test this speculation.

2.3. P600 and syntax-semantics interactions

We have previously proposed that language comprehension is served by partially independent but highly interactive streams of semantic and syntactic processing (Kim & Osterhout, 2005).[3] In previous statements, we focused on cases of clear semantic attraction to an interpretation that is inconsistent with the syntactic cues, where morphosyntactic editing could render the sentence plausible (e.g., Hoeks et al., 2004; Kim & Osterhout, 2005; Kolk et al., 2003). However, several studies find that such "global" semantic attraction is not necessary for P600 to occur, as in the case of some animacy violations, where no morphosyntactic edit can render the sentence plausible (e.g., Kuperberg et al., 2007). Furthermore, the current findings indicate that semantic attraction is not always sufficient to elicit P600. Here, we briefly elaborate and extend our theoretical view and address some of the diversity in the syntax-semantics interactions leading to P600 effects.

2.3.1. The lexico-syntactic stream

We envision the syntactic stream as a mechanism that incrementally analyzes the words in a sentence, retrieving an informationally rich lexico-syntactic category, or "treelet", for each word, based on the word's identity and local context. Treelets encode much of the syntactic environment of a given word, such as the position and number of a verb's arguments (Kim, Srinivas, & Trueswell, 2002; Srinivas & Joshi, 1999; see Hagoort, 2005 for a similar perspective on lexico-syntactic contributions to language comprehension). We further propose that treelets encode the thematic role associated with each syntactic position. For instance, different treelets are required for the verbs in "The man slept" and "The soup simmered", in which the subject noun is an Agent/Experiencer or a Theme, respectively. We do not distinguish between an initial stage of basic category level (e.g., noun, verb) and finer-grained syntactic analyses (as in, e.g., Bornkessel & Schlesewsky, 2006; Friederici, 2002). Recognition of the appropriate treelet for each word in a sentence accomplishes much of the information-processing task performed by a more conventional syntactic parser, because treelets are highly restricted in their combinatory possibilities (far more than basic grammatical categories; Srinivas & Joshi, 1999). The computations of the lexico-syntactic stream are modulated by local context and may be modeled by a simple recurrent neural network (SRN), in which re-entrant feedback of previous activation states allows maintenance of information over time (Elman, 1990).

2.3.2. The semantic stream and semantic attraction

The semantic stream activates structured, generalized knowledge representations about events and their participants, which are acquired through real world and linguistic experience (Altmann, 1999; Boland, Tanenhaus, Garnsey, & Carlson, 1995; Hare, Jones, Thomson, Kelly, & McRae, 2009). Activity within the semantic stream is constantly modulated by input from lexico-syntactic treelets. We further propose that event-representations can be activated via "direct" associations with individual words (e.g., Hare et al., 2009), with especially robust activation when multiple words within a sentence associate with the same event. For instance, a *devour-a-meal* event-representation receives multiple sources of direct activation from "The hearty meal was devouring". This is the basis of what we have termed "semantic attraction" (Kim & Osterhout, 2005). This description of the semantic stream does not require that all event-representations activated during sentence comprehension are stored representations of previously experienced events. Event-representations of novel events like *devour-a-rutabaga* will also be accessible. We expect such event-representations to have strong overlap with representations of more frequent events (interpretation by analogy). We expect access of novel event-representations to be constrained by lexico-syntactic cues. Furthermore, weaker forms of semantic attraction should exist, even for novel events; for instance, the inanimacy of "rutabaga" may generate attraction to the Theme role of a *devouring* event, given knowledge about devouring events in general.

2.3.3. Syntactic "fragility"

We propose that lexico-syntactic representations are generally "fragile", such that they are prone to reprocessing, reflected in P600, when they do not integrate with some (at least moderately) plausible event-representation within the semantic stream.[4] Such fragility does not preclude profound lexico-syntactic influences on semantic interpretation. For instance, lexico-syntactic cues drive very different semantic interpretations of "The thief recognized the cop" and "The cop recognized the thief". Here, "thief" and "cop" are each plausible as Agent and Theme for "recognized", and syntactic analysis determines which interpretation emerges. However,

[2] Carlson and Tanenhaus (1988) propose that recognition of a verb includes the selection of a single thematic grid, which represents the number and type of thematic roles assigned by the verb. For instance a grid characterized by {Agent, Theme} would assign an Agent and Theme (e.g., "the boy ate the apple" or "the apple was eaten by the boy"), while {Theme} would assign only a Theme role (e.g., "this book reads well").

[3] In some models, 'independence' is used to mean that a given processing system is free from influence by another system, for instance in models of sentence comprehension that posit that syntactic analysis is temporarily free from influence by semantic constraints (e.g., Frazier, 1987). Here we take independence to mean that two or more systems compute distinct representations, and that neither is completely determined by the other. The distinct representations of these systems are correlated, and the two systems can interact constantly, with each providing constraints that influence the other. Central to our claim is the idea that semantic processing operates to a certain extent without being controlled by syntactic analysis; this does not mean that semantic processing is immune from influence by syntactic processing.

[4] Ferreira, Bailey, and Ferraro (2002) have also described syntactic representations as fragile, with a related but somewhat different interpretation, in which syntactic representations decay rapidly (Sachs, 1967) without reinforcement from semantic representations.

when lexico-syntactic analyses directly conflict with semantic processing (e.g., “The meal was devouring ... ”), lexico-syntactic analyses will often undergo reprocessing, manifest in P600.[5]

Several factors may modulate the degree of fragility in lexico-syntactic analysis. One factor, explored by the current study, is the nature of the syntactic cues. We suggest that sentence and discourse context may be another factor, which can tax the processing resources required to maintain syntactic representations, rendering syntactic representations vulnerable to alternative analyses. Context-induced fragility might resolve a potential contradiction in the literature. Although we attribute the reduced P600 in our multiple-edit repair condition to the specific syntactic cues involved, Kuperberg et al. (2007) found robust P600 elicited by animacy violations with similar local syntactic cues (e.g., “Every morning at breakfast, the eggs would plant...”). It is possible that the presence of lead-in contexts (e.g., “Every morning at breakfast,”) in Kuperberg’s stimuli engender greater syntactic fragility than simpler sentences, making P600 more likely.[6] Viewed in this way, context potentially affects a number of other semantic P600 findings (e.g., Kolk et al., 2003; Nieuwland & Van Berkum, 2005), and its impact warrants further investigation (see also Kuperberg, 2007; Kuperberg et al., 2007 for discussion of possible context effects on the P600).

2.3.4. Pattern completion may constrain and anticipate thematic role assignments

We further propose here that processing within the semantic stream includes pattern completion of event-representations, which activates plausible but *unmentioned* thematic role assignments (e.g., Hare et al., 2009). Such pattern completion may be another source of syntax-semantics conflicts that generate P600.

Semantic pattern completion might, for example, contribute to Nieuwland and Van Berkum’s (2005) finding of P600 elicited by animacy-violating nouns such as “The woman told the suitcase ...” (stimuli were Dutch), which occurred in a rich discourse about a tourist checking in an overweight suitcase at an airport (“tourist”, “suitcase”, and “woman” are all mentioned in the preceding discourse). The same sentences without context elicited N400, rather than P600 effects (a separate, unpublished study described by Nieuwland & Van Berkum, 2005 for related results, see Sikos & Kim, 2011). The context may drive anticipatory commitment to “tourist” as Goal of “told” and also to “suitcase” as Theme of “lifted”, “weighed”, or “approved” (all are plausible, given the discourse context). Lexico-syntactic analysis contradicts these semantic commitments by signaling that “suitcase” is Goal of “told”, leading to P600. Nieuwland and van Berkum (2005) attribute the absence of an N400 effect in the context-embedded sentences to a “semantic illusion” in which comprehenders anticipate and temporarily perceive “tourist” instead of “suitcase”. We suggest instead that “suitcase” is perceived accurately and that its contextual appropriateness explains the lack of N400 effect. In a similar manner, the lead-in contexts of Kuperberg et al. (2007), although short, may also generate pattern completion effects. A context like “Every morning at breakfast, the eggs would ...” could activate a *breakfast-with-eggs* event-representation, including anticipatory commitments to “eggs” as Theme of events like “eat”, “fry”, or “serve”. Lexico-syntactic analysis contradicts these commitments, by signaling that “eggs” is Agent of “plant”, leading to P600. Other potentially related findings include late positivities elicited by words that are unexpected but plausible, when they occurred in strongly constraining semantic contexts (Federmeier, Wlotko, De Ochoa-Dewald, & Kutas, 2007) and also late positivities elicited by words that are plausible but introduce a new discourse referent, which therefore needs to be integrated into the discourse context (Burkhardt, 2006).

Semantic pattern completion might also help explain P600 effects elicited by anomalies containing only partial semantic attraction. van Herten, Chwilla, and Kolk (2006) report P600 for the Dutch equivalent of “John saw that the elephants the trees pruned ...” (English translation: “John saw that the elephants pruned the trees ...”). Here, there is a semantic attraction between “trees” and “pruned”, but this does not span the entire sentence, and one cannot conclude that the system finds a plausible but ungrammatical interpretation of the entire sentence. Van Herten et al. (2006) conclude that the local attraction supports a “meaningful concept”, which conflicts with syntactic analysis. We propose that this meaningful concept is an event-representation (e.g., *prune-some-trees*), which pattern completes to include a human Agent for the event (e.g., a gardener). This pattern-completed detail contradicts the lexico-syntactic signal that “elephant” is the Agent.

2.4. Conclusions

The current findings contribute to growing evidence that combinatory semantic processing during sentence comprehension operates with substantial independence from, and can sometimes dominate syntactic analysis (e.g., Kim & Osterhout, 2005; Kolk et al., 2003; Kuperberg et al., 2007; Nieuwland & Van Berkum, 2005). Several parallel-streams architectures seem compatible with these findings (Bornkessel-Schlesewsky & Schlesewsky, 2008; Kim & Osterhout, 2005; Kolk & Chwilla, 2007; Kuperberg, 2007; see also Hagoort, 2005). However, existing proposals leave unanswered critical questions about the nature of the processes serving sentence comprehension and the interactions between them.

We propose here that syntactic analyses vary—from fragile to robust—in their ability to resist challenges from semantic processing. The conditions that modulate the robustness of syntactic analyses, including differences in syntactic cues and types of context, need further exploration. Recent work suggests that this robustness may also be modulated by inter-individual differences (Nakano, Saron, & Swaab, 2010) and by cross-linguistic differences in the priority of specific linguistic features (Bornkessel & Schlesewsky, 2006). Further investigation is needed to understand the mechanisms and scope of semantic pattern completion (see also e.g., Hare et al., 2009) and its interactions with syntactic analyses.

Finally, the current and related findings shed light on the functional significance of the P600 but leave much unknown. Kolk and Chwilla (2007) propose that semantic P600 effects reflect a domain-general executive function response, and others have drawn domain-general conclusions about the P600 (e.g., Bornkessel-Schlesewsky et al., in press; Coulson et al., 1998). We find these conclusions plausible but also suggest that in many sentence processing situations, the eliciting conditions of P600 are consistent with reprocessing focused on the lexico-syntactic analysis, while difficulty with semantic access or integration manifests in N400 effects (e.g., Kutas & Federmeier, 2000). N400 and P600 may both reflect domain-general mechanisms, which are selectively recruited by semantic and lexico-syntactic processing difficulty, respectively (see also Osterhout & Hagoort, 1999).

[5] We do not assume that such reprocessing always succeeds in finding an alternative syntactic analysis; only that it attempts to do so.

[6] Bornkessel-Schlesewsky and Schlesewsky (2008) provide an alternative explanation for P600 without N400 seen by Kuperberg et al. (2007). First, the system assumes a passive construction based on the auxiliary “would” and the inanimacy of the subject noun. This assumption generates a prediction for the auxiliary verb “be” following “would”. Given this prediction, the main verb “plant” presents an unexpected category violation, which causes a failure to initiate the “compute linking” operation, leading to P600 effects. This account would seem to incorrectly predict that our multiple-edit repair stimuli would also elicit P600 without N400. However, it is possible that the presence of context modulates the degree of anticipatory commitment to the passive construction.

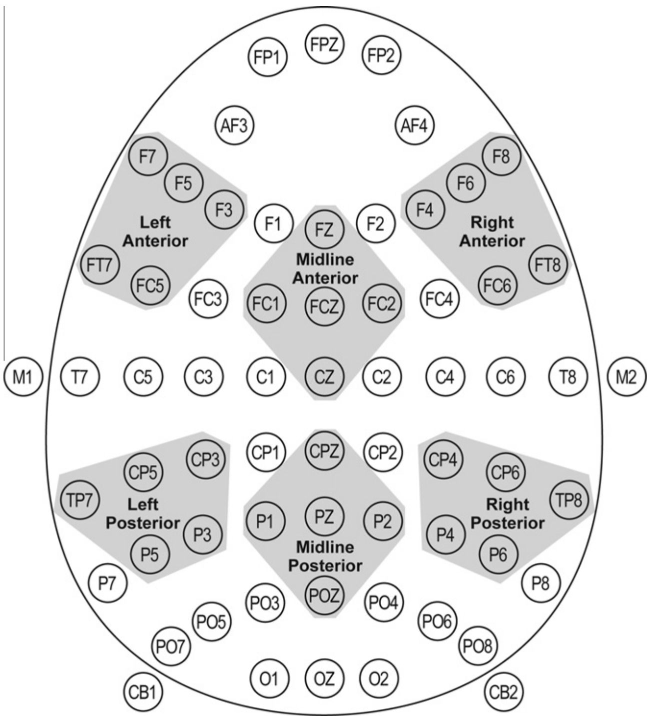

Fig. 3. 64-Channel scalp-electrode array, with gray shading highlighting the six channel-groups used for statistical analysis: left-anterior, left-posterior, right-anterior, right-posterior, midline-anterior, midline-posterior.

2.5. Methods

2.5.1. Participants

Fifty-five students from the University of Colorado at Boulder participated in the experiment for course credit. Fifteen participants were not included in the statistical analyses due to excessive electrophysiological artifacts (nine) or for behavioral response accuracy below an 85% threshold (six). The remaining 40 participants (20 females) ranged in age from 18 to 25 (mean = 20.0 years). All participants were right-handed (eight reported ambidextrous abilities) native English-speakers with normal or corrected-to-normal vision.

2.5.2. Stimuli

Ninety-six stimulus items were created, each in three forms, which were labeled control, single-edit-repair, and multiple-edit-repair (1a–c). Control (1a) and single-edit-repair (1b) sentences were identical to the control and semantic attraction violation conditions from Kim and Osterhout (2005), Experiment 1. Multiple-edit-repair sentences (1c) contained the same content words as single-edit-repair sentences but altered the syntactic cues. In both single-edit-repair and multiple-edit-repair stimuli, the syntactic cues unambiguously signaled an Agent interpretation of the initial noun phrase, which was highly implausible. The noun phrase was highly attractive, however as Theme for the verb. Single-edit-repair stimuli could be repaired to a well-formed and plausible sentence by changing the verb's inflection ('–ing' to '–ed'). Multiple-edit-repair stimuli could also be repaired but required more morphosyntactic changes: adding the verb 'be' and adding the inflection '-ed' to the verb. Each list contained 160 filler sentences. Of these, 16, 16, and 128 were semantically anomalous (e.g., "This old blender doesn't beg ice cubes anymore."), syntactically anomalous (e.g., "The angry driver will honks the horn at pedestrians."), and well-formed and plausible (e.g., "Seattle is famous for its rainy weather and pleasant temperatures."), respectively. Thus, each list contained 256 sentences in total, with 62.5% well-formed and 37.5% anomalous. Stimuli were pseudo-randomly ordered.

2.5.3. Procedure

Participants were tested in a single session lasting about 90 min, including 30 min of experiment preparation. Each participant was randomly assigned to one stimulus list and seated in a comfortable chair in front of a LCD monitor. The participant was instructed to read normally and to try to understand the sentences. Each trial consisted of the following events: A fixation cross appeared in the center of the screen for 650 ms, after which a stimulus sentence appeared one word at a time in the center of the screen. Each word appeared for 500 ms, followed by a 100 ms blank screen. Every sentence was followed by a screen asking participants to determine whether the preceding sentence was a normal sentence of English. This screen remained up until one of two buttons on a button-box ("Yes" or "No") was pressed. Participants used their thumbs to respond, with half the participants using their right thumb to answer "Yes". Behavioral responses were followed by a "Continue?" prompt, appearing on screen until either button was pressed. A random-length blank-screen interval of 500–1000 ms followed each trial.

2.5.4. Data acquisition

Continuous EEG was recorded from 64 sintered Ag/Ag–Cl electrodes embedded in an elastic cap (Neuroscan QuikCaps) arranged according to the extended 10–20 system (Fig. 3). Vertical eye movements and blinks were monitored with two electrodes placed above and below the left eye, and horizontal eye movements were monitored by electrodes placed at the outer canthi of each eye. EEG was also recorded over left and right mastoid sites. EEG was referenced on-line to a vertex electrode and later re-referenced to an average of the left and right mastoid channels. Impedences were maintained below 10 kΩ.

EEG was amplified and digitized at a sampling frequency of 1000 Hz (Neuroscan Systems). After recording, data was down-sampled to 250 Hz and filtered with a bandpass of 0.1–30 Hz. ERPs were averaged off-line within each experimental condition (control, single-edit-repair, multiple-edit-repair) for each subject at each electrode site in epochs spanning −200 to 1000 ms relative to the onset of the target verb. Epochs characterized by eye blinks or excessive muscle artifact were rejected; this led to rejection of 5%, 4%, and 5% of the trials in the control, single-edit-repair, and multiple-edit-repair conditions, respectively.

ERP components of interest were identified based on visual inspection of ERPs and topographic maps, as well as prior findings. Voltages were averaged for analysis within six channel-groups (Fig. 3): left-anterior (F3, F5, F7, FT7, FC5), left posterior (CP3, CP5, P3, P5, TP7), right-anterior (F4, F6, F8, FT8, FC6), right-posterior (CP4, CP6, P4, P6, TP8), midline-anterior (FZ, FC1, FCZ, FC2, CZ), midline-posterior (CPZ, P1, PZ, P2, POZ). For each of these channel-groups, we quantified ERPs for analysis as mean voltages within windows of 300–600 ms (capturing a broad negativity) and 650–900 ms (capturing a broad positivity) after stimulus onset. We also analyzed voltages in 50–150 ms (N1), 150–300 ms (P2) windows to test for experimental effects on earlier components. These dependent measures were analyzed with repeated measures analyses of variance (ANOVA). ANOVAs were conducted separately at midline (midline-posterior and midline-anterior) and lateral (left/right-anterior and left/right-posterior) channel-groups. For the midline analysis, the factors were sentence-type (control, single-edit-repair, multiple-edit-repair) and position (anterior, posterior). For the lateral sites analysis, factors were sentence-type (control, single-edit-repair, multiple-edit-repair) and hemisphere (left, right) and position. The Greenhouse and Geisser (1959) correction for inhomogeneity of variance was applied to all ANOVAs with greater than one degree of freedom in the numerator. In such cases, the corrected p-value is reported.

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