Anatomy of the N400:
Brain electrical activity in propositional semantics

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1.0 Introduction

A key to the advancement of cognitive ERP research will be improved methods for the identification and separation of ERP components — i.e., subsequences of the scalp electrical potential that are assumed to index specific sensory or cognitive processes. While traditional ERP analyses have met with considerable success over the past few decades, leading to well-defined hypotheses about the electrophysiological correlates of distinct cognitive subsystems, e.g., Rugg & Coles (1995), there remain certain ambiguities in interpretation. The present paper is concerned with one such ambiguity, namely, the status of the N400 response to semantic violations vis-à-vis the more generic P300 response to rare or unexpected events.

Prior research, reviewed below, has suggested that the N400 response to sentence-final semantic anomalies may be influenced by latency shifting of the P300 (also “P3,” “P3b,” or late positive complex). The present study examines this hypothesis in more detail. The central method of analysis is visual decomposition of the response to both mid-sentence and sentence-final words, using a 128-channel electrode array to better characterize the spatial distribution of the effect and topographic maps to examine effects over time. In addition, a split-sample statistical verification of all effects is carried out, using repeated measures ANOVA. This descriptive approach is intended to clarify the relationship between sentence-final components, including the end-of-sentence P300/LPC, and the N400 response, by comparison of mid-sentence and sentence-final congruity effects. Further, comparison of mid-sentence and sentence-final words may permit separation of effects due to sentence-final semantic integration from the response to semantic violation per sé.

A primary goal of this study is to begin to address the question of whether the N400 can be attributed to a neurophysiological process that is distinct from the P300/LPC. While it has generally been assumed that the N400 is a distinct component, unique to the domain of semantic expectancy, prior analyses have not sufficiently addressed another plausible theory, namely, that the difference in response to appropriate and inappropriate sentence endings could be related to differences in timing and within-subject variability of the P300/LPC. Because the present study is primarily descriptive, the latency-shifting hypothesis is not tested directly, although present analyses are suggestive. A secondary goal, then, is to point to the need for more advanced ERP analysis techniques that can examine this hypothesis more directly.

The N400/P300 question is in one sense domain-specific, having direct implications for theories of semantic processing. The hope, however, is that the general methodological nature of the problem can be abstracted away from this specific domain of application, and that the proposed strategies for addressing the core analysis issues will be of more general interest to researchers in cognitive electrophysiology.

2.0 Background

The N400 effect

The discovery of the N400 response to unexpected words was itself unexpected (Kutas & Hillyard, 1980a; Kutas & Hillyard, 1980b). Prior research had shown that a mid-latency positive component, known as the P300 or P3b, was enhanced to rare or deviant events (Duncan-Johnson & Donchin, 1977; Squires, Squires, & Hillyard, 1975). Kutas and Hillyard (1980a) therefore reasoned that a deviant sentence ending should generate an analogous effect, possibly differing in latency or morphology from the classical P300/P3b. In their original experiment, the terminal word of a sentence was either semantically appropriate (congruous) or inappropriate (incongruous). Subjects viewed a sequence of words on a screen, presented one at a time, and responded with a button press whether the resulting sentence was meaningful, or not. During the task, electrical potentials (ERPs) were recorded from the scalp, using a 10–20 electrode array, with mastoid reference.

Surprisingly, rather than an enhanced positivity in the incongruous condition, Kutas and Hillyard observed what appeared to be an altogether different effect, a negative-going deflection peaking around 400ms after onset of the unexpected terminal word (the “N400”). Figure 1 shows an example of the typical (grand-averaged) response to congruous and incongruous endings. The dark line indicates an averaged response to a normal ending, such as "I take my coffee with milk and cream," while the pale line indicates the response to an anomalous ending, e.g., "I take my coffee with milk and feet." Note that it is the difference (incongruous minus congruous) that constitutes the N400 effect, although the term “N400 component” is often used to refer to the negative deflection observed in single channel waveplots.

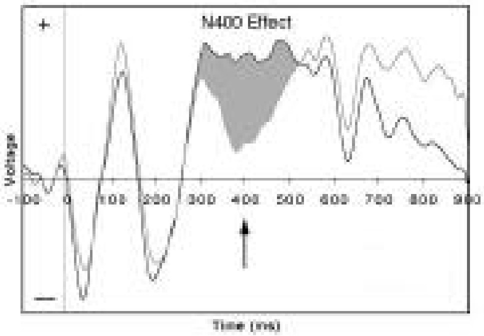


Figure 1. N400 effect to terminal words in a sentence. Averaged data from present study (57 subjects) at right parietal P4 (86). In this and all subsequent waveplots, positive is plotted up. Word offset at 450ms.

A large body of research has replicated this effect and extended the initial findings to different modalities (Anderson & Holcomb, 1995; Besson & Macar, 1986; Holcomb, Coffey, & Neville, 1992) and different linguistic contexts, including word pairs and larger discourse contexts, as well as sentences (Bentin, 1987; Chung et al., 1996; Van Burkum, Hagoort, & Brown, 1999; Weisbrod et al., 1999).

Functionally, the N400 has proven a sensitive measure of cognitive state, responding systematically in amplitude, latency, and topographic distribution to a variety of psycholinguistic manipulations. For example, N400 amplitude has been shown to vary inversely with degree of semantic relatedness, or priming, regardless of congruence (Holcomb & Neville, 1991; Kutas, Lindamood, & Hillyard, 1984), as evidenced by decreased amplitude of the N400 to a word that is incongruous with respect to the sentence context, but semantically associated with (primed by) the immediately preceding word (e.g., *snow* in the sentence “I like my cereal with cold *snow*“). Another important finding is that N400 amplitude is tightly (inversely) correlated with cloze probability, a measure of expectancy for a word in a particular sentential context (Kutas & Hillyard, 1984). As expectancy for a congruous sentence-final word is increased, N400 amplitude shows a corresponding linear decrease in amplitude. These results imply that semantic anomaly is neither necessary nor sufficient to elicit an N400. Rather, the N400 appears to reflect degree of *expectancy* for a word, as a function of prior (explicit or implicit) context.

Prior studies have reported distinct patterns of response (P300, N200, N250, etc.) during nonlinguistic and linguistic, but nonsemantic (e.g., grammatical) tasks (Kutas & Hillyard, 1983; Neville, 1991; Neville, 1985), suggesting that the N400 may be an index of *semantic expectancy*, in particular, rather than expectancy in general. N400 amplitude has further been correlated with word length, frequency, concreteness, and familiarity (Dien, Frishkoff, & Tucker, 2000; Van Petten, 1993; van Petten, 1995; Van Petten & Kutas, 1990), indicating that the N400 may be language-specific, in contrast with other cognitive potentials, such as the P300/LPC. In sum, prior research suggests that the N400 exhibits a high degree of functional specificity.

The N2 hypothesis

In spite of the robustness and functional specificity of the N400, several researchers have attempted to show that the N400 effect may be due to subtle shifts in timing or morphology of other components, which have been linked to violations of expectancy outside the linguistic domain. For example, Polich (1985) proposed that the N400 could be a latency-shifted (delayed) N2. The N2 is a negative component with an mid-anterior distribution that, like the P300, is sensitive to violations of expectancy. The largest effects are evoked with an oddball paradigm, using low-frequency targets (Naatanen & Gaillard, 1983). The N2 and P300 often appear together, although they can be dissociated (Polich, Vanasse, & Donchin, 1980).

The hypothesis that the N400 is really a delayed N2 is consistent with the longer response times to semantically anomalous words, e.g., in a lexical decision task (Kleiman, 1980); cf. current results. An immediate difficulty with this hypothesis, however, is that the N2 has a more focal, frontal distribution than the diffuse, centroparietal N400. Thus, it has been disputed whether the distributions of the N400 and N2 are sufficiently close to regard them as scalp projections of the same neural source. Although at least one study claimed to find no significant differences in topography of the N2 and N400 components (Deacon, Breton, Ritter, & Vaughan, 1991), the low spatial density in this study (8 electrodes) makes it difficult to evaluate this claim. Moreover, Connolly et al. reported a significant difference in topography of the N2 and N400, using only 5 electrodes (Connolly, Stewart, & Phillips, 1990). The N2 in this study was more anterior and more medial than the N400 response, consistent with previous findings. Further, Connolly's study, the N2 and N400 negativities were found to co-occur, which would be impossible if they were the same component (unless the N2 were evoked twice, e.g., once to a nonlinguistic violation of expectancy and a second time to the linguistic violation, a possibility that was acknowledged in this report).

Other studies attempted, with mixed results, to separate the N2 and N400 functionally by showing differential sensitivities to cognitive manipulations. For example, while the amplitude of the N2 is sensitive to stimulus probability (frequency of unexpected targets), some researchers claimed that N400 amplitude was insensitive to differences in ratio of congruous to incongruous trials (Kutas et al., 1984). Holcomb (Holcomb, 1988), however, reported that the difference in response (N400 effect) to words in a lexical prime-target context is enhanced when the proportion of related to unrelated prime–target pairs is high (67%), as opposed to when it is low (17%), a finding that is roughly consistent with the sensitivity of N2 to relatedness proportion (Breton, Ritter, Simson, & Vaughan, 1988). Because high relatedness proportions tend to induce strategic (attentional) processing, some researchers have interpreted this to suggest that the N400, like the N2, may be due in part to controlled (attentional), as well as automatic, priming.

In spite of such inconsistencies in the literature, the N2/N400 debate has largely been put to rest, due in large measure to positive (as opposed to negative) results that have argued for both cognitive and electrophysiological separation of the N2 and N400. Most researchers now agree that the N400 is a distinct component, unique to the domain of semantic expectancy. The sorts of arguments advanced for or against the N2 hypothesis nonetheless illustrate that superficial similarities or differences between components are by themselves insufficient to determine whether they are linked to the same or different underlying neurophysiological processes.

The Latency-shifting P300 hypothesis

A different kind of N400 hypothesis was proposed by Curran and associates (Curran, Tucker, Kutas, & Posner, 1993). In this first dense-array (64-channel) study of the N400, animated scalp topography was used to track dynamic changes through time in the scalp distribution of the response to sentence-final semantic anomalies. The following figure from this study shows the response to congruous and incongruous sentence endings 408, 464, and 584 ms after word onset. Lighter colors indicate positivity with respect to baseline (baseline is in pink), and darker colors indicate negativity.

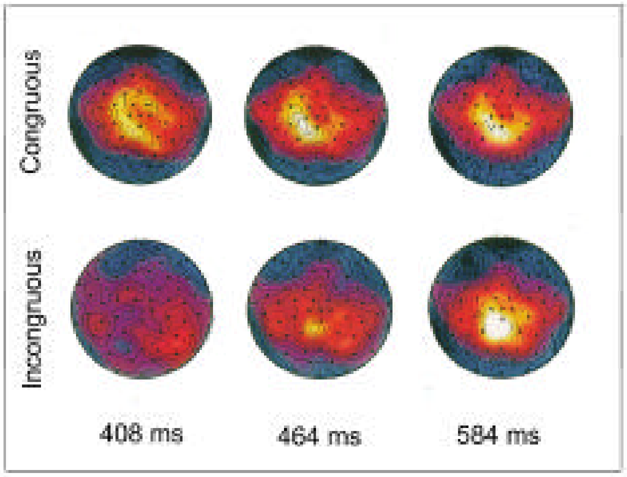
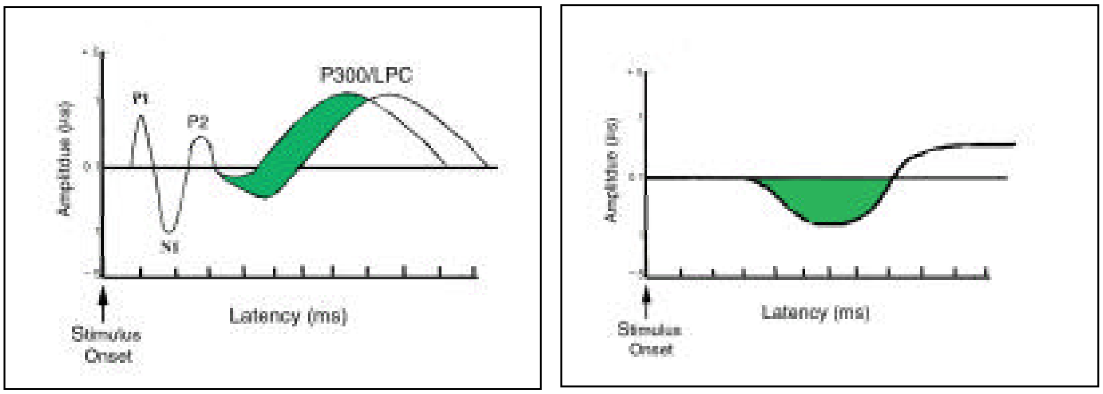


Figure 2. Topographic maps of 64-channel data shown at 408, 464, and 584 ms. From Curran, et al., 1993

The temporal dynamics of the response (Fig. 2) gave an important clue to the nature of the N400 effect. A broad centro-parietal positivity (the P300/LPC) was observed between 360 and 600 ms in the congruous condition. During this same epoch, the response to the incongruous word was comparatively “flat” — i.e., there was no net positivity or negativity anywhere on the scalp. At around 580ms the same broad positivity emerged in the incongruous condition, while the P300/LPC to the congruous word was beginning to fade. On the bases of these spatiotemporal patterns, Curran et al. concluded that the P300/LPC response was latency-shifted, or delayed, to the incongruous word, perhaps reflecting the longer time to resolve the semantics of the unexpected, anomalous word with respect to the preceding context. They further proposed that latency-shifting of the P300/LPC could account for some or all of the difference in response to congruous and incongruous words at 400ms. Figures 3a and b below illustrate this hypothesis. Let condition 1 be the response to the appropriate sentence ending, and condition 2 be the response to the inappropriate ending. When condition 1 is subtracted from condition 2, a relative negativity results (shown by the green shaded area under between the curves). This simplified model shows how latency-shifting of a positive component can give rise to a negativity in the difference wave (Figure 3b).



Figures 3a, b. Hypothetical model of how latency-shifted positivity can produce an apparent negativity (subtraction of condition 1 from condition 2). Difference wave shown in b (left-hand frame).

In support of the latency shifting P300/LPC (henceforth, “LSP”) hypothesis, Curran et al. appealed to the nondistinct morphology of the response to incongruity (Fig. 2) as evidence for the *lack of a P300 response*, rather than the presence of a distinct, negative (N400) response. In the most extreme case, they suggested that in so far as scalp topography is suggestive of neural organization, the N400 and P300 could be generated by one and the same neural source. However, the use of voltage maps to support a given component structure, is not by itself, conclusive, since superposition of the underlying components renders scalp topography inherently ambiguous. In this regard, the topographic argument should probably be viewed as an argument for the plausibility of the LSP hypothesis, rather than as direct support. In fact, on closer inspection, there appear to be two plausible interpretations of the data. In addition to the author’s interpretation, the spatial distribution of the response to incongruous words may reflect a superposition of multiple components (e.g., an N400 negativity superposed on the early P300 positivity), which cancel out, leaving the putatively “flat” distribution that was observed in the topographic maps (Fig. 2). This ambiguity in the scalp response underscores the need for more refined methods of analysis.

Despite inherent ambiguities in the scalp data, the LSP proposal received support from the application of other analytic techniques to these same data, as well as to independent samples evoked with the same or similar experimental paradigms. For example, single-trial analysis, using Woody filters (Woody, 1967), showed that single-trial P300s peaked later and were more variable in the incongruous condition (Chung et al., 1996). In addition, principal components analysis (PCA) of the N400 data PCA failed to extract a distinct N400 factor, but revealed a P300 factor that accounted for almost all of the variance due to congruousness (Dien, 1998a).

Objections to the LSP Hypothesis

An objection could be raised that the N400 and P300 were effectively dissociated in an early study by Kutas and Hillyard (Kutas & Hillyard, 1980c). This study compared the response to two types of violations: physical (the last word of a sentence appeared in large print) versus semantic (the last word of the sentence was semantically inappropriate). In the context of physical deviations, most subjects showed an enhanced P300/LPC, whereas semantic deviations elicited an enhanced negativity relative to semantically appropriate endings. However, while this study may appear to support a “double dissociation” between the N400 and P300 components, it does not effectively address the hypothesis that the N400 effect to the incongruous words could be due to condition differences in the nature of the P300/LPC. In particular, it does not circumvent effects of latency jitter (variability) in the averaged data, or the possibility of spurious effects in the difference wave due to latency shifting of the late positive component (cf. Fig. 3b). In the case of latency jitter, it is conceivable that detection of physical anomalies (i.e., the oddball uppercase task) requires less effort than the semantic task, resulting in minimal variability across trials (or across conditions). In this case, the lack of an N400 effect in the physical anomaly condition could be explained by lack of P300 latency variability. This account is purely speculative, but suggests that the comparison of responses to physical and semantic anomalies, by itself, is not sufficient invalidate the LSP hypothesis.

More critically, the latency shifting hypothesis should accommodate the reported absence of the late positivity following the N400 deflection in mid-sentence contexts (Kutas & Hillyard, 1983) and single word contexts (Bentin, 1987). There is also some indication that the late positivity is absent or reduced following the N400 when there is no overt response (Fischler, Childers, Achariyapaopan, & Perry, 1985), although in the one published 128-channel study of the N400, there was a following positivity, even though no overt response was required (Johnson & Hamm, 2000). Clearly, the lack of a positivity following the N400 would make latency shifting of the P300/LPC untenable as the sole explanation for the N400 effect. An additional problem for the latency shifting hypothesis could be the finding that N400 amplitude varies continuously (inversely) with cloze probability of a word in sentence-final context. It is not clear how this could be explained by latency shifting of the P300. These are important issues that need to be further examined in regard to the latency-shifting P300 hypothesis.

Implications for a neuropsychological theory of expectancy

Functionally, it is plausible that the response to semantic deviants (the N400) could be related to a generic process for detection of unexpected or rare events (the P300/P3b). A well-conditioned response for detection of rare events has obvious adaptive significance. On the other hand, rather than a single dedicated mismatch-detection process, it seems equally possible that there are multiple, domain-specific processes for detecting and responding to deviations from expectancy. Indeed, the past several decades of cognitive neuroscience research have demonstrated a strong tendency towards localization of function. Improved neuropsychological methods, including bloodflow (fMRI) and ERP methods, as well as recent breakthroughs in animal research, have revealed an impressive degree of functional–anatomic specificity in both sensory and cognitive processing. In language-related ERP research, distinct linguistic subsystems appear to be paralleled by complex differentiations of neurological response seen as distinct ERP components, including a left anterior negativity (LAN) and late positive (P600) response to syntactic violations, in addition to the N400 effect (Munte, Szentkuti, Wieringa, Matzke, & Johannes, 1997; Neville, 1991; Osterhout, 1997). This suggests that the different types of linguistic violations can be mapped to different neurological subsystems, using electrophysiology as a guide.

To summarize, there are two current hypotheses relating the scalp electrical N400 data to models of cognitive neurological function. The first, and most widely held, view is that the N400 is a unique component of the ERP, reflecting a dedicated neurological process for tracking degree of semantic expectancy. The second hypothesis is that the sentence-final N400 is due in whole or in part to latency-shifting of the P300/LPC response to rare or unexpected stimuli. Given that the P300/LPC is not language-specific, this second hypothesis raises the possibility that semantic processing (in at least some contexts) may involve a more domain-general set of cognitive neuropsychological processes. To help address this issue, the present report makes use of recent improvements in methods for characterizing the scalp topography of ERPs. In addition, sentence-position of the target words was manipulated to examine the relationship between the N400 and end-of-sentence processes, particularly the late P300/LPC. While we can't hope to resolve the complex relationship between semantics and expectancy processes in a single study, directly addressing problems of component identification and separation in the N400 paradigm can only clarify future attempts to unpack this richly complex effect.

Methodological Issues

Improved characterization of the N400 effect requires that we address certain methodological issues. Because a central issue is that of ERP component identification and separation, and because ERP components are defined by a cluster of physical and functional properties (Rugg & Coles, 1995), both spatiotemporal and functional (cognitive experimental) manipulations are key. Showing differential sensitivities to cognitive manipulations is one means of separating components. However, establishing that two responses are the “same” or “different” under different experimental conditions is not trivial. For example, prior studies of the relationship between the N2, P300 and N400 effects, although not conclusive, suggest that experimental manipulations may be insufficient to establish the relation between two putatively distinct responses. This suggests the need for better characterization of ERP scalp topography, in addition to improved cognitive–linguistic manipulations. For this reason, the present study focuses on spatiotemporal properties of the N400, as characterized using high-density, reference-independent measures. Our belief is that improved characterization of the electrophysiological properties of the N400 will provide a good basis for future cognitive experimental manipulations.

Animated topography of the ERP provides one means of constraining hypotheses about component structure. It is a fairly recent method made possible by advancements in dense-array, reference-independent measures of scalp electrical activity (Tucker, Liotti, Potts, Russell, & Posner, 1994). Although ERPs are often touted for their fine temporal resolution, the usual focus on static effects (e.g., peak amplitude across a single time interval) fails to exploit the full potential of scalp electrical measures for uncoupling dynamic overlapping effects through time. By contrast, animated topography permits visual decomposition of the ERP response, revealing correlated effects across both space and time — a kind of superficial latent factor analysis. Although ambiguities remain due to the spatial and temporal overlap of ERP components, dipole effects can often be seen clearly in the animated maps. In addition, the temporal coherence of multiple effects may point to a particular component structure. In this way it is possible to peel away layers of the response, revealing more transparent relations between underlying components of the ERP.

The analytic techniques in this study are primarily descriptive and should be viewed as precursors to more advanced methods, such as factor analysis (PCA, SVD) and trilinear decomposition to characterize the major spatial and temporal components of the response. In fact, it is likely that such methods will be required to provide conclusive support for a particular component structure.

Present Study

The present study was designed to examine the effects of both sentence position and congruousness of the target word on the timing and spatial distribution of the ERP response. In addition, a new stimulus set was constructed to address some shortcomings of prior stimulus sets and to characterize more precisely the notion of “semantic anomaly” in terms of formal semantic relations between arguments of the propositions encoded by different sentence structures.

Subjects

Seventy-eight subjects were recruited from several introductory courses in Psychology at the University of Oregon. All subjects were native English speakers and right-handed. The average age was 20 years (standard deviation = 5); 54 women and 24 men participated. Academic course credit was given in exchange for participation.

Experimental Design

The stimuli consisted of 360 English sentences, half of which contained a semantic anomaly and half of which were perfectly normal English sentences.

For this experiment, a "semantic anomaly" was defined as a combination of words in which the semantic characteristics of one word are logically inconsistent with those of another word. More precisely, a *semantic incongruity* is a sentence for which a propositional argument, denoted by a noun or noun phrase, cannot be meaningfully combined with the predicate, denoted by a verb or adjective. For example, “The stone eats (ate, is eating)” is strictly semantically incongruous, because the verb “eat” cannot take an inanimate object as its argument (we say that such a verb *subcategorizes* for a particular set of noun phrases).[1] Strictly speaking, any sentence containing such an anomaly is "meaningless" in the sense that it cannot be true or false on any interpretation. This definition contrasts with a more liberal definition, in which any departure from normal (pragmatic) expectations counts as a semantic incongruity. For an intuitive sense of this distinction, consider the following sentence pair:

(1) Mary spotted a *striped orange* under the children's bed.
(2) Mary spotted a *tangled orange* under the children's bed.

Sentence (1) is odd, because oranges are not usually striped. On the other hand, an orange could be striped; e.g., it is easy to imagine a toy orange that is striped (perhaps the children drew the stripes on it with crayons). By contrast, a “tangled orange” (sentence (2)) is uninterpretable: oranges aren’t the kind of thing that can be tangled, because they are round, solid objects, not long stringy ones. Thus, the first sentence is pragmatically odd, while the second is semantically incongruous.

The semantic—pragmatic distinction can be more precisely characterized in terms of predicate logic, a formalism that is commonly used to represent “deep-level,” “underlying,” or propositional semantics. In natural language, verbs and adjectives are used to denote concepts that function as predicates. The verb “eat” denotes the concept EAT, which is similar to a predicate in that it represents an action or event that is participated in or performed by someone or something (the argument): e.g., EAT(MARY) is the proposition (predicate—argument structure) denoted by the English sentence “Mary eats (ate, is eating).” *A congruous sentence*, in this framework, is one in which the corresponding proposition is “well-formed,” in particular, where the argument (‘MARY’) belongs to the class of objects that can be meaningfully combined with the predicate (‘EAT). A sentence that is congruous can be assigned a truth-value, according to whether the proposition is observed to correspond to a real state of affairs (‘is true’) or not (‘is false’). A *semantic incongruity* is a sentence for which the underlying argument (denoted by the noun or noun phrase) cannot be meaningfully combined with the predicate

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[1] There are well-known objections to this way of representing natural language semantics in general (Lakoff, 1987). The predicate—argument structure metaphor is nonetheless useful in the present, restricted context, because it helps account for an important part of natural language semantics, namely, the role of semantic features in sentence-level (propositional) semantics.

(denoted by the verb or adjective). For example, “The stone eats (ate, is eating)” is logically or semantically incongruous, because EAT cannot take an inanimate object as its argument.[2] Accordingly, this sentence cannot be either true or false, since it is technically meaningless.

Adjectives have a semantic function similar to that of verbs and can be likewise be predicated of nominal concepts. In the previous examples —(1) and (2) above — STRIPED(ORANGE) is the proposition denoted by the adjective—noun phrase “striped orange”; it is congruous, because there is no feature of the concept ORANGE that is inconsistent with the feature of BEING STRIPED. The fact that it is unusual for oranges to be striped or even that no orange has ever been observed to be striped does not render the proposition meaningless; the sentence is therefore pragmatically odd or improbable, but not semantically incongruous. By contrast, the SOLIDNESS feature of ORANGE is incompatible with BEING TANGLED. Therefore, the adjective—noun phrase “tangled orange” is semantically incongruous in the narrow sense.

Most, if not all, prior N400 sentence studies have included sentences that are pragmatically implausible (to varying degrees), rather than strictly semantically anomalous, in the above sense. It is therefore impossible, using these stimuli, to disentangle the effects of semantic violation and pragmatic implausibility and, consequently, to determine the effects of real-world (pragmatic) information during semantic processing. This linguistic distinction may be irrelevant to basic mechanisms of semantic processing, or it may be the case that the distinction is one of degree (as suggested by the graded relation between N400 amplitude and cloze probability), rather than a categorical difference reflected in distinct electrophysiological patterns.

To control for the influence of varying degrees of semantic cohesion, and to optimize the semantic constraints on the N400, we constructed sentences that were semantically ill-formed at the phrase (rather than sentence) level. This led us to specify three types of phrase structures that transparently encode the propositional semantic relations (predicate–argument structures) that give rise to semantically wellformed (congruous) or illformed (incongruous) sentences. These three structures are adjective plus noun, subject plus verb, and verb plus object. In these phrase

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semantic structures, adjective and verbs both act as semantic predicates, imposing semantic constraints on their arguments (nouns or noun phrases).

This stricter definition encouraged us to formulate a stimulus set that was tightly controlled in terms of the structural semantic context for the N400 response, rather than treating grammatical structure as a “random variable.” Sentences were also constructed to satisfy several structural semantic criteria. Each incongruous sentence contained only one semantic anomaly, and all sentences were syntactically well-formed. Lexical ambiguities, word repetitions, and word combinations that could be interpreted idiomatically or metaphorically were avoided as much as possible.

To address the contribution of sentence-final components to the N400 effect, we also included both mid-sentence and sentence-final targets. Thus, each sentence fell into one of three structural categories, defined by the grammatical structure of the anomalous word combination (adjective plus noun, subject plus verb, and verb plus object), and every sentence was classified according to the position of the target (“anomalous”) word (mid-sentence or sentence-final). This resulted in 12 experimental conditions in all.

In each sentence, the second word in the anomalous word combination was designated as the target "anomalous" word, that is, the earliest point in the sentence where a reader could detect the incongruity. However, we emphasize that anomalousness is a relational concept; that is, semantic incongruity is determined by the relationship between two or more words, in the manner described above, rather than being defined as a single word that doesn't fit the global sentential context.

Procedure

Subjects performed a semantic judgment task while seated inside a sound-attenuated room at a distance of approximately 60 cm from the computer monitor. Word stimuli subtended a visual angle of approximately .955 degrees. On each trial, a fixation point ('+' symbol) appeared for 500 ms, followed by a sentence, presented one word at a time. Each word was presented for 450 ms, and the inter-word interval was 150 ms. The last word in each sentence was marked with a period. Subjects were instructed to make their response as soon as the last word in a sentence disappeared from the screen; after the subject's response, there was a 1000 ms wait before the next trial. To minimize eye and movement artifacts, subjects were asked to move their head and jaw as little as possible and to blink only after they made their response.[3]

Each session began with a 1-minute recording of resting EEG, followed by 15 practice trials. For the main part of the experiment, stimuli were presented in 6 blocks of 60 sentences, randomized over all conditions. The response key for 'yes' judgments was counterbalanced across subjects. The stimuli were Helvetica font, 26 (dots per inch) white letters, presented on a black background. All letters were lowercase, except for the first letter of the initial word of each sentence.

Data Acquisition & Preprocessing

ERPs were recorded using a 129-channel electrode array, with vertex recording reference (Tucker, 1993b). Figure 4 shows the channel configurations, with the international 10-20 electrode sites overlayed for comparison with conventional recording arrays.

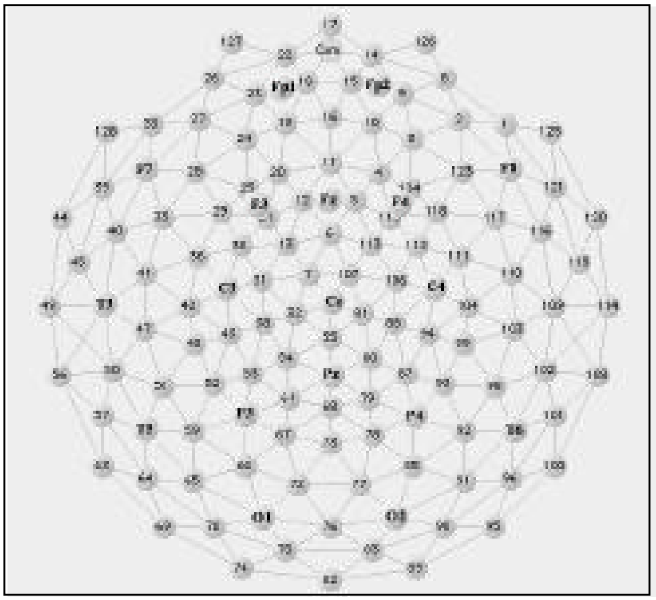

Figure 4. 128-channel electrode array. International 10–20 sites shown in bold. Note that some of these locations fall in between channels on the 128-channel map.

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[3] Pilot data from 13 subjects indicated that without instructions about when to blink, subjects overwhelmingly tended to blink during the the last word of the sentence, resulting in unequal numbers of good trials between mid-sentence and sentence-final conditions, after rejection of blink artifacts. For this reason, we gave all subjects in the actual experiment explicit instructions to hold their blinks until after they made their response. This modification avoided unequal n's between the four cells.

In addition to high-density spatial sampling, the 128-channel net provides data well below (inferior to) conventional recording sites (Fig. 5). Improved sampling of the inferior surface proved critical in characterizing the component structure of the ERPs in the present dataset.

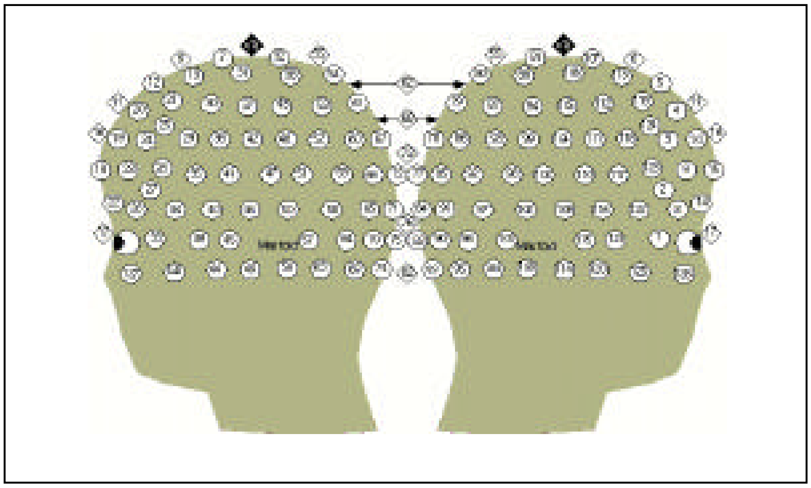

Figure 5. Approximate locations of 128-channel array on the scalp surface. "VR" is vertex reference. EOG channels are 126 (right) and 127 (left). Channel 17 is the common reference. Mastoid channels are 57 (left) and 101 (right).

Data were sampled at a rate of 250 per second (every 4 ms) and were amplified with a .1-hz highpass filter.[4] Trials were edited online for eye blinks and head movements. The remaining trials were segmented into 1-second epochs, starting 100 ms before onset of the target word and terminating 900 ms after onset. Segmented data were averaged across trials (within subjects and within condition) and digitally filtered with a 40-Hz lowpass filter. After further channel and subject exclusion (see below), bad channels were interpolated.[5] The data were then baseline corrected, using the average of the 100ms pre-stimulus epoch, and re-referenced to either the average of the mastoids or the average of the 128 recording sites, using EGIS tools (Tucker et al., 1994). Trial-averaged data were subjected to statistical analysis of variance (Section 6). Finally, the ERPs were averaged across subjects, and the resulting grand average was used for waveform and topographic visualization.

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[4] With NetAmps (ä EGI), a .1Hz highpass analogue filter is equivalent to a 1 second time constant. Although Donchin and Duncan-Johnson (Duncan-Johnson & Donchin, 1979) showed that a 1 second time constant slightly attenuates the P300 wave, we believe it is unlikely to affect the N400, which is a fairly focal event. A current study (n=24) is testing this directly, using a within-subjects design in which half of the sentences are recorded at .1Hz (1 second), and half at .01Hz (10 seconds).

[5] The total percentage of data interpolated was less than .5%.

Reaction times were measured from the offset of the final word in each sentence. Responses slower than 1500 ms or initiated before sentence offset were not recorded. In addition, each response was coded as “correct,” “incorrect” or “non-response.” Only correct responses entered into final analyses.

Subject & Channel Exclusion Criteria

Multiple criteria were used for channel and subject rejection with the aim of mimimizing electrophysiological artifacts and maximizing homogeneity of the resulting dataset. To this end, thirteen subjects were rejected for either low trial counts (70% or fewer good trials out of a total of 350) or poor quality EEG due to excessive artifacts (blinks, head movements). Another five subjects were excluded due to uneven cell counts or because there were fewer than 15 good trials in two or more cells. After applying these criteria, 60 subjects remained.

Errors and Nonresponses

The mean error rate across the 60 subjects was 7% (s.d.=9%), and the average number of nonresponses was also 7% (s.d.=3%). Waveforms for all responses and correct responses only were compared, and no differences were noted. Therefore, only correct responses were included in subsequent analyses. Three subjects had more than 10% errors or nonresponses, and their data were excluded from further analyses, leaving a total (final n) of 57 subjects.

Behavioral results

Response time

As expected, reaction times to incongruous words were longer than to congruous words, F(1, 56) = 22.12, $p<.001$. Interestingly, the cost in RT for incongruous targets was reflected in both the final and nonfinal conditions, although the difference was stronger for terminal words, Congruousness*position F(1, 56) = 9.52, $p<.01$ (congruousness*position). Given that the cost due to mismatch detection occurs very rapidly, it is surprising to see this cost reflected in reaction times to nonterminal words at the end of the sentence. One explanation could be that the evaluation triggered retrieval of the mid-sentence target, and this retrieval took longer for the incongruous than for the congruous word. By comparison, for terminal words, the delay in reaction time may be due to increased time to search for a valid sentence interpretation.

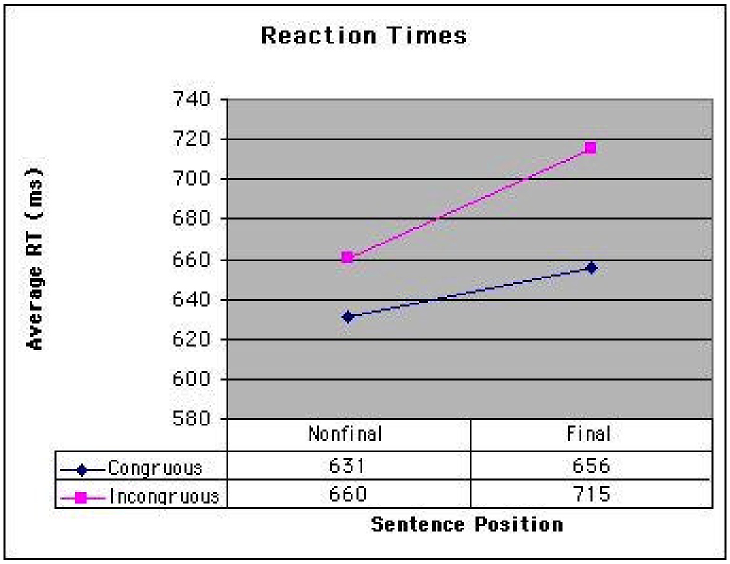


Figure 6. Reaction times to evaluate congruity or incongruity of the sentence. Responses were always initiated after offset of final word.

We assume that the RT effect is an index of increased time to process the incongruous word with respect to prior context. Several studies have shown a positive correlation between P300 latency and response time (Donchin & Coles, 1988; Duncan-Johnson, 1981; Kutas, McCarthy, & Donchin, 1977), so this effect also seems consistent with the LSP hypothesis, suggesting that the delayed P300/LPC could reflect greater effort to access or resolve the semantics of the incongruous word, particularly at the end of the sentence.

5.0 ERP Data

Both averaged mastoid-referenced and average referenced waveplots were examined for replication of sentence-final effects reported in prior studies, as well as for differences due to referencing bias (Curran et al., 1993; Dien, 1998b).

To provide a spatiotemporal framework for mid-latency experimental effects, this section begins with a description of the early stages of the ERP, for which congruousness of the target word was a nonsignificant (or not a reliably significant) factor, when we performed analyses of effects, using repeated-measures analysis of variance to quantify the effects for each major time interval (Section 6.0). Condition effects are then described for data re-referenced either to the average of the two mastoids (channels 57 and 101) or to the average over all 128 channels (the “average reference”).

Early perceptual processing of language

For ease of illustration, early ERP events are displayed dynamic maps of electrical field potentials (Fig. 7), created using linear splines of the 128-channel average-referenced data onto a two-dimensional surface. The average-reference of a 128-channel dataset provides an adequate approximation of the zero surface integral (Tucker, 1993b; Tucker et al., 1994), making this reference an appropriate choice for visualizing the topography of the components over time.

In all four experimental conditions, the first major feature of the waveform is a right-lateralized posterior P1, beginning around 100ms and peaking at 125 ms after word onset. The P1 is followed by a strongly left-lateralized inferior temporal negativity ("early N1"), beginning at around 160 ms. Left-lateralization of the N1 in response to language stimuli has been observed in prior studies (e.g., Neville, Kutas, Chesney, & Schmidt, 1986), and may be related to handedness and/or ease of visual language processing (Brunswick & Rippon, 1994). The early N1 negativity increases and expands to become a more broadly distributed posterior N1, with bilateral foci at temporo-occipital sites. Simultaneously, a broad, bilateral P2 negativity develops over frontal sites, creating an “N1/P2 complex” that peaks around 204ms. Next, the N1 evolves into a focal negativity at the left temporal lobe and then appears to “migrate” along the temporal lobe, terminating with a pronounced left temporal negativity at around 268 ms.

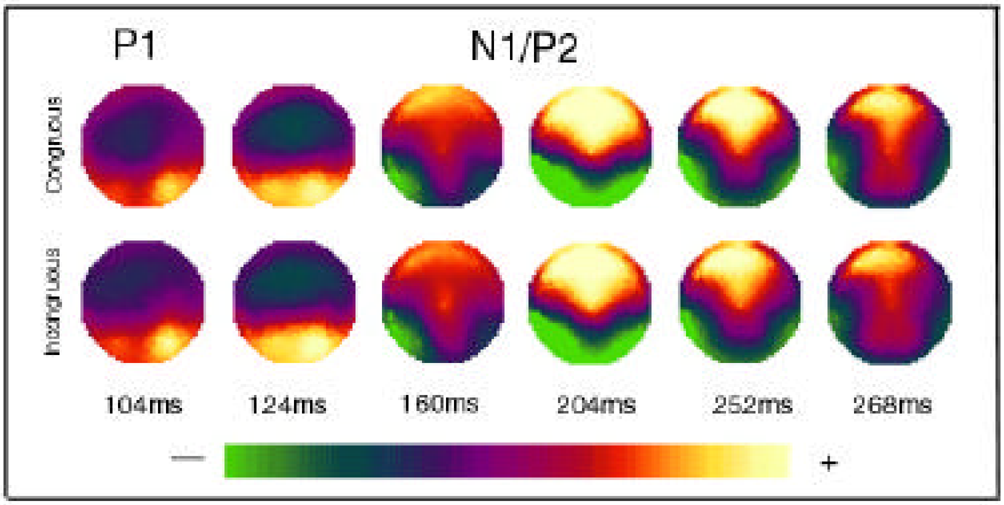


Figure 7. Early ERP events, common to all conditions.

Concurrent with the development of the left temporal negativity, the P2 frontal positivity progresses down the center of the scalp to become a focal parieto-occipital positivity (the "P1r" or "P1 reprise") with a distribution similar to the P1, but more anterior and more bilateral. Note that the P1r is more pronounced in later intervals, with onset of the N400 effect (e.g., Figure 12).

Mastoid-referenced data

Figure 8 shows a 1-second response to congruous and incongruous sentence-final words, re-referenced to the average of the two mastoids (channels 57 and 101).

A prominent feature of the mastoid plots is the attenuation of the waveforms at posterior sites, particularly in the inferior temporal and occipital regions, and enhancement of the anterior positivity, particularly for the early N1/P2 epoch. Consistent with this interpretation, inspection of the average reference data indicates that the average value of the two mastoids in this time period is negative (this was confirmed algebraically). These patterns point to an active source near the mastoids, possibly in the posterior temporal lobe.

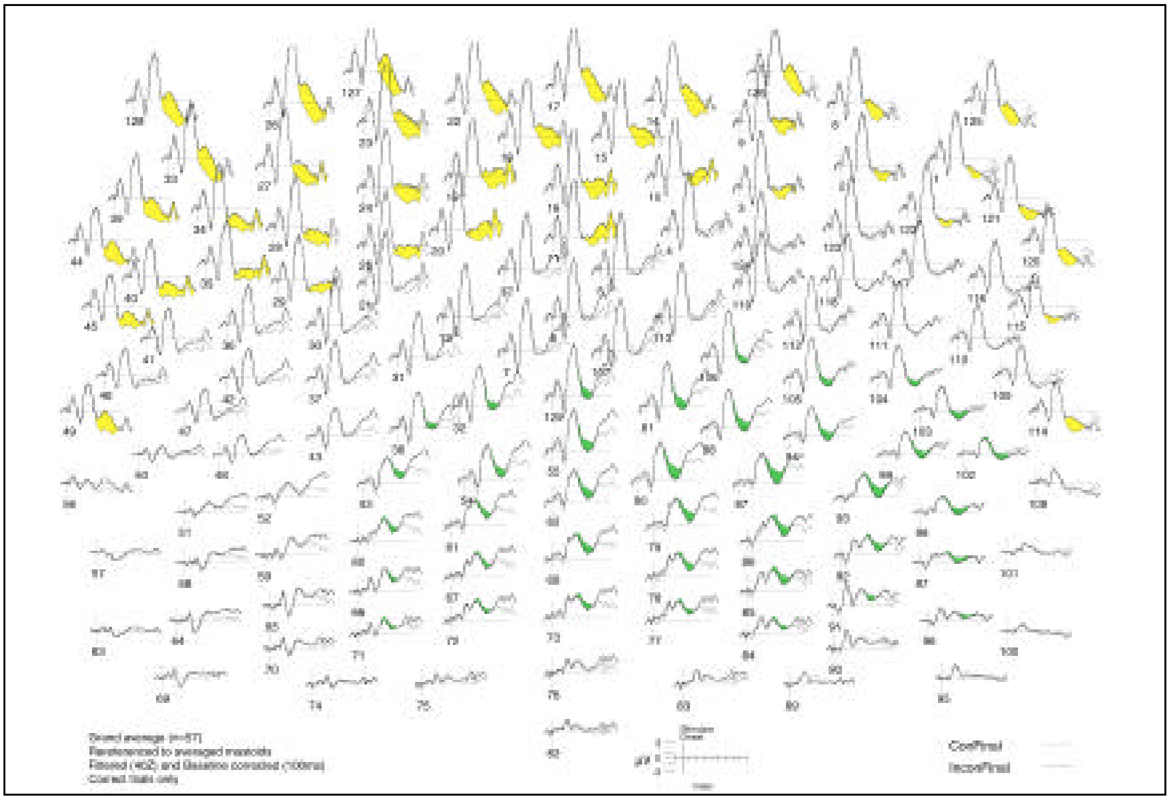


Figure 8. Grand-averaged response to congruous (light line) and incongruous (dark line) sentence endings. Data referred to averaged mastoids. Baseline is 100ms prior to word onset.

Examination of the mid-latency (300–600ms) epoch indicates replication of the classical sentence-final N400 effect. A clear difference, approximately 200ms in duration, is observed between the congruous and incongruous response (effect shaded in light green). The incongruous response is more negative, beginning approximately 350 ms after onset of the target word, and peak analysis of the difference wave indicates that this enhanced negativity is strongest over right centro-parietal sites, congruent with prior literature. A polarity inversion is seen in left fronto-temporal regions, resulting in an anterior positivity that is stronger over the left hemisphere (effect in yellow). Peak analysis indicates that the strongest positivity in the N400 epoch (360–420ms) is around channels 26 and 127.

In previous 64-channel studies of N400 topography, the inferior positivity was not seen in the mastoid-referenced plots, emerging only in the average-referenced data, e.g., (Curran et al., 1993). However, the first published data on the N400 using 128 channels reported an enhanced frontal positivity to the incongruous word in both mastoid-referenced and reference-independent data (Johnson & Hamm, 2000), consistent with the present mastoid referenced dataset.

Figure 8 shows that the responses to incongruous and congruous words diverge again around 600 ms, that is, in the late positive, or LPC, window. In this epoch, incongruous words evoke an enhanced posterior positivity and enhanced anterior negativity. Broadly speaking, this later LPC effect appears to be spatially correlated with the N400 effect. That is, as the N400 difference gets large, so too does the LPC difference, and inversely, suggesting that the two effects may be indexing the same neurophysiological event. On the other hand, there are clear differences in the topographies of the early and later congruity effects (see below).

It is further possible to plot the *difference* between the congruous and incongruous response at a single timepoint to better illustrate the distribution of the N400 effect. The difference wave indexes effects specific to the congruity manipulation, subtracting out effects that fail to distinguish the two conditions. Examination of the difference wave at the mastoids shows only a small net positivity, suggesting that referencing bias may have little effect on the N400 topography in these data (but cf. Curran et al., 1993; Johnson & Hamm, 2000).

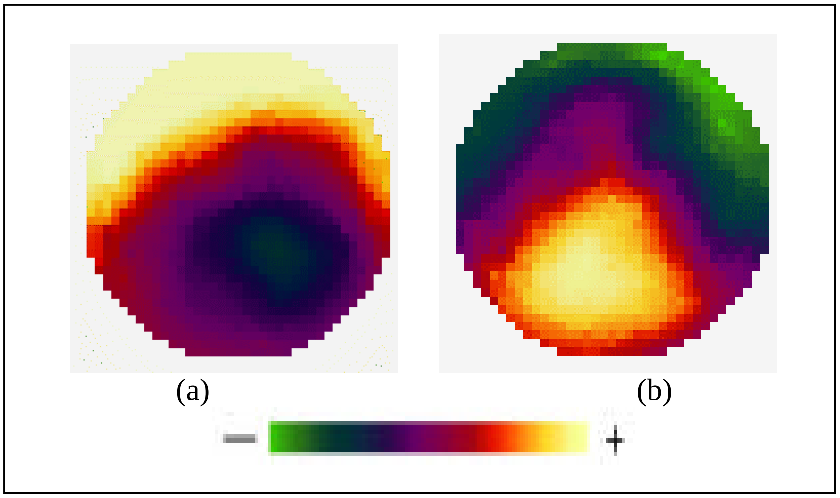


Figure 9. (a) Difference wave (incongruous – congruous) for mastoids-referenced data at 400ms after target onset. (b) Difference wave at 840ms. Yellow indicates incongruous more positive than congruous. Blue-green indicates incongruous more negative than congruous.

Figure 9b shows the late "LPC" effect: the difference wave shows that the response to incongruous words is more positive in this later interval that than the response to congruous words. This may seem consistent with the idea that the late positive complex is delayed to the incongruous word, accounting for both the early "N400" and late "LPC" effects. However, the topographies of the two effects are clearly distinct. While the early effect seems consistent with a single dipole, oriented tangentially to the cortical surface, the later effect has a more complex topography, suggesting that it may require more than one source generator to account for this effect. Further, the lateralization patterns are different. The early N400 effect is lateralized, consistent with a source dipole oriented towards the left hemisphere, whereas the later effect is more symmetrical, if anything, suggesting a stronger dipole oriented towards the right hemisphere, given the right lateralization of the enhanced frontal positivity to the incongruous word.

In effect, these patterns suggest that the topographic distribution of the early and late effects are nonidentical, posing at minimum a challenge for the LSP hypothesis as the sole explanation for the early N400 effect.

Average-referenced data

Average referenced data (Fig. 10) show the same condition effects as the averaged mastoids dataset. The primary difference is that the N1/P2 complex is more evenly distributed across the scalp. Left lateralization of the N1 is again evident, and was confirmed in the split-sample ANOVA (Section 6.0).

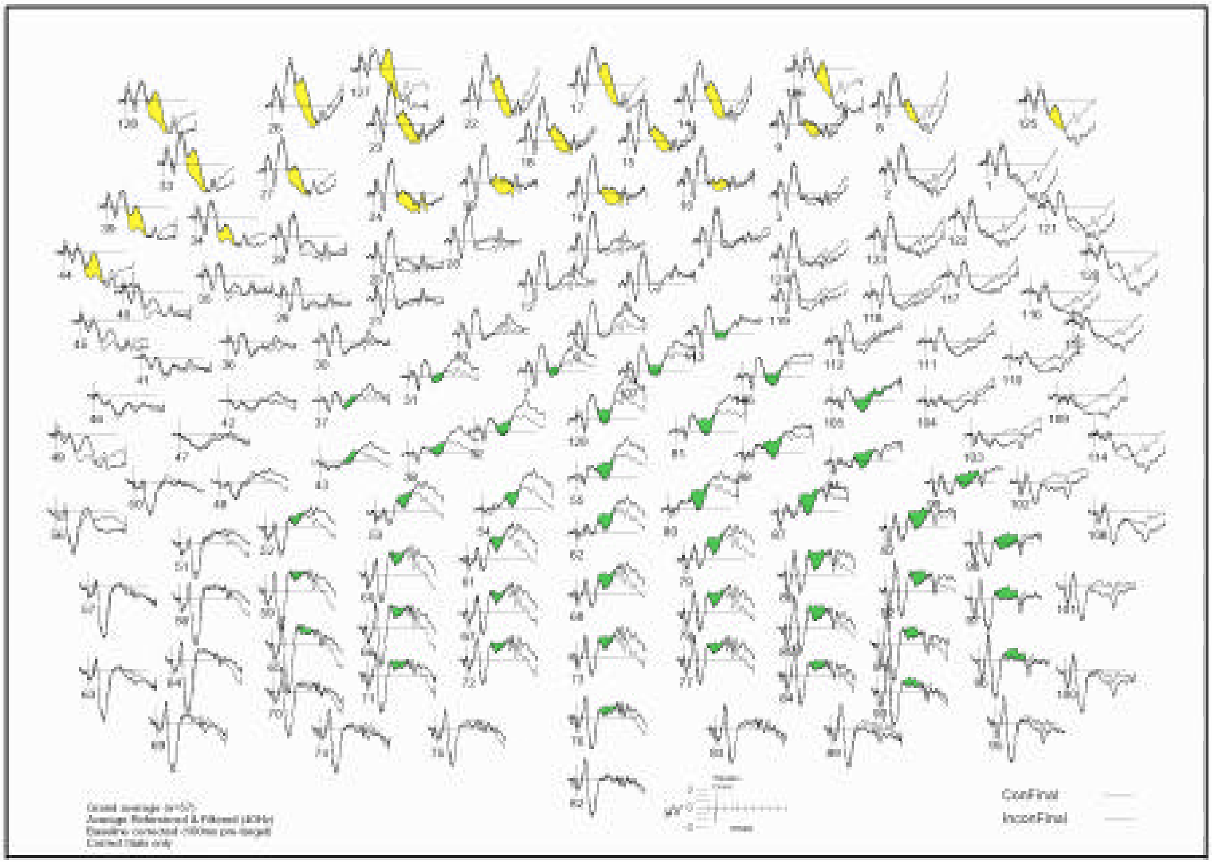


Figure 10. Grand-averaged response to congruous (light line) and incongruous (dark line) sentence endings. Data referred to average of 128 channels. Baseline is 100ms prior to word onset.

The same dipole structure is shown with green indicating that incongruous is more negative than congruous, and yellow indicating the reverse.

Figure 11 shows the difference wave (incongruous – congruous) at 400 and 840 ms for the average referenced data. The topographies of the two effects are much the same as was described for the mastoid referenced data.

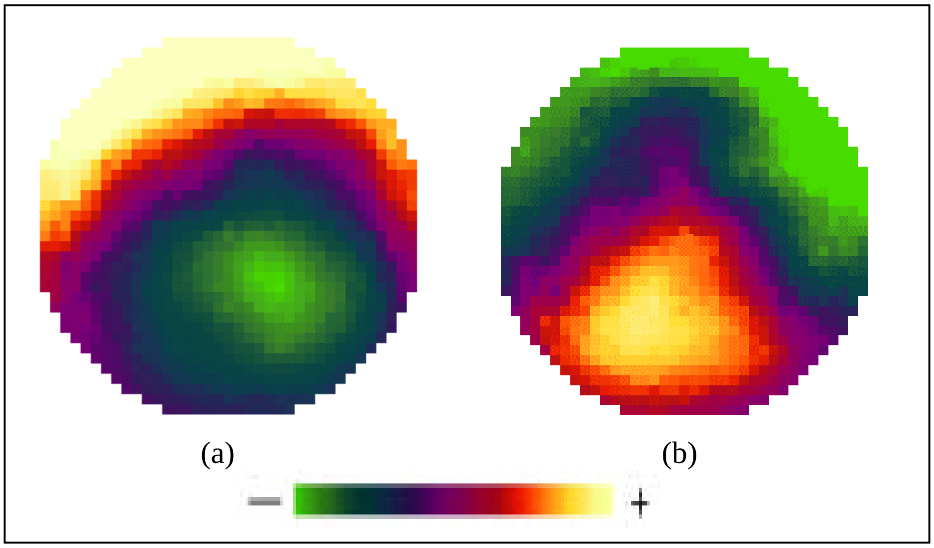


Figure 11. (a) Difference wave (incongruous – congruous) for average referenced data at 400ms after target onset. (b) Difference wave at 840ms. Yellow indicates incongruous more positive than congruous. Blue-green indicates incongruous more negative than congruous.

Animated Topography of the N400 Effect

The use of the average reference allows us to characterize the spatiotemporal development of the N400 negativity, since it is assumed that the average of the data approximates zero with adequate spatial sampling, providing a stable reference for the "active" electrode sites across time (Dien, 1998b; Tucker, 1993b). Recall that both the congruous and incongruous response showed a left-lateralized N1 at 160ms, which developed into a rapidly changing inferior temporal negativity, terminating with a left antero-temporal negativity at around 268 ms. The next major event was the bilateral P1r, seen clearly in Figure 12 below (top and bottom figures at 292ms). It is at this point (around 300ms) that the two conditions noticeably diverge: for incongruous sentence-final anomalies, the negativity fades around 350 ms, just as the frontal positivity is emerging; for congruous sentences, the P1r extends through the N400 epoch, gradually merging with the early P300 (beginning around 370ms).

The temporal dynamics of these condition effects were examined with Student's t-test animations, which show the timecourse of the difference between conditions normalized by the variance across subjects (middle row of topographic maps). These t-animations should be considered exploratory (posthoc) only. For example, no attempt was made to correct for autocorrelation of effects over time. T-animations are especially valuable in forming hypotheses about the number of neural sources that could be generating observed effects, and their interactions, since these animated difference waves permit visual “decomposition” of the waveform, taking into account temporal covariance. Here, red indicates that the congruous response was significantly more positive than the incongruous response, and blue indicates the opposite effect.

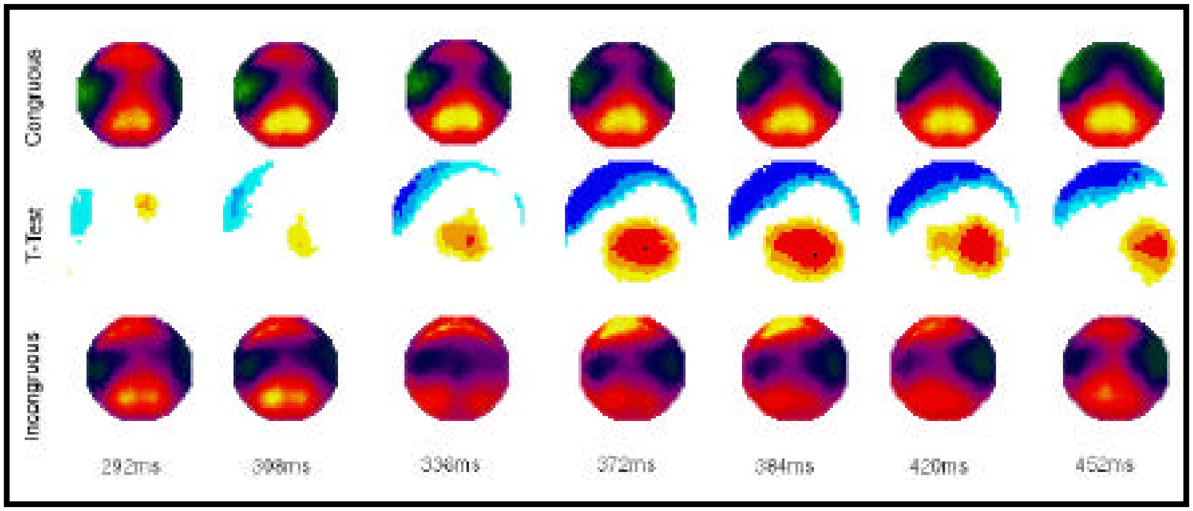


Figure 12. Animate topography of the N400 effect to sentence-final words. Top row, congruous response. Bottom row, incongruous response. Middle row, “twave” (difference wave normalized by variances across subjects).

The middle row of “twaves” suggests temporal coherence of the centroparietal effect (the N400) and the anterior effect (P400 or anterior positivity). Not only are the inverse polarities suggestive of a dipole structure, but the scalp topography itself is consistent with a single equivalent dipole. Tentative source models of these data have localized this dipole to the medial temporal lobe(Frishkoff, Davey, & Tucker, 2000, in preparation-a). Note that with respect to underlying component structure, these data are still ambiguous. On one interpretation, there could be a “P300” dipole at 400ms in the congruous condition that is inactive (or significantly less active) than in the incongruous condition. In an alternative scenario, the early P300 positivity in the incongruous condition could be cancelled by the superposition of a distinct, N400 dipole (negative posteriorly, positive anteriorly).

Development of the late (LPC) congruity effect is seen in the first frame of Figure 13, starting at around 550 ms with an enhanced centromedial positivity and right temporal negativity to the incongruous word. Note that the negativity becomes more posterior and increasingly left lateralized, beginning around 800 ms.

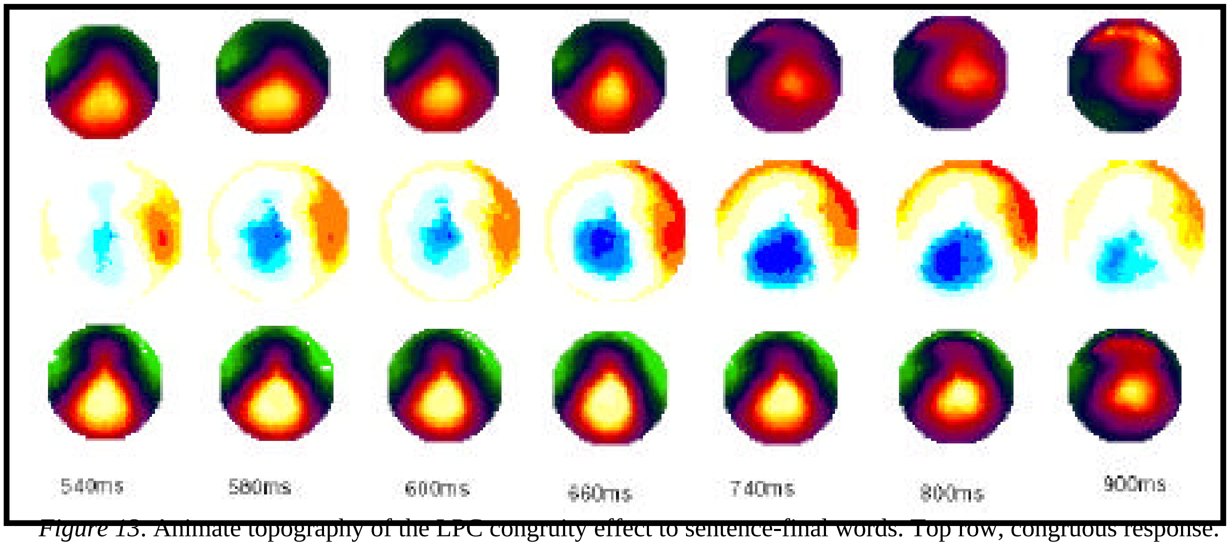


Figure 13. Animate topography of the LPC congruity effect to sentence-final words. Top row, congruous response. Bottom row, incongruous response. Middle row, “twave” (difference wave normalized by variances across subjects).

Although this later “LPC effect” is suggestive, it still fails to provide conclusive support for either the LSP or the N400 hypothesis. It could be argued that this late LPC effect supports the LSP hypothesis: the P300/LPC arrives and peaks earlier for the congruous word, giving rise to the early effect, and peaks later to the incongruous word (explaining the later effect). However, this interpretation fails to account for several effects. First, the topographies of the early and late difference effects are clearly distinct, as mentioned earlier, whereas simple latency shifting of the positive component predicts identical spatial effects, shifted in time. The later effect is more medial, and seems more consistent with a right temporal than a left temporal dipole, suggesting that the this effect may not be simply a recapitulation of the earlier (N400) congruity effect. Second, LSP fails to explain the larger amplitude of the late positivity in the incongruous condition (particularly given that increased latency jitter would predict the opposite effect).

An alternative interpretation is that the LPC effect is independent from the earlier, N400 effect, but this account should then explain how are the early and late effects are related. Are they manifestations of a single cognitive process, or do they index different stages of semantic processing? Given that the sentence-final data were ambiguous, it was hoped that the response to nonterminal words would tip the balance in favor of one or the other interpretation.

Mid-sentence data

Figure 14 shows the response to mid-sentence congruous and incongruous words. Notice that the effect size is much smaller (though still significant) in comparison with the sentence-final N400 effect. This difference may be due to discrepancies in “cloze probability” of the mid-sentence and sentence-final words. A typical mid-sentence target was only the third or fourth content word in the sentence, and there was probably too little information at that stage to evoke strong expectancies for mid-sentence targets. To address this issue, an effort is underway to characterize the sentences in terms of expectancy for the target word, using cloze probability as an index of subjective probability of (expectancy for) the stimulus.

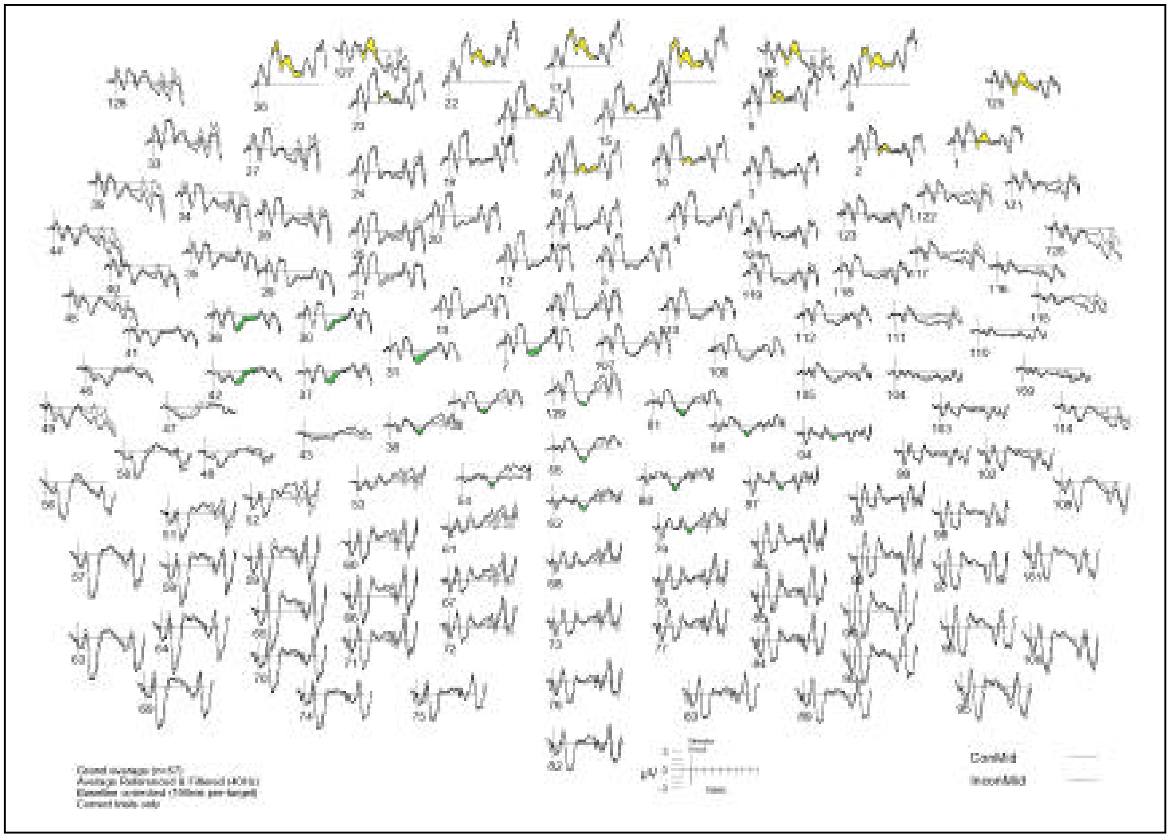


Figure 14. Grand-averaged response to congruous (light line) and incongruous (dark line) mid-sentence words. Data referred to average of 128 channels. Baseline is 100ms prior to word onset.

Topography of the mid-sentence N400 effect (incongruous – congruous) is shown below (Fig. 15).

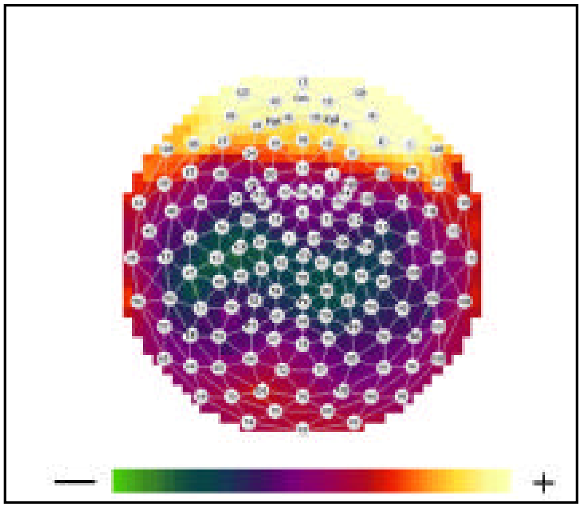


Figure 15. Topographic distribution of the response to incongruous minus congruous word at 400ms.

The distribution of the N400 effect is notably different for nonterminal as compared with terminal words. The mid-sentence effect is more bilateral, more anterior, and (as seen in the split-sample analysis) more variable. Nonetheless, there are important similarities between the mid-sentence and sentence-final congruity effects. For example, the mid-sentence effect shows a similar timecourse, with onset of the N400 effect at around 300 ms after target onset (Fig. 16).

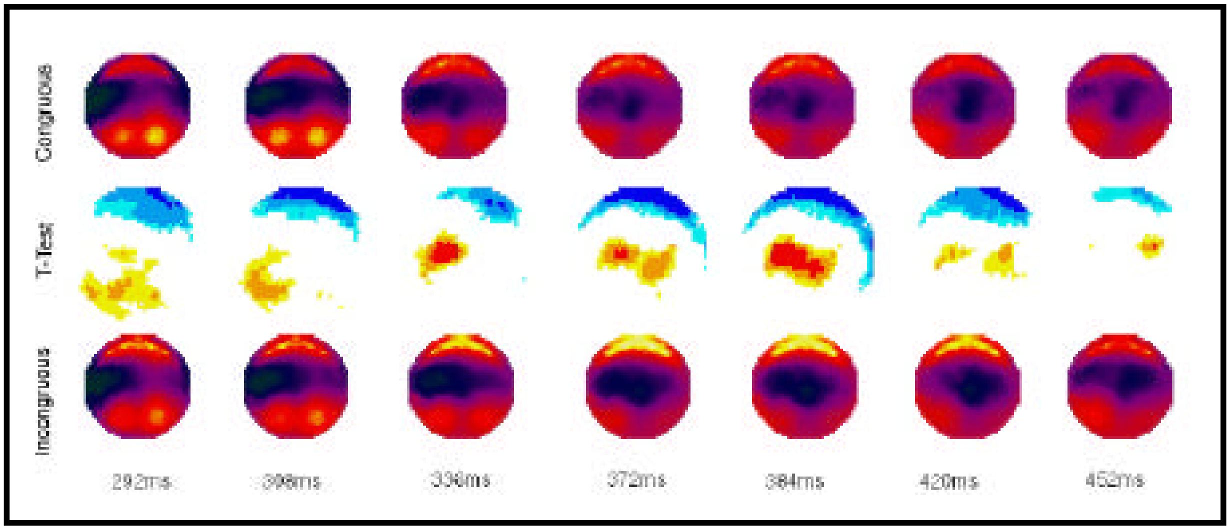


Figure 16. Animated topography of the N400 effect to mid-sentence words. Top row, congruous response. Bottom row, incongruous response. Middle row, “twave” (difference wave normalized by variances across subjects).

Examination of the later epoch shows that the late “LPC” congruity effect is seen for the mid-sentence targets, as well, extending past onset of the following word at 600 ms.

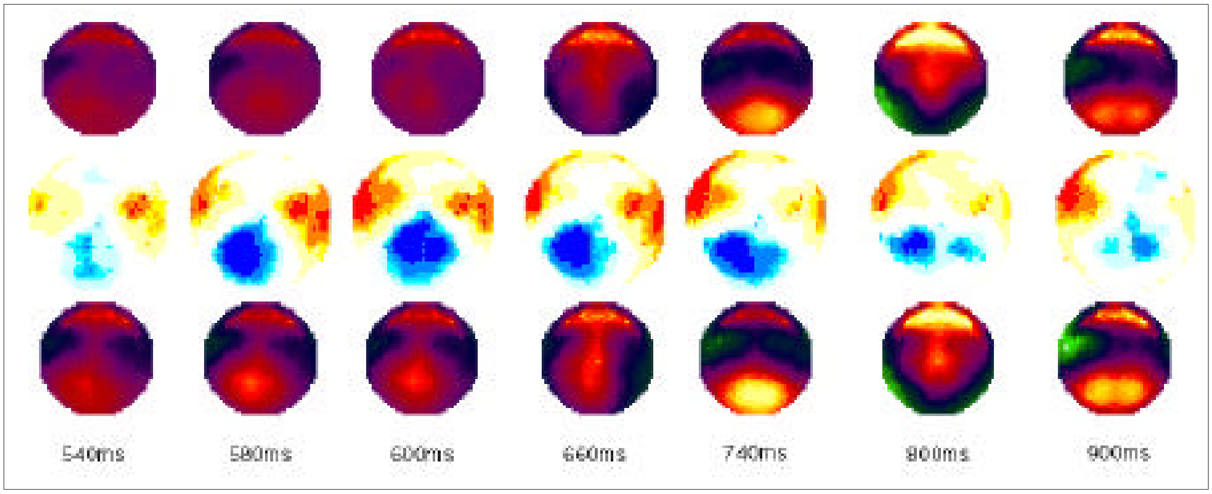
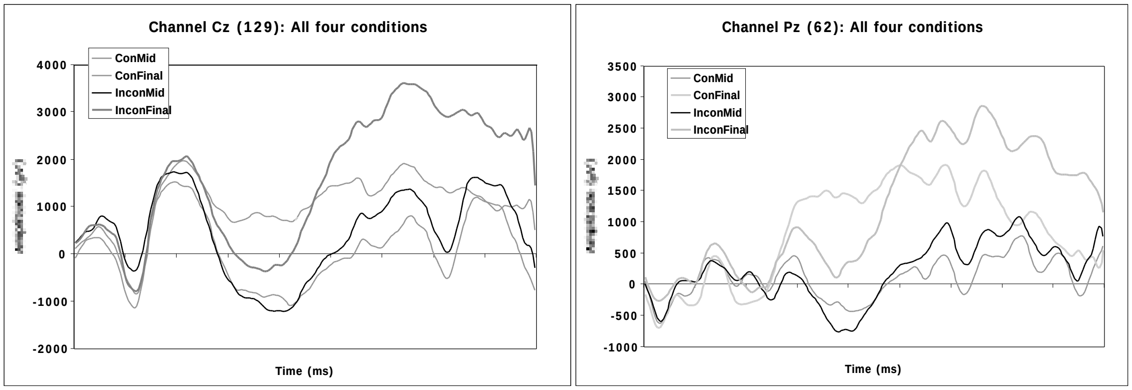


Figure 17. Animated topography of the LPC effect to mid-sentence words. Top row, congruous response. Bottom row, incongruous response. Middle row, "twave" (difference wave normalized by variances across subjects).

Comparison of Mid-sentence and Sentence-Final Congruity Effects

Direct comparison of the response to mid-sentence and sentence-final words is best seen in single-channel plots of the response in all four conditions.

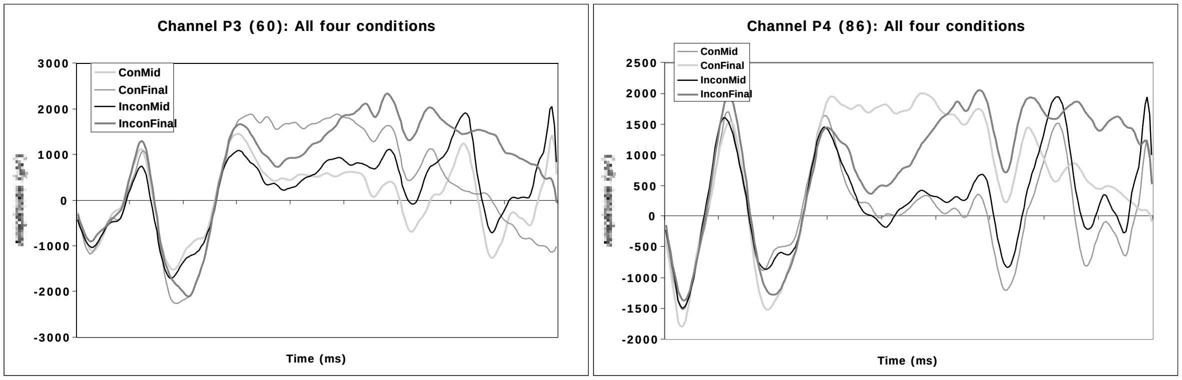


Figures 18a, b. Response at Cz and Pz. Data baseline corrected 100ms before word onset.

It is immediately apparent from these single-channel plots (Figs. 18a,b) that the response to mid-sentence words is more negative than to sentence-final words, starting at around 300ms after word onset, regardless of congruity. Thus, in particular, the negative deflection at around 400ms (the N400) is larger for the mid-sentence words. This observation is consistent with Van Petten's finding that N400 amplitude is inversely correlated with sentence position; every open-class (content) word in a sentence is thought to evoke an N400 response, regardless of congruence, but later in the sentence, the N400 is attenuated, possibly reflecting the increasing constraints on expectancy as the sentence context accumulates (Van Petten & Kutas, 1990).

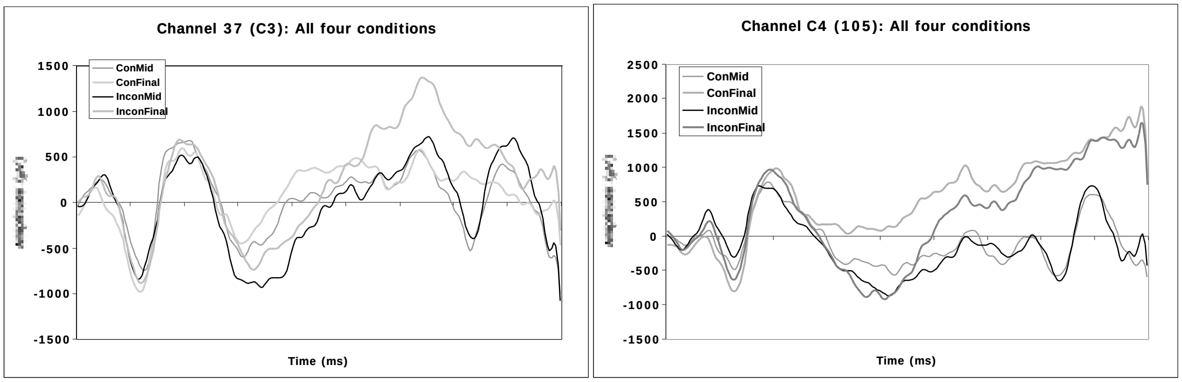
Examination of Figures 18a and b (mid central and parietal electrode sites) further indicates that morphology of the response to all four conditions is similar, except that in the congruous final response, there is a pronounced early positivity, starting at around 250ms. This suggests that the distinguishing event among the four conditions may be the early part of the P300/LPC, which may be linked to the sentence-final semantic “wrap-up” that occurs earlier for the congruous final response.

The following figures display the response in each condition at more lateral sites (corresponding to conventional electrode sites in the 10–20 system). Note that the N400 effect is attenuated at lateral parietal sites (both hemispheres) to mid-sentence stimuli, whereas it is enhanced over right parietal cortex and slightly attenuated over left parietal cortex (Figs. 19a, b),



Figures 19a, b. Response at lateral parietal sites (P3, left hemisphere; P4, right hemisphere). Data baseline corrected 100ms before word onset.

Over lateral central regions (C3 and C4), mid-sentence stimuli evoke a relatively good response, somewhat stronger over the left hemisphere (C3). Interestingly, the later “LPC” effect is not correspondingly larger over these regions. By contrast, the N400 effect is smaller overall at lateral central sites for the terminal words (as compared with parietal regions), and is strongest over the right hemisphere. In 20b, there is again a clear dissociation between the early (N400) and late (LPC) congruity effects: practically no late effect is observed over C4.



Figures 20a, b. Response over lateral central regions (C3, left central; C4, right central). Data baseline corrected 100ms before word onset.

In summary, inspection of individual channel plots suggests a possible dissociation of the early (N400) and later (LPC) congruity effects, based on topographic distribution. The following section tests more rigorously for experimental effects and differences in spatial distribution of these effects.

Analysis of Variance (ANOVA)

For statistical characterization of component effects, repeated-measures analyses of variance with both planned and post hoc comparisons were conducted on two subsamples (each n=28) for the time intervals of interest. Only effects that survived this split replication were considered significant (see Appendix B for full report). The Greenhouse–Geisser correction for inhomogeneity of variance (df greater than 2) was applied in each case.

To quantify differences in topography for the four conditions (congruous mid and final, and incongruous mid and final targets), the 129-channel array was divided into 12 channel sets, reflecting three spatial factors: caudality (anterior—posterior), laterality (left—right), and verticality (inferior—mid—superior). The channel subsets that were entered as variables into the ANOVA are shown in Table 1 (cf. Curran et al., 1993 for an ANOVA design use with a similar, 64-channel dataset)**.**

CAUDAL	**LATERAL**	**VERTICAL**	**CHANNELS**
ANTERIOR	LEFT	INFERIOR	127,128,44,49,22,26,33,39,45
ANTERIOR	LEFT	MID	18,23,27,34,40,46,19,24,28,35,41,20,25,29,36,42
ANTERIOR	LEFT	SUPERIOR	12,21,30,37,13,31,7
ANTERIOR	RIGHT	INFERIOR	126,125,120,114,14,8,1,121,115
ANTERIOR	RIGHT	MID	15,9,2,122,116,109,10,3,123,117,110,4,124,118,111,104
ANTERIOR	RIGHT	SUPERIOR	5,119,112,105,113,106,107
POSTERIOR	LEFT	INFERIOR	56,63,69,74,57,64,70,75
POSTERIOR	LEFT	MID	50,58,65,71,47,51,59,66,72,48,52,60,67
POSTERIOR	LEFT	SUPERIOR	43,53,61,38,54,32
POSTERIOR	RIGHT	INFERIOR	108,100,95,89,101,96,90,83
POSTERIOR	RIGHT	MID	102,97,91,84,103,98,92,85,77,99,93,86,78
POSTERIOR	RIGHT	SUPERIOR	94,87,79,88,80,81

Table 1. Channel subsets used for analysis of variance.
Twelve subdivisions reflect 2 (caudality) x 2 (laterality) x 3 (verticality) spatial factors design

Figure 21 illustrates how the spatial factors are distributed over the 129-channel electrode array.

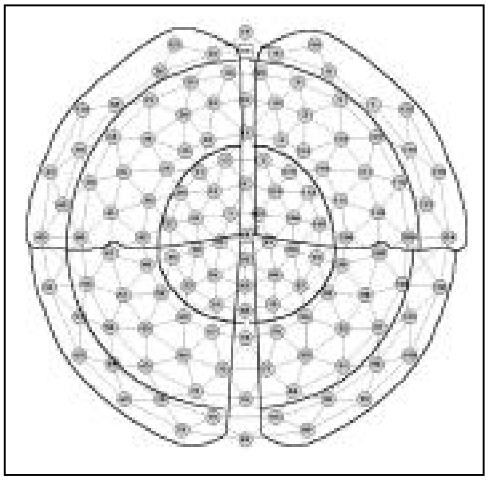


Figure 21. Channel divisions used in split-sample ANOVAs.

Mean amplitude over the channels in each subset was calculated for each time interval of interest. Peak amplitude was not used, because it affords a greater risk of picking out local minima (maxima), which may not represent a given channel grouping. The three spatial factors were crossed with congruence and sentence position of the target. This yielded a 2 (Congruence) x 2 (Sentence Position) x 2 (Caudality) x 2 (Laterality) x 3 (Verticality) fully factorial design, conducted on two subsamples (each n=28), to provide cross-validation of all statistically significant effects. Results of ANOVAs were for each epoch (“component” interval) of interest are reported below.

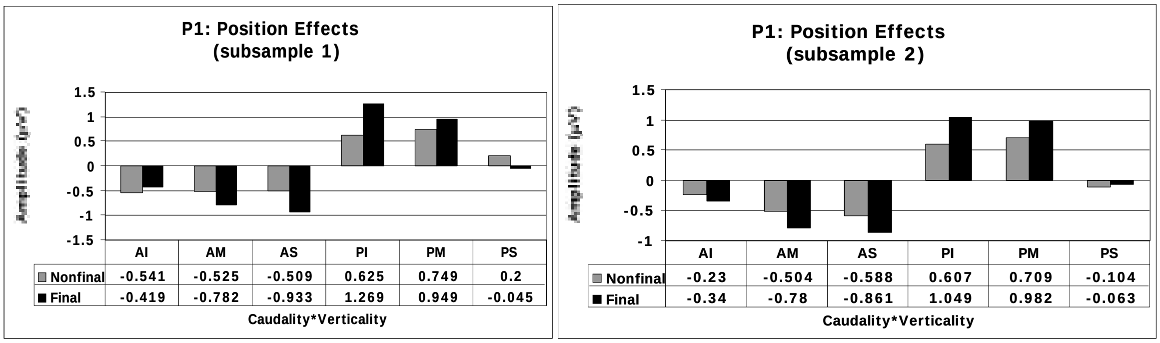
Windowing

Epochs of interest were chosen from inspection of grand-average waveforms and animated topographies. Particular caution was exercised in selection of later windows (i.e., the N400 and LPC intervals), since latency variability across trials and across subjects increases for later, endogenous ERPs. For the long-latency effects, individual subject ERPs were examined separately, and every effort was made to identify, for each subject with a clear N400/LPC effect, the initial and end samples for both the N400 and LPC response to terminal words.

Due to the rich topography of the response in each time window, it is typical for many effects involving spatial factors to emerge as significant. For ease of discussion, only the highest-order, most informative results are discussed. A complete report (both significant and nonsignificant results) is given in Appendix B.

P1 window:100-140 ms.

There were no reliable effects of congruence (either main effects or interactions) in the P1 window (100–104ms). The most interesting (and the only 3-way) effect in this time interval is a weak, but reliable interaction between position, caudality, and verticality. This effect was significant for both subsamples, F(2, 54)=5.2, p<.05 and F(2, 54)=3.6, p<.05 (Figs. 22a, b) for subsamples 1 and 2, respectively. The general pattern of response in this interval is an anterior negativity and posterior positivity (the "P1") distributed as shown in Figures 22a & b.



Figures 22 a, b. Position*spatial factors (caudality, verticality) interaction.

Figures 22a and b suggest that terminal words are slightly more negative towards the front of the head and more positive towards the back. It is possible that this position effect reflects enhanced CNV to the terminal word. Further studies will be needed to corroborate this finding, using different time constants (e.g., .1Hz vs. .01Hz) to manipulate the amplitude of the CNV wave.

In Figures 23 a & b, the P1 appeared to be right lateralized, and split-sample ANOVAs confirmed this effect. In both subsamples, there was an enhanced posterior positivity on the right side of the head. For sample 1, this effect was highly significant, F(1, 27) =11.74, p<.01. For subsample 2, the interaction was less strong, but still significant at the .05 alpha level.

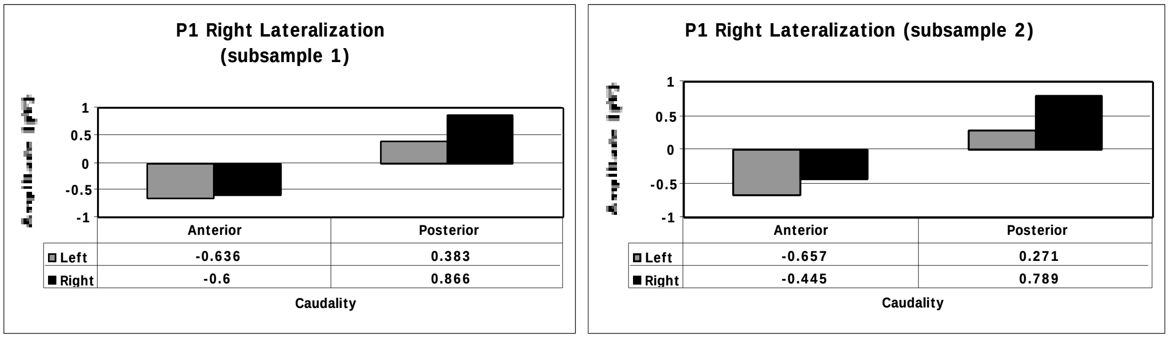
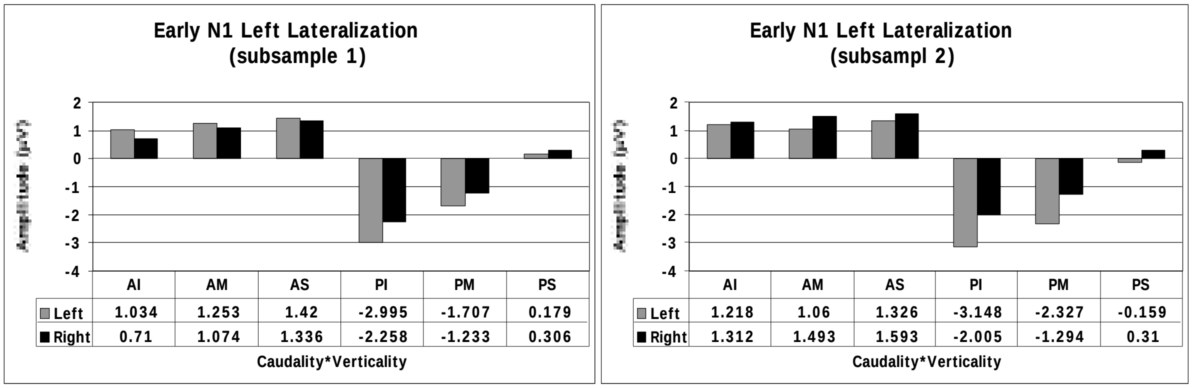


Figure 23a, b. Right lateralization of the P1, shown in 3-way laterality*caudality interaction.

Right-lateralization of the P1 was reported by Kutas in a study of lateralization of event-related potentials to language stimuli (Kutas, Van Petten, & Besson, 1988a), but this effect appears not to be well understood.

Early N1 window: 168-208ms

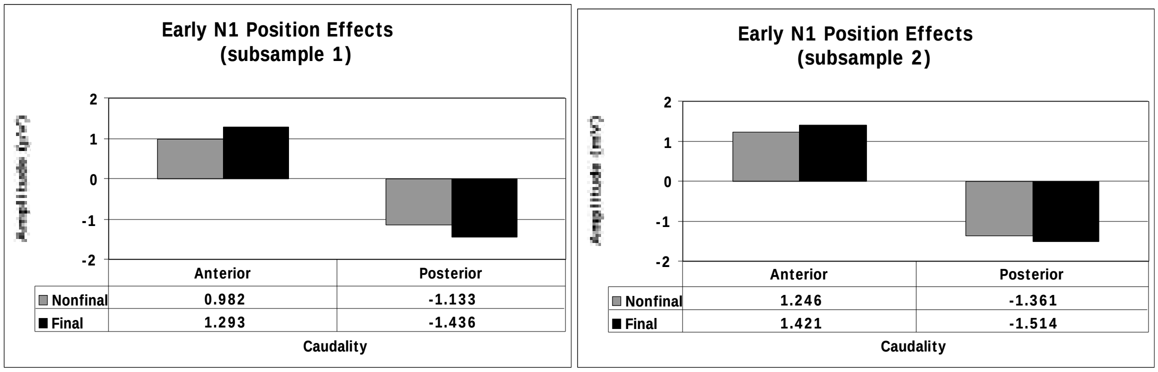
In 168–208ms epoch, spatial factors revealed a familiar N1 pattern of electrical potentials, with overall anterior positivity and posterior mid-inferior negativity (Fig 5). The N1 was markedly left-lateralized, caudality*laterality*verticality F(2, 54)=12.68, p<.001 for subsample 1 and F(2, 54)=13.60, p<.001 for subsample 2 (cf. Fig 7).



Figures 24a, b. Left lateralization of the early N1, shown in a 3-way laterality*caudality*verticality interaction.

Left-lateralization of the N1 to word stimuli has been observed in prior studies (Brunswick & Rippon, 1994; Curran et al., 1993; Neville et al., 1986). An auditory ERP study by Brunswick and colleagues, comparing evoked potentials in dyslexic and nondyslexic children, suggests that N1 lateralization may be linked to phonemic awareness. Thus, this effect may be implicated in early word form analysis.

There were no effects of congruence of the target word during the N1 epoch. However, for subsample 1, there was a strong interaction between position and caudality, F(1, 27)=8.13, p<.01. For subsample 2, the effect was in the same direction, but did not reach significance, F(1, 27)=3.20, p=.08.



Figures 25a, b. 2-way position*caudality interaction

Interestingly, position effects for the early N1 epoch are the reverse of the effects seen during the P1 epoch. This reversal may reflect the beginning of the CNV release, as the sentence-final semantics are brought to a close. Together, these patterns suggest overall enhanced processing of the sentence-final stimuli, but the level of processing that is affected (visual, orthographic, semantic, etc.) is unclear.

Late N1 window: 212–252ms

The late N1 epoch captures the beginning of the early left temporal migration of the N1 negativity up the temporal pole. The dominant pattern is a left-lateralized posterior negativity that is strongest at inferior sites (cf. Fig. 7).

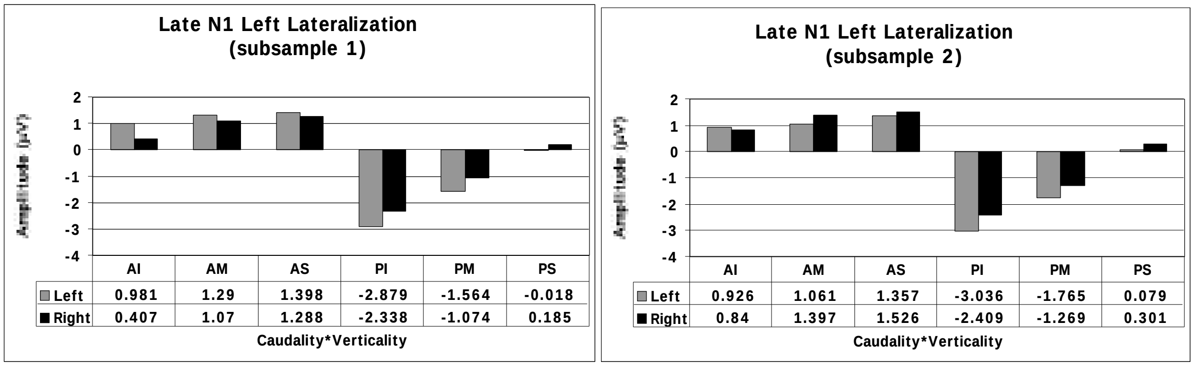


Figure 26a, b. Lateralization of the late N1 shown in 3-way laterality*caudality*verticality interaction.

In the late N1 epoch, congruence remains a nonsignificant factor. Sentence position interacts weakly with verticality, F(2, 54)=3.56, p=.06 for subsample 1 and F(2, 54)=6.91, p=.01. Terminal words appear to show enhanced effect, similar to the P1 and early N1 epochs.

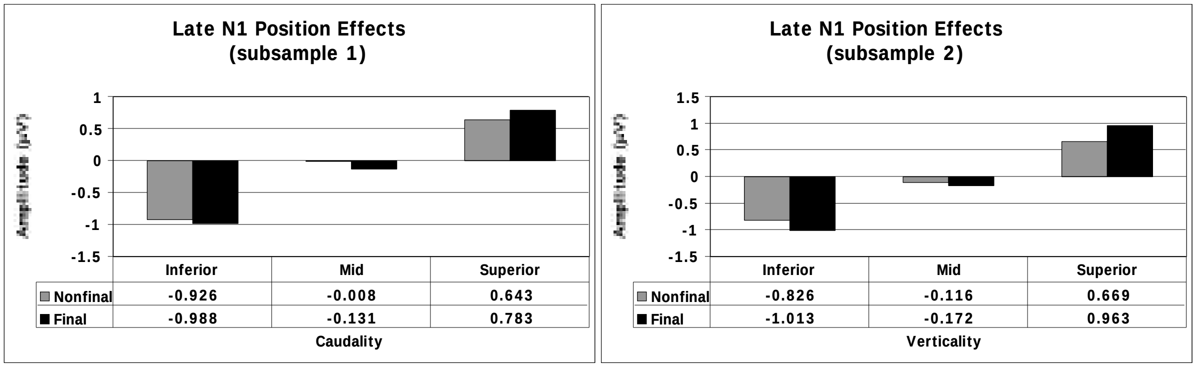


Figure 27a, b. 2-way position*verticality interaction.

Late Temporal window:260–300ms

Spatial distribution of the response between 260 and 300 ms is more complex than in prior epochs. Overall, there is a mid/superior positivity and inferior negativity during this epoch. The mid/superior positivity is right lateralized, while the negativity is left-lateralized, with strongest the strongest effects at inferior posterior sites (Figs. 28a, b), laterality*caudality*verticality F(2, 54)= 3.62, p<.01 for subsample 1 and F(2, 54)= 5.91, p< .01 for subsample 2.

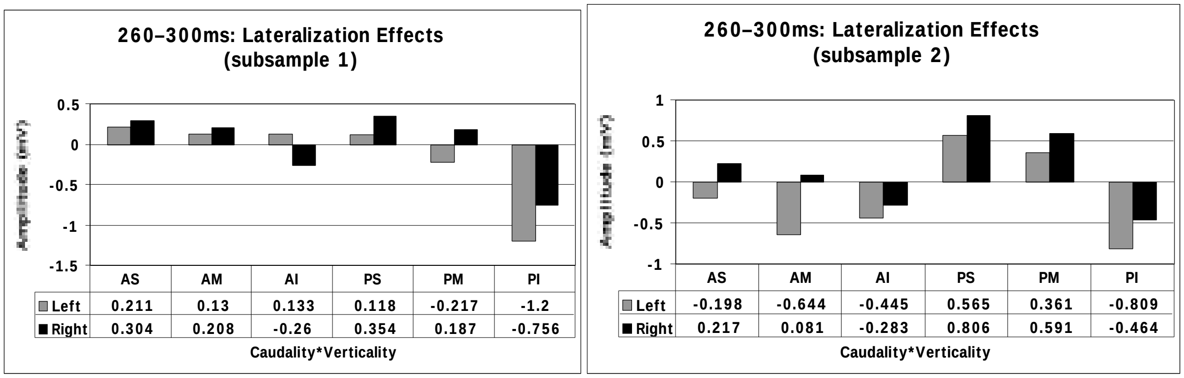


Figure 28a, b. 3-way laterality*caudality*verticality interaction.

In addition, between 260 and 300ms, we see the first signs of differentiation between congruous and incongruous targets, with the most reliable effects over superior regions (Figs. 29a, b). Congruity*verticality F(2, 54)= 4.49, p<.05 for subsample 1 and F(2, 54)= 6.64, p< .01 for subsample 2.

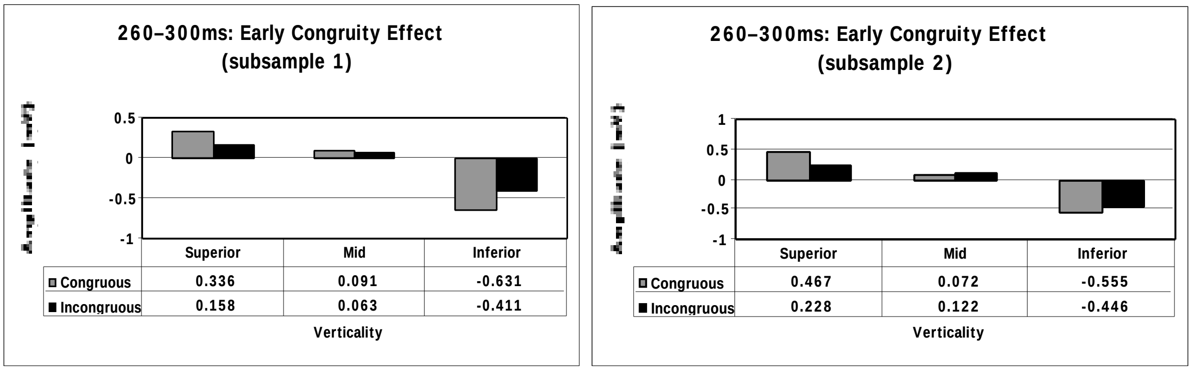


Figure 29a, b. Early congruity effects shown in 2-way congruity*verticality interaction.

Early N400 window:300-340ms

The N400 effect emerges more strongly between 300 and 340 ms, with incongruous sites more negative at posterior sites and more positive at inferior sites (Figs. 30a, b), Congruity*verticality F(2, 54)= 11.04, p<.01 for subsample 1, and F(2, 54)= 13.98, p<.001 for subsample 2. It may be significant that the enhanced positivity to the incongruous word (the polar inversion of the N400 effect) is seen only over inferior sites. This may explain why the dipole structure of the N400 has rarely been observed, since few N400 studies have used high-density recordings, sampling over inferior regions of the scalp.

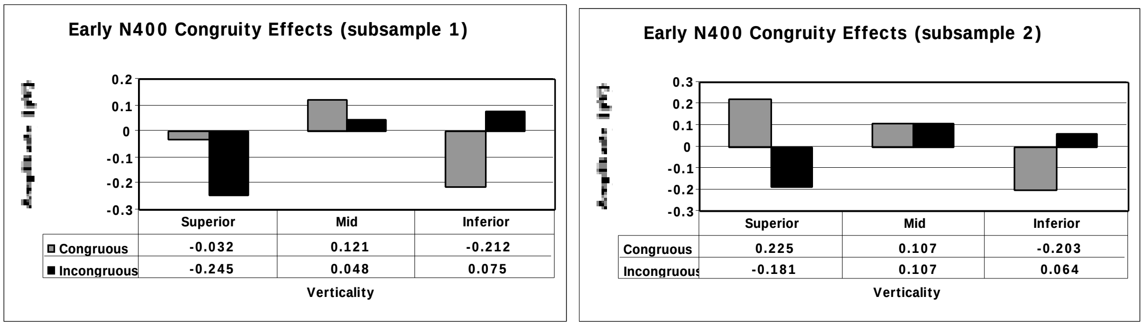


Figure 30a, b. Congruity effects shown in 2-way congruity*verticality interaction.

Lateralization of the congruity effect is already seen in the early N400 epoch. Moreover, the patterns of lateralization differ for terminal and nonterminal words, Position*congruity*laterality F(1, 27)= 4.44, p< .05 for subsample 1, and F(1, 27)= 11.23, p<.01 for subsample 2. For nonterminal words, there is an enhanced left hemisphere negativity and right hemisphere positivity to the incongruous word (Figs. 31a, b). From the topographic maps in Figure 16, the N400 effect to nonterminal words appeared slightly left lateralized, consistent with these results.

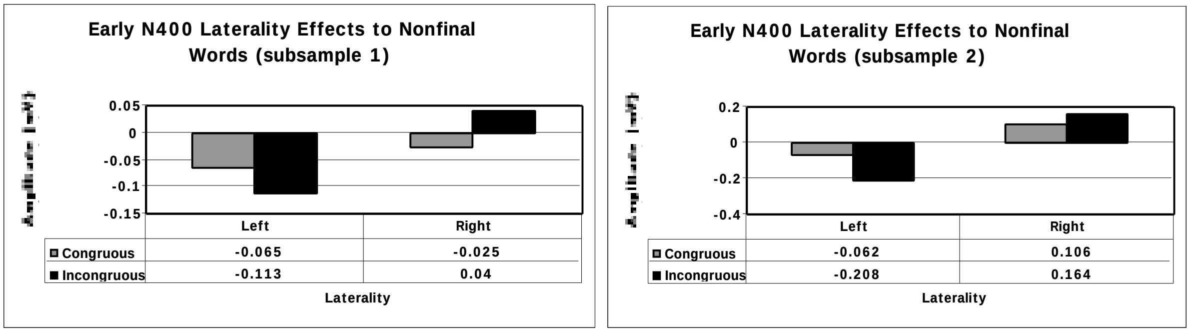


Figure 31a, b. Congruity effects shown in 2-way congruity*laterality interaction for nonfinal words only.

For terminal words, the opposite effect is seen. For both samples, the response to incongruous words is more negative over the right hemisphere and more positive over the left hemisphere. In subsample 1, it appears that this effect is due to an enhanced response to the incongruous word, while the response to the congruous word seems to drive the effect in sample 2. However, given the relative nature of ERP effects, these differences may not be meaningful.

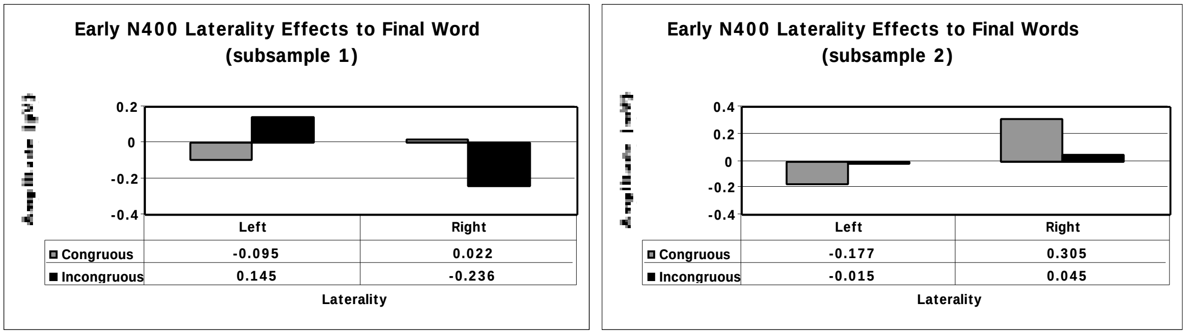


Figure 32a, b. Congruity effects shown in 2-way congruity*laterality interaction for final words only.

N400 window:340–420ms

The topography of the N400 effect can be seen most clearly in Figures 33a & b, particularly for the posterior superior (PS) anterior inferior (AI) channel groups, Congruity*caudality*verticality F(2, 54)= 24.16, p< .001 for subsample 1, and F(2, 54)= 8.52, p<.01 for subsample 2.

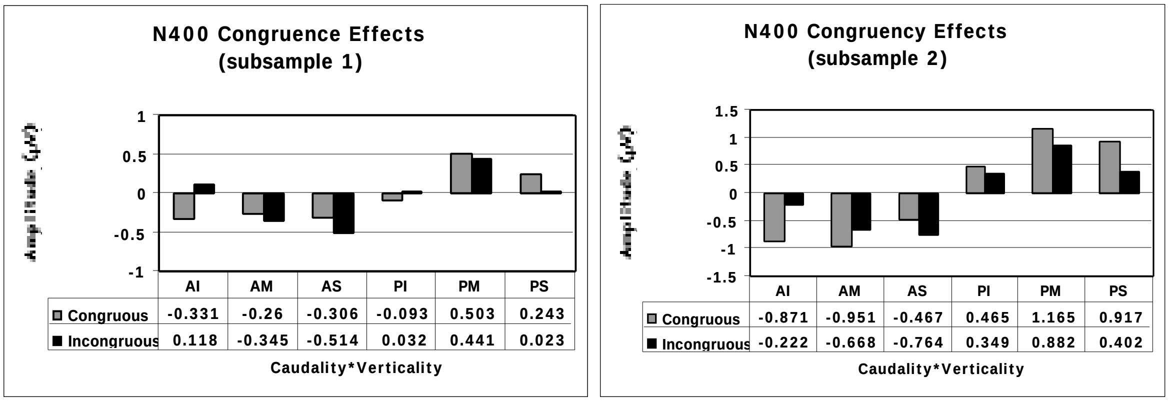


Figure 33a, b. Congruity effects shown in 3-way congruity*caudality*verticality interaction.

Note, however, that this graph collapses over sentence position of the target, obscuring the differences in topography of the N400 to mid-sentence and sentence-final words. A congruence*position*verticality interaction (graphed in Figures 34–35a,b) shows the difference in topographic distribution of the N400 effect to mid-sentence and sentence-final words, F(1, 27)= 18.73, p< .001 for subsample 1, and F(1, 27)= 2.94, p<.05 for subsample 2.

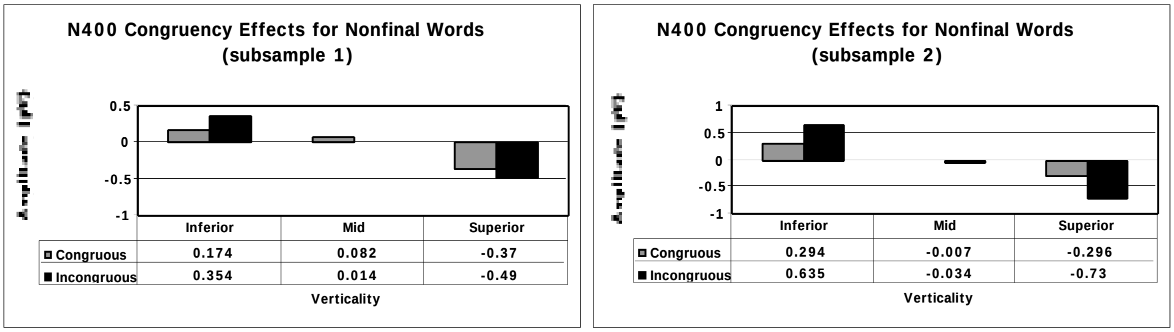


Figure 34a, b. Congruity effects shown in 2-way congruity*caudality interaction for nonfinal words only.

The same vertical distribution is observed for both mid-sentence and sentence-final conditions: enhanced superior negativity and enhanced inferior positivity to the anomalous target. One difference, however, is that the congruity effect to nonterminal words appears as a *quantitative* difference (slight enhancement of congruous response), whereas the N400 effect to terminal words reveals a *qualitative* difference in the distribution of the response to congruous and incongruous stimuli. In sample 1, the congruent word evokes a topography consistent with an early P300 effect (positive posterior/superior and negative anterior/inferior), while the response to the incongruous word appears comparatively flat. In sample 2, the congruous word shows the same P300 topography, whereas the incongruous word shows an opposite and quiescent (though not entirely flat) topography.

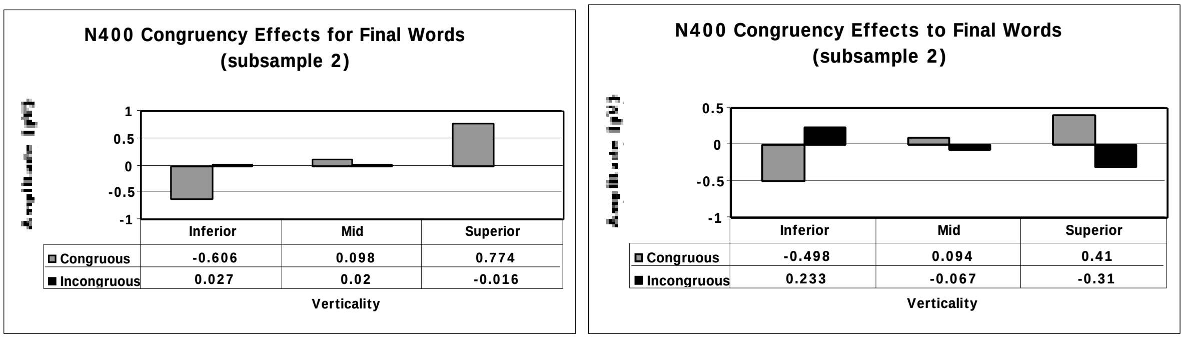


Figure 35a, b. Congruity effects shown in 2-way congruity*caudality interaction for final words only.

In addition to the differences in caudal distribution of the N400 effect, mid-sentence and sentence-final words show distinct patterns of lateralization. Congruity*laterality effects for the nonterminal words are not consistent over the two samples. Specifically, the incongruous response shows opposite lateralization effects between the two samples (more negative in the right hemisphere for sample 1 and more positive in the left hemisphere for sample 2), although the interaction for subsample 1 does not reach significance, Congruity*position*laterality F(1, 27)= .08, and F(1, 27)= 13.55, p<.01 for subsample 2. It is possible that some of this variability could be explained if subjects were divided into those with familial right handedness versus those with familial left handedness (cf. (Kutas, Van Petten, & Besson, 1988b)).

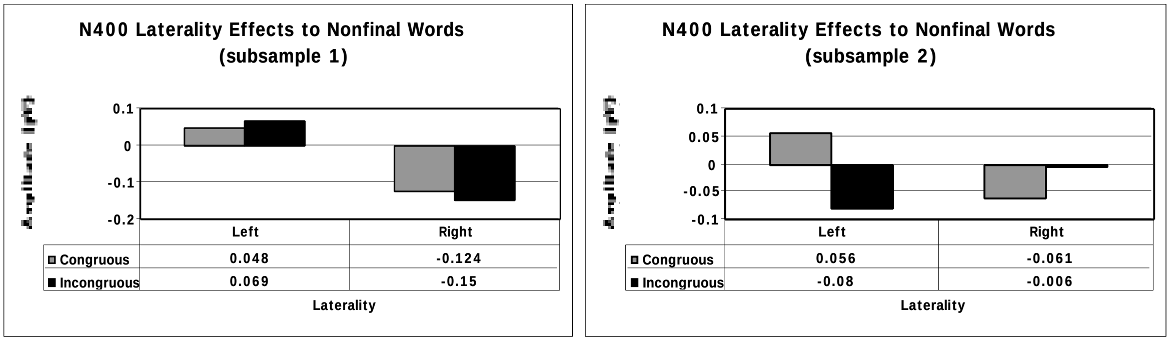


Figure 36a, b. Congruity effects shown in 2-way congruity*laterality interaction for nonfinal words only.

Terminal words show a strong congruity effect that inverts between the hemispheres: the incongruous word is more negative than the congruous response over the right hemisphere, and more positive over the left hemisphere. This effect was robust across the two samples.

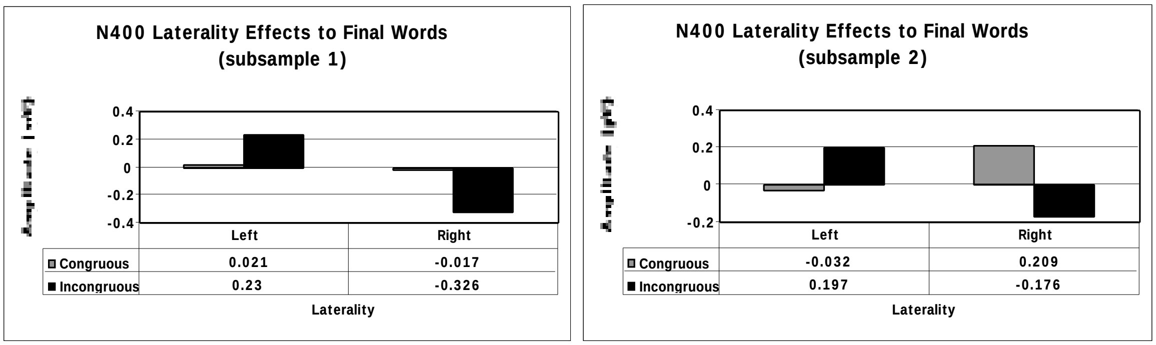


Figure 37a, b. Congruity effects shown in 2-way congruity*laterality interaction for final words only.

In addition, there was a reliable effect of word position that cut across the semantic manipulation, Position*caudality*verticality F(2, 54)= 2.74, p=.08 not quite significant for subsample 1, and F(2, 54)= 6.73, p<.01 for subsample 2. Note that while the response to nonfinal words showed a negative superior/ positive mid–inferior effect, the response to terminal words inverted front –to-back (positive posterior/negative inferior). This difference may be due to the sentence-final CNV release.

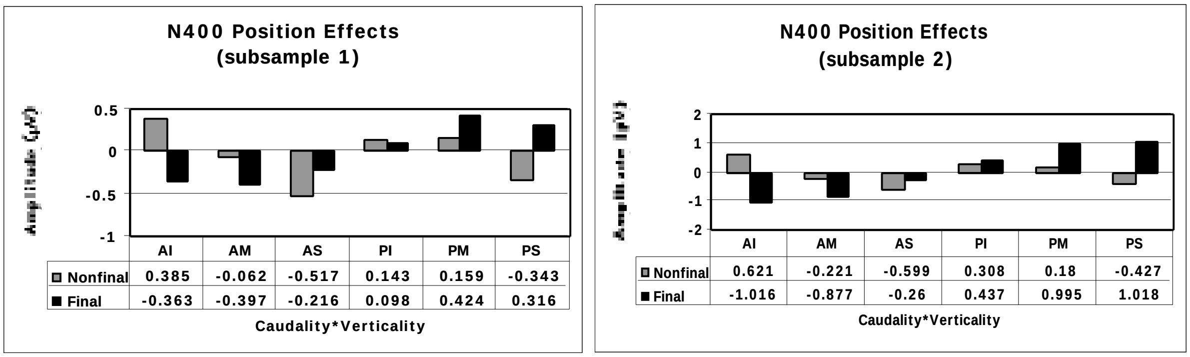


Figure 38a, b. Position effects shown in 3-way position*caudality*verticality interaction.

LPC window:580–800ms

The LPC congruity effect (580–800ms) shows a superior/inferior polar inversion, similar (but opposite in polarity) to the N400 congruity effect. Figures 39a-d break out this effect to nonfinal versus final words. The interaction between congruousness, verticality, and sentence position was highly significant for both samples, F(2, 54)= 4.05, p<.05. for subsample 1, and F(2, 54)= 8.00, p<.01 for subsample 2.

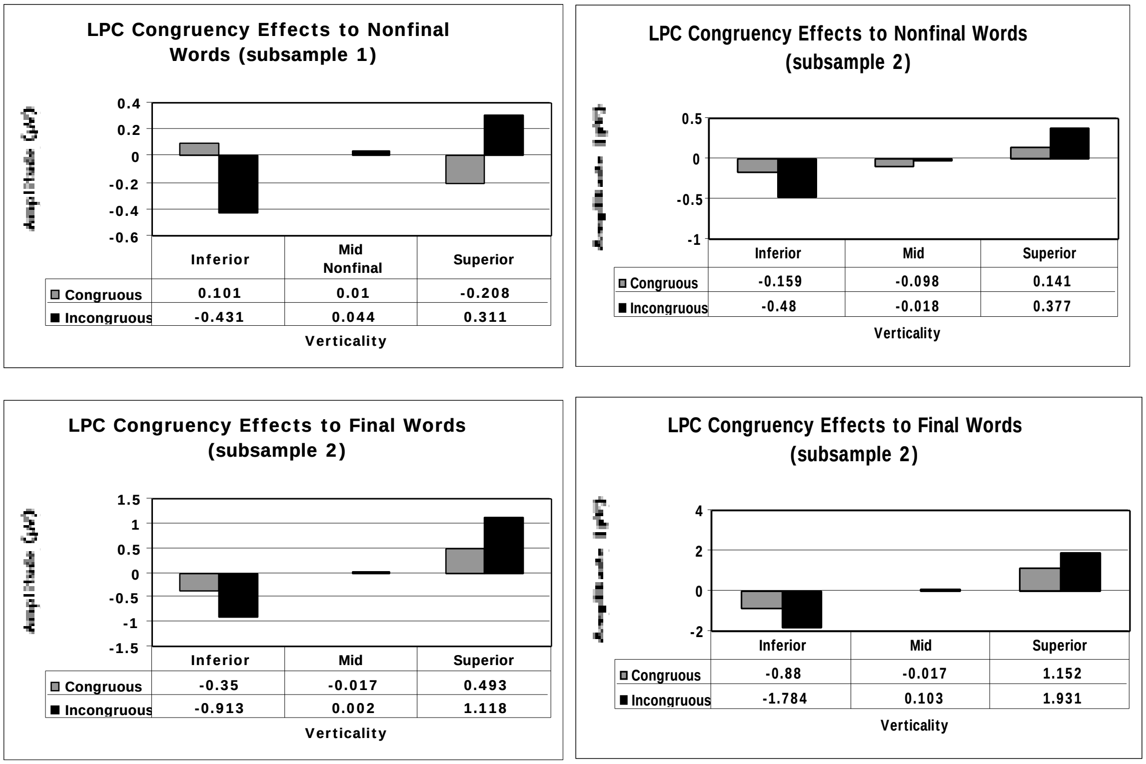


Figure 39a–d. Congruity effects shown in 2-way congruity*verticality interaction for nonfinal and final words. The interaction between congruousness, verticality, and sentence position was significant for both samples.

The position effect during the LPC window (Figs. 40a,b) is likely a composite effect, due to multiple factors that distinguish the mid-sentence and sentence-final conditions, including CNV release and response preparation in the sentence-final condition and preparation for the following word in the nonfinal condition, Position*Caudality*Verticality F(2, 54)= 22.31, p<.001 for subsample 1, and F(2, 54)= 8.06, p<.001 for subsample 2.

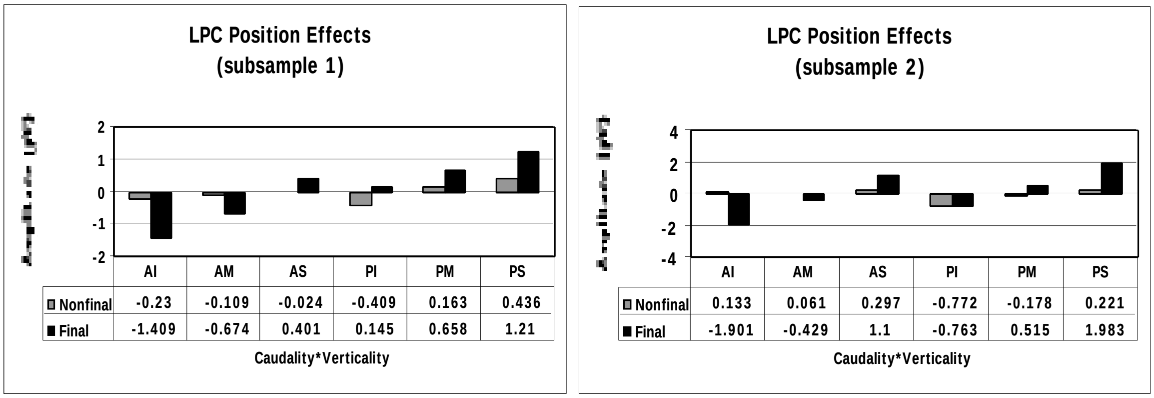


Figure 40a, b. Position effects shown in 3-way position*caudality*verticality interaction.

The difference between mid-sentence and sentence-final words was slightly enhanced over the right hemisphere, particularly for subsample 1 (Fig 41a), Position*Laterality*Verticality F(2, 54)= 7.97, p<.01 for subsample 1, and F(2, 54)= 5.24, p<.05 for subsample 2.

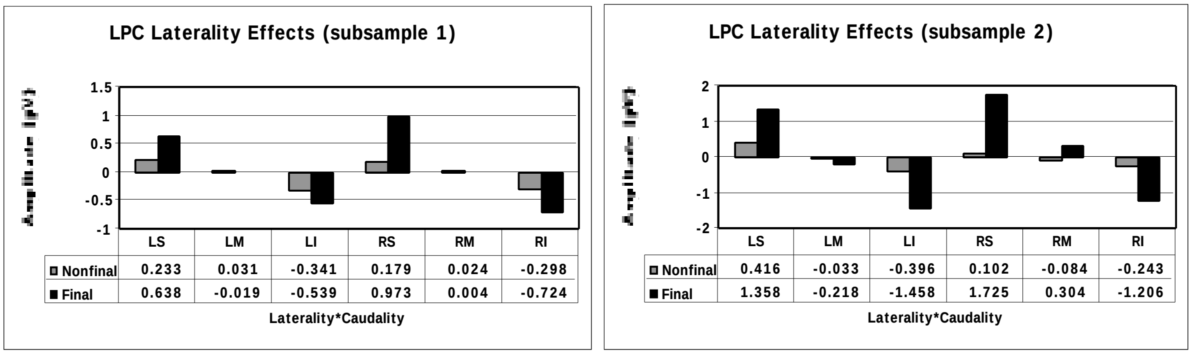


Figure 41a, b. Laterality effects shown in 3-way position*laterality*verticality interaction.

Summary

Both mastoid-referenced and average-referenced waveforms showed replication of the classical N400 effect to sentence-final semantic anomalies, with enhanced right parietal negativity to the incongruous word. In addition, improved sampling of inferior regions of the scalp revealed a frontal inferior positivity, somewhat left-lateralized. The temporal coincidence of these two effects suggests that they derive from a common source, rather than two distinct sources. Further, a later congruity effect was seen for both mid-sentence and sentence-final words. This effect was precisely the inverse of the earlier (N400 effect). However, careful examination of the topography of the early (N400) and later (LPC) congruity effects revealed distinct spatial distributions, indicating that they reflect nonidentical neural processes.

Discussion

Recent neurophysiological studies have suggested that expectancy violations may fall into discrete categories (e.g., physical, grammatical, or semantic), as evidenced by distinct characteristic patterns of brain electrical activity. Congruent with this trend, the N400 response to semantic anomaly has been characterized as a unique electrophysiological marker of semantic expectancy, distinct from other expectancy-related components, such as the N2/N200 and P300/P3b to unexpected nonlinguistic events. Thus, rather than a single mismatch detection process for semantic and nonlinguistic stimuli, recent evidence points to discrete expectancy-based processes for different categories of stimuli.

It is worth considering, however, whether a modular theory of brain-cognitive function constitutes the most appropriate model for the N400. In contrast with the highly articulated, and well-localized, functions of the neocortex, certain processes, such as primitive states of arousal, occur at a more primitive, less articulated level, forming a common substrate for higher level cognitive and sensory processing (Tucker, 1993a; Tucker, 2000, in press; Tucker & Luu, 1998). While semantic processing is commonly viewed as a high-level cognitive function, there may be aspects of semantics that tap into these more primitive, arousal-based and early categorization processes. In conceptual development, Mandler has characterized semantic categories and concepts in early infancy as image-based and nonpropositional (Mandler, 1992), implicitly linking early semantic processing to lower levels of stimulus evaluation. Similarly, neurolinguistic studies of patients with subcortical lesions have reported decrements in semantic processing, suggesting that the neocortex may not be the sole locus of meaning comprehension (Crosson, 1999). Further, the past century of linguistic research has shown that semantics, however it is implemented in the brain, is complex and multitiered. In this regard, it would be important to know what level of semantic processing is tapped by the N400 response, to help determine how this pattern is related to nonlinguistic processes of stimulus categorization and expectancy.

Methodologically, the current emphasis on spatiotemporal dynamics has enabled us to better characterize the componential structure of the N400 effect. In addition to the enhanced centroparietal negativity that is typically seen to semantic violations, improved sampling of inferior regions of the scalp revealed a frontal positivity that appeared to represent the dipole inversion of the centroparietal effect. A recent report, which included the first published N400 data using the 128-channel array, found the same enhanced frontal positivity, but it was more bilateral (Johnson & Hamm, 2000). Johnson and Hamm argued that the frontal positivity (“P400”) is distinct from the enhanced parietal N400 negativity. Using animated topography to show the timecourse of the effects, the present report suggests that these two effects vary in a temporally coherent manner, pointing to single (equivalent) dipole. While it is theoretically possible that the effects are due to multiple linked cortical networks, the single-dipole interpretation offers a more parsimonious account. Preliminary source analysis of the difference wave (incongruous–congruous response) implicates a single source in medial temporal lobe (Frishkoff et al., 2000, in preparation-a), strengthening this interpretation.

An additional focus of the present study was how the N400 effect is influenced by latency-shifting of the P300/LPC (LSP hypothesis) for both intermediate and sentence-final words. Several lines of evidence have proven consistent with this hypothesis, including the longer response time to incongruous words (cf. Fig. 6), as well as PCA data showing correlation of the P3 factor with effects of semantic congruity (Frishkoff, Dien, Hough, & Tucker, 2000, in preparation-b; Tucker & Dien, 2000, in preparation), and single-trial analysis showing increased peak latency and variability of the P300 response to incongruous words (Chung et al., 1996). In addition to demonstrating the existence of latency shifting of the P300/LPC, however, a strong version of the LSP hypothesis would assert that the N400 effect is due entirely to delay of the P300/LPC to anomalous words. Although nothing in the present data precludes this scenario, a weaker version of the LSP hypothesis may be more compatible with the present results. A weaker version of the LSP hypothesis could accommodate some effect of the LSP, without denying the existence of a distinct N400 response. Research in progress is examining each of these possibilities, using a brain electrical mapping (BESA) of equivalent dipoles to model overlap of components across time (Frishkoff et al., 2000, in preparation-a). This analysis will also serve as cross-validation for the principal components analysis of the N400 effect (Frishkoff et al., 2000, in preparation-b). If existence of a distinct N400 response were conclusively demonstrated, the strong LSP hypothesis would have to abandoned. In this case, however, it would still be important to determine when latency-shifting of the L300/LPC occurs and how it interacts with changes in amplitude of the N400 response. Application of more sophisticated analysis methods, such as PCA and trilinear decomposition, may help shed light on some or all of these important questions.

Appendix A: Stimuli

Congruous–Nonfinal
Tina visited the old mansion on the hill.
Barry picked a ripe tomato from his garden.
Phil pasted a colorful stamp on the envelope.
Tom hung a large picture on the wall.
Barbara peeled the thick skin from the orange.
Mindy bit the tough stem off an apple.
Fran fed the leftover meat to her cat.
Alan scrubbed the black dirt off his shoes.
Sally met a blind man in an alley.
Tim took his little sister to the movies.
Martin pushed the elderly woman off a cliff.
John prepared a special dinner for his mother.
Lynn found an ancient fossil in a cave.
Larry hit his big brother with a stick.
Mike planted a small tree in the forest.
Ellen wrote a long letter to her sister.
Ned closed the front door on his foot.
Oliver ate the cold bacon with some coffee.
Phil told a funny story to his children.
Ron gave an engagement ring to his girlfriend.
Steve bought a new sweater at the mall.
Victor caught a frightened mouse in his trap.
Alex hid his shaking hands in his pockets.
Bobby lifted the little girl onto the podium.
Greg pulled the bad comedian off the stage.
Jerry returned the generous loan to his brother.
Mike planted a new tree in the forest.
Ben played a sad song on the harp.
Tony buried a dead cat in the backyard.
Don shook the gray dust from an old blazer.
A closet door shut in the wind.
A bright light shined in her eyes.
The heavy window closed on her finger.
A passing car stopped along the road.
A young girl waved to her father.
The broken stool lay in a corner.
The satin pillow sat on a shelf.
The boiling water spilled in his lap.
The wet rag dripped onto the floor.
The mischievous boy winked at his partner.
The cracked vase smashed onto the floor.
The spoiled milk oozed down the drain.
The little frog hopped down the sidewalk.
The vicious dog barked at the stranger.
The green fern hung from a hook.
The fussy princess complained about the bed.
The closet door shut in the wind.
The tired baby yawned in his crib.
The evening star shone in the sky.
The open door led to a garden.
An old lady walked along the beach.
Some dark clouds hung in the sky.

The obedient horse listened to his master.
The math teacher spoke to her class.
The patient customer waited for some help.
The avid gambler stayed until midnight.
The rotten fruit dropped from a low branch.
The dance instructor spoke loudly into the microphone.
A red jacket hung from the coat rack.
A rusty nail lodged in the wood floor.
Liz filled the bottle with soda.
Peter sprayed the wall with paint.
Erin drank some milk with lunch.
Richard left his briefcase at work.
Mother dished some cereal into a bowl.
Terry locked the door to the safe.
Pat set the dishes in the sink.
Paul took the letters from the mailbox.
Tom lifted the suitcase onto a chair.
Darrel kicked the rock into the pond.
Eric threw the ball to the catcher.
Mary thanked her teacher for the help.
Karen kissed her daughter on the cheek.
Oliver lit a match in the dark.
Rick split the wood with an axe.
Mary lost her wallet on the train.
Nancy gave her order to the waiter.
Kim missed her bus in the morning.
Dale bought a watch for his coworker.
Alan sent a message to his boss.
Bill poured some wine for the guests.
Greg pushed his friend into the pool.
Ian built a castle out of clay.
Jan hung the towel on the rack.
Lillian mixed the eggs into the batter.
David killed the fly with a swatter.
Don captured a fish in the water.
Laura knitted a sweater for her best friend.
Tina spent her allowance at the candy store.
Kate removed the cake from the oven.

Congruous–Final
During class, Susan wrote a brilliant essay.
On Christmas, Oliver unwrapped his birthday present.
On television, Bob watched a nature show.
In the winter, Dana took a sewing class.
In her spare time, Lucy wrote love poems.
In the kitchen, Jennifer fixed a hot lunch.
In the afternoon, Tom tended his vegetable garden.
At the circus, Tim saw a funny clown.
In the forest, Pat found a wounded squirrel.
On the table, Mary placed some linen napkins.
In the barn, Sam fed the impatient hogs.
On the exam, Rich gave the wrong answer.
On the airplane, Bill watched a dramatic film.
In the doorway, Larry presented some fresh flowers.
On her walk, Sarah picked some yellow roses.
At the funeral, Gary heard some somber music.

In the office, Jerry received some technical forms.
In the courtroom, Ted presented the criminal case.
During the game, Pete caught a fly ball.
In the race, Mary twisted her right ankle.
Before the dance, Paul played some soft music.
On the front desk, Nancy left some files.
At the park, Lisa invented a new game.
For the summer, Tom bought a swimming pool.
In the morning, Carrie practiced her aerobic exercises.
In the oven, Ellen baked a chocolate cake.
At the concert, David played a solo piece.
From the airplane, Jack saw his mother’s house.
At the party, Tom danced a slow waltz.
On the ground, a pigeon pecked some tiny seeds.
In the storm, the window shook.
In summer, an apple tree bloomed.
In the battle, two brothers fought.
In the woods, a bird sang.
In the spring, the lake thawed.
In the refrigerator, the butter hardened.
In the valley, their voices echoed.
After the drilling, the dust settled.
In the trees, the fruit rotted.
On the playground, the full moon shone.
In the carton, a cracked egg spilled.
From the east, a strong wind blew.
Outside her door, the alley cat cried.
In the driveway, a blue car appeared.
In the heat, the ice cream melted.
On the trip, her silk dress wrinkled.
In the spring, a new chicken hatched.
During the confusion, a young calf escaped.
In the moonlight, the fresh snow sparkled.
In the darkness, the clumsy robber stumbled.
In the air, the huge balloon burst.
In the meadow, the tame horses grazed.
Over the mountains, the morning sun rose.
In the breeze, the fall leaves rustled.
Among the distant mountains, a volcano erupted.
On the rooftop, a proud rooster crowed.
In the breeze, the wet clothes dried.
In the parking lot, the engines roared.
At the altar, the devoted monk prayed.
During an important meeting, the telephone rang.
Before moving, Phil sold his house.
At school, Rob studied world geography.
At church, Larry sang a religious hymn.
In the afternoon, Pat burned some cookies.
Within twenty minutes, Matt completed the oral exam.
At the movies, Tom saw an old friend.
Under the mattress, Bob discovered some hidden cash.
On the bus, Paul finished a serious novel.
In the newspaper, Sally read a depressing article.
During his vacation, David crafted a huge birdhouse.
In the park, Janet climbed a small tree.
On the weekend, Paul attended a humorous play.

In his notes, Dennis recorded a strange occurrence.
In the lake, Betty noticed a striped fish.
In the desert, Peter saw a prickly cactus.
For the potluck, Susan baked a delicious casserole.
Before her class, Lucy recited a famous poem.
At the reunion, Ned presented a long speech.
In the end, Alice won the challenging race.
From his desk, Ted shouted his pompous demands.
At the beach, Lindsay built a beautiful sandcastle.
From the dock, Carolyn caught a small fish.
In her suitcase, Marcia kept a blank notepad.
In his coat, Gregg hid a loaded gun.
In his defense, Jack cited an early precedent.
After the game, Matt ordered a large pizza.
At the hearing, Bruce rejected the defense plea.
Before the show, Dana trimmed her own hair.
During the storm, the wind shook the house.
For the final lesson, Rick memorized a difficult song.

Incongruous–Nonfinal
Mitch sprayed the hollow bush with cool water.
Sam bought a roasted ticket for the potluck.
Alice threw the unripe pole in the garbage.
Jack noticed the blunt sand on the sidewalk.
Tom hid the flat marble in his pocket.
Lynn wrapped a cozy ant around her shoulders.
Tim placed a tall glove on his workbench.
Jack left the short cereal in the sink.
Pat washed the fidgety floor with special soap.
Dick anticipated a crowded wind at the coast.
Sue expected a cloudy mailman in the afternoon.
Phil sent a long ring to his girlfriend.
Mary spotted a tangled orange under the children's bed.
Rob brought his skillful briefcase to the company meeting.
John saw a pointed hole near the street corner.
Dan avoided the stuffy pin at the shopping mall.
Mike swept the broken puddle from his front porch.
Rich used his spicy hand in the second game.
Anne set the peaceful box on the kitchen counter.
Dan took the sour truck to an outdoor market.
Pete chased the speedy wall down the school corridor.
Nancy wiped the spilled ceiling with a hand towel.
Dale received an open saucer from his younger brother.
Jill ate a deep sandwich on her lunch break.
Barry found a spacious button on the closet floor.
Lynn ordered a noisy cake for her surprise party.
Matt sought a heavy vacation for his hard work.
Dale saw a bumpy rabbit on his mountain hike.
Bill sent a thick warning to his best friend.
Bill discovered a red idea at the grocery store.
The chicken bubbled in the pot.
Sand trickled from the widening crack.
The table scattered in the wind.
The sand unfolded along the tabletop.
The honey crumbled into a jar.
A branch oozed from the roof.

The thunder melted into the ocean.
A deer curved through the woods.
The discussion warped from the heat.
Her toenail drooped in the water.
The band dripped onto the stage.
The weather rotted in the autumn.

John's book complained about the cold winter.
The steam collapsed in the weight room.
The moss ripened in the warm sun.
The stick stepped into a messy puddle.
The lamp choked on a thick bone.
The screen inflated in the warm air.
Pond water multiplied in the summer months.
The hill snored in the hot afternoon.
The table rang in the chess match.
The pond sagged under its huge load.
The gravel dissolved in the mud puddle.
The stone played in the living room.
The glass bled onto a white towel.
The long feather bore into the hard concrete.
The kitchen chair barked at a passing cat.
The poor idea stood in a soup line.
The warm milk shattered from the sudden impact.
The kitchen ceiling spilled onto the green carpet.
Anne tore the powder into fragments.
Phyllis ripped the stream in half.
Mary crumbled the water onto a plate.
Matt scratched the certainty with a knife.
Pete murdered the tower with an axe.
Jan untangled the oil from the rope.
Ben opened the plate with a key.
Jack poured the brick into a bucket.
Sue mixed the chair with a spoon.
Lynn plugged the decision with some cotton.
Bob tamed the apple with a whip.
We rolled the x-ray across the floor.
Jim carved some syrup on the table.
Dan twisted the computer around a tree.
Mitch closed the pineapple at three o'clock.
Andrew crushed the balloon with a hammer.
Gale sharpened the paper with a stone.
Alice clogged the bone with a towel.
Rachel shredded the stone in her hands.
Ed inhaled the window through a pipe.
Jan tightened the soil for the winter.
Richard sprayed the picture on the wall.
Tiffany drank the bread with her dessert.
Ed ground the vinegar in a press.
Tom polished the smoke with a rag.
Matt spread some toys on the cake.
Jerry unpeeled the dust from the shelves.
Carrie drained the plate into the sink.
Dale crumpled an egg in his fist.
Rob snagged the trailer on a signpost.

Inconguous–Final
Stooping lower, Denny inspected the wiry garden.
At dinner, Sally suppressed her noisy wonder.
At night, Ian noticed the invalid umbrella.
Before the race, Bill had a salty nap.
From her fingernail, Jan removed the slender dirt.
At the market, Jan bought a tight bowl.
In the pit, Dale built a sturdy soup.
With a ruler, Liz measured the loose distance.
In the boardroom, Mae raised a gooey objection.
For her work, Mary needed an airtight needle.
In the forest, Kathy heard an ancient crash.
In the kitchen, Fred had a brief toaster.
From the window, John observed the shiny race.
Last night, Mary went to a tall concert.
In the summer, Ted maintained an frenetic garden.
In the air, Tim had a choppy lunch.
On the canvas, Karen painted an angry line.
During the rehearsal, Joe noticed an agile shoe.
In high school, Bob had a moody bicycle.
In his office, Kris kept a whispering jacket.
In his hand, Greg held a juicy hammer.
In a week, Dana replaced the corrupt armchair.
In the tunnel, Janice saw a dead accident.
All at once, John recognized the tall clouds.
After the party, Susan left behind her alcoholic purse.
In the basement, Chris fixed the creaky pant leg.
Losing his grip, Victor fell on a flighty branch.
After the movie, Jim walked along the sticky river.
In his new shoes, Pete crossed the flimsy pond.
Using all her strength, Anne climbed the jagged rope.
During the test, his paper snapped.
In early spring, a haystack bloomed.
In the breeze, the tower rustled.
In Alaska, a large boulder erupted.
In the forest, a fern echoed.
Over the fire, the smoke cracked.
In the bathtub, her cheerfulness floated.
In the playpen, the blankets fought.
During the earthquake, his fear shook.
In the confusion, a ring escaped.
In the explosion, her shoe burst.
In the sun, the fish ripened.
In the sky a bird twinkled.
In the article, his theory wrinkled.
Through the flowers, the snake stumbled.
In the meadow, the grass grazed.
In the open, the secret dried.
During the night, a silence howled.
In the morning, the sweat reopened.
In the distance, an entrance roared.
In the rain, the lightening hardened.
On the horizon, a rainbow crowed.
In the valley, a cow rumbled.
At the theater, the popcorn screamed.
In the city, an alley caved in.

In the warm air, theory screen inflated.
Under the lamp, the butter elapsed quickly.
In the horses' barn, a flower hatched.
In the still air, a light resonated.
In the meeting, a decision was thawed.
In the laundry room, a creak dropped.
Standing up, Tom blocked the patience.
Before leaving, Phil drained the mailbox.
Before swallowing, Fred chewed the coffee.
During the game, Sam fractured his hat.
In the kitchen, Sally minced the wine.
Near the seashore, Bill mounted a memory.
In the morning, Lynn fed her toes.
Before the show, Patty dressed her song.
In the bathroom, Alvin hung a thought.
At the wedding, Melvin hugged his wish.
In the afternoon, Paul read a game.
During a fight, Barry dented the meadow.
For an hour, Larry kneaded the article.
After an hour, Steve reached the argument.
In the end, Mary outran the cup.
In the field, Sandy planted a meeting.
Along the way, Karen bent a path.
On his head, Darren carried a judgment.
In the darkness, Billy lit his toe.
At the command, Darrell climbed the notebook.
At the rest area, John refilled the dog.
In a mixing bowl, Sarah mashed the juice.
Leaving the parking lot, Barry scraped a rainbow.
In the back yard, Tom squished the fence.
On her day off, Sally mended an accident.
Using some pliers, Barry snapped off the paint.
Running for the plane, Ned dropped his departure.
Before leaving the house, Peter locked his shirt.
On the front porch, Greg pruned his happiness.
Falling from the ladder, Edgar bruised the curtains.

Appendix B: Split-half Repeated Measures ANOVAs

P1 window (100–140ms)	**Half 1**		**Half 2**	
	F value	**p value**	**F value**	**p value**
Congruence	2.082	0.161	1.633	0.212
Position	0.405	0.530	2.225	0.147
Caudality	26.585	0.000	21.984	0.000
Laterality	4.559	0.042	5.533	0.026
Verticality	16.126	0.000	12.512	0.001
Congruence*Position	0.018	0.895	5.062	0.033
Congruence*Caudality	0.694	0.412	0.746	0.395
Position*Caudality	4.265	0.049	10.898	0.003
Congruence*Laterality	2.293	0.142	3.703	0.065
Position*Laterality	0.638	0.432	0.15	0.701
Caudality*Laterality	11.738	0.002	4.382	0.046
Congruence*Verticality	3.639	0.064	2.589	0.112
Position*Verticality	22.792	0.000	3.349	0.075
Caudality*Verticality	15.477	0.000	9.75	0.001
Laterality*Verticality	4.524	0.022	3.728	0.039
Congruence*Position*Caudality	0.581	0.453	17.336	0.000
Congruence*Position*Laterality	0.261	0.614	3.247	0.083
Congruence*Caudality*Laterality	1.032	0.319	0.094	0.761
Position*Caudality*Laterality	0.104	0.750	0.17	0.684
Congruence*Position*Verticality	0.051	0.841	1.836	0.185
Congruence*Caudality*Verticality	1.896	0.168	0.507	0.598
Position*Caudality*Verticality	5.204	0.015	3.619	0.051
Congruence*Laterality*Verticality	1.088	0.335	0.058	0.898
Position*Laterality*Verticality	1.262	0.285	2.706	0.086
Caudality*Laterality*Verticality	8.498	0.002	1.706	0.202
Congruence*Position*Caudality*Laterality	0.563	0.459	0.769	0.388
Congruence*Position*Caudality*Verticality	3.29	0.060	5.223	0.023
Congruence*Position*Laterality*Verticality	1.422	0.251	0.867	0.404
Congruence*Caudality*Laterality*Verticality	0.068	0.928	0.598	0.523
Position*Caudality*Laterality*Verticality	0.733	0.451	0.062	0.923
Congruence*Position*Caudality*Laterality*Verticality	1.306	0.278	0.168	0.822

N1 window (168–208ms)	**Half 1**		**Half 2**	
	F value	**p value**	**F value**	**p value**
Congruence	**0.55**	**0.465**	**0.601**	**0.445**
Position	**0.172**	**0.681**	**0.688**	**0.414**
Caudality	**56.237**	**0.000**	**47.835**	**0.000**
Laterality	**0.524**	**0.475**	**17.257**	**0.000**
Verticality	**22.513**	**0.000**	**32.587**	**0.000**
Congruence*Position	**1.095**	**0.305**	**2.725**	**0.110**
Congruence*Caudality	**0.948**	**0.339**	**0.046**	**0.832**
Position*Caudality	**8.13**	**0.008**	**3.204**	**0.085**
Congruence*Laterality	**0.781**	**0.385**	**0.121**	**0.731**
Position*Laterality	**0.005**	**0.943**	**0.827**	**0.371**
Caudality*Laterality	**16.339**	**0.000**	**10.236**	**0.004**
Congruence*Verticality	**0.17**	**0.714**	**0.58**	**0.493**
Position*Verticality	**1.59**	**0.219**	**0.709**	**0.418**
Caudality*Verticality	**46.319**	**0.000**	**70.582**	**0.000**
Laterality*Verticality	**2.075**	**0.149**	**3.537**	**0.048**
Congruence*Position*Caudality	**1.163**	**0.290**	**4.328**	**0.047**
Congruence*Position*Laterality	**0.262**	**0.613**	**4.829**	**0.037**
Congruence*Caudality*Laterality	**1.425**	**0.243**	**0.001**	**0.970**
Position*Caudality*Laterality	**0.54**	**0.469**	**0.215**	**0.647**
Congruence*Position*Verticality	**0.053**	**0.856**	**0.791**	**0.399**
Congruence*Caudality*Verticality	**1.555**	**0.225**	**0.656**	**0.476**
Position*Caudality*Verticality	**4.066**	**0.038**	**1.072**	**0.332**
Congruence*Laterality*Verticality	**0.088**	**0.890**	**0.279**	**0.655**
Position*Laterality*Verticality	**0.368**	**0.633**	**3.548**	**0.054**
Caudality*Laterality*Verticality	**12.684**	**0.000**	**13.599**	**0.000**
Congruence*Position*Caudality*Laterality	**0.798**	**0.380**	**3.752**	**0.063**
Congruence*Position*Caudality*Verticality	**0.857**	**0.409**	**2.752**	**0.095**
Congruence*Position*Laterality*Verticality	**1.356**	**0.266**	**1.08**	**0.336**
Congruence*Caudality*Laterality*Verticality	**0.733**	**0.477**	**0.184**	**0.769**
Position*Caudality*Laterality*Verticality	**5.319**	**0.019**	**0.148**	**0.826**
Congruence*Position*Caudality*Laterality*Verticality	**0.502**	**0.583**	**0.408**	**0.608**

Late N1 window (212–252ms)	**Half 1**		**Half 2**	
	F value	**p value**	**F value**	**p value**
Congruence	1.019	0.322	4.421	0.045
Position	2.042	0.165	1.057	0.313
Caudality	47.667	0.000	60.303	0.000
Laterality	0.145	0.707	5.12	0.032
Verticality	27.97	0.000	36.549	0.000
Congruence*Position	0.767	0.389	0.682	0.416
Congruence*Caudality	0.205	0.655	2.881	0.101
Position*Caudality	19.569	0.000	1.939	0.175
Congruence*Laterality	0.138	0.713	3.255	0.082
Position*Laterality	0.084	0.774	1.818	0.189
Caudality*Laterality	25.186	0.000	2.83	0.104
Congruence*Verticality	0.333	0.598	0.241	0.667
Position*Verticality	3.561	0.062	6.912	0.010
Caudality*Verticality	31.814	0.000	82.932	0.000
Laterality*Verticality	1.378	0.260	1.277	0.281
Congruence*Position*Caudality	0.002	0.963	2.47	0.128
Congruence*Position*Laterality	0.116	0.736	3.52	0.072
Congruence*Caudality*Laterality	0.011	0.917	4.159	0.051
Position*Caudality*Laterality	3.19	0.085	3.37E-04	0.986
Congruence*Position*Verticality	0.106	0.780	0.063	0.852
Congruence*Caudality*Verticality	0.754	0.450	5.32	0.018
Position*Caudality*Verticality	6.483	0.007	2.843	0.092
Congruence*Laterality*Verticality	0.085	0.911	0.285	0.661
Position*Laterality*Verticality	3.208	0.068	4.939	0.018
Caudality*Laterality*Verticality	15.829	0.000	9.509	0.001
Congruence*Position*Caudality*Laterality	0.255	0.618	2.437	0.130
Congruence*Position*Caudality*Verticality	0.421	0.584	2.604	0.108
Congruence*Position*Laterality*Verticality	1.413	0.252	0.641	0.494
Congruence*Caudality*Laterality*Verticality	2.738	0.082	1.533	0.229
Position*Caudality*Laterality*Verticality	9.386	0.002	0.313	0.703
Congruence*Position*Caudality*Laterality*Verticality	0.716	0.472	0.271	0.713

Temporal Negativity window (260–300ms)	**Half 1**		**Half 2**	
	F value	**p value**	**F value**	**p value**
Congruence	0.163	0.690	2.805	0.106
Position	0.207	0.653	1.026	0.320
Caudality	1.255	0.273	1.091	0.306
Laterality	0.609	0.442	7.023	0.013
Verticality	11.073	0.002	13.976	0.000
Congruence*Position	0.945	0.340	3.701	0.065
Congruence*Caudality	0.038	0.848	0.725	0.402
Position*Caudality	4.012	0.055	0.785	0.383
Congruence*Laterality	2.42	0.131	0.489	0.490
Position*Laterality	1.971	0.172	0.257	0.617
Caudality*Laterality	7.789	0.010	0.926	0.345
Congruence*Verticality	4.488	0.040	6.638	0.008
Position*Verticality	13.48	0.000	14.859	0.000
Caudality*Verticality	10.964	0.001	12.134	0.000
Laterality*Verticality	5.572	0.011	2.282	0.127
Congruence*Position*Caudality	0.005	0.942	4.573	0.042
Congruence*Position*Laterality	0.865	0.361	8.328	0.008
Congruence*Caudality*Laterality	0.01	0.920	1.858	0.184
Position*Caudality*Laterality	1.171	0.289	0.45	0.508
Congruence*Position*Verticality	1.537	0.227	0.19	0.704
Congruence*Caudality*Verticality	6.839	0.006	1.597	0.218
Position*Caudality*Verticality	3.083	0.073	0.923	0.383
Congruence*Laterality*Verticality	0.789	0.430	0.81	0.418
Position*Laterality*Verticality	2.17	0.142	6.284	0.006
Caudality*Laterality*Verticality	17.521	0.000	5.906	0.009
Congruence*Position*Caudality*Laterality	0.056	0.815	9.841	0.004
Congruence*Position*Caudality*Verticality	1.115	0.321	3.457	0.063
Congruence*Position*Laterality*Verticality	0.908	0.402	1.674	0.204
Congruence*Caudality*Laterality*Verticality	3.582	0.046	0.688	0.462
Position*Caudality*Laterality*Verticality	6.956	0.006	0.253	0.755
Congruence*Position*Caudality*Laterality*Verticality	0.174	0.808	0.368	0.621

Pre-N400 window (300–340ms)	**Half 1**		**Half 2**	
	F value	**p value**	**F value**	**p value**
Congruence	**0.000**	**0.985**	**9.528**	**0.005**
Position	**0.001**	**0.982**	**6.446**	**0.017**
Caudality	**1.816**	**0.189**	**18.313**	**0.000**
Laterality	**0.011**	**0.918**	**3.429**	**0.075**
Verticality	**0.875**	**0.372**	**0.722**	**0.428**
Congruence*Position	**0.610**	**0.442**	**0.092**	**0.764**
Congruence*Caudality	**0.303**	**0.587**	**6.802**	**0.015**
Position*Caudality	**1.035**	**0.318**	**5.763**	**0.024**
Congruence*Laterality	**1.711**	**0.202**	**0.826**	**0.372**
Position*Laterality	**2.246**	**0.146**	**5.10E-05**	**0.994**
Caudality*Laterality	**1.590**	**0.218**	**5.005**	**0.034**
Congruence*Verticality	**11.041**	**0.002**	**13.976**	**0.000**
Position*Verticality	**17.437**	**0.000**	**23.706**	**0.000**
Caudality*Verticality	**7.153**	**0.006**	**8.082**	**0.001**
Laterality*Verticality	**10.267**	**0.000**	**3.499**	**0.046**
Congruence*Position*Caudality	**6.386**	**0.018**	**1.091**	**0.306**
Congruence*Position*Laterality	**4.435**	**0.045**	**11.266**	**0.002**
Congruence*Caudality*Laterality	**0.197**	**0.661**	**2.061**	**0.163**
Position*Caudality*Laterality	**0.846**	**0.366**	**0.734**	**0.399**
Congruence*Position*Verticality	**6.878**	**0.011**	**1.073**	**0.320**
Congruence*Caudality*Verticality	**8.419**	**0.002**	**5.646**	**0.014**
Position*Caudality*Verticality	**0.360**	**0.637**	**0.473**	**0.563**
Congruence*Laterality*Verticality	**0.591**	**0.515**	**0.018**	**0.937**
Position*Laterality*Verticality	**3.610**	**0.052**	**3.99**	**0.040**
Caudality*Laterality*Verticality	**17.850**	**0.000**	**4.324**	**0.025**
Congruence*Position*Caudality*Laterality	**0.579**	**0.454**	**6.162**	**0.020**
Congruence*Position*Caudality*Verticality	**4.337**	**0.034**	**1.551**	**0.226**
Congruence*Position*Laterality*Verticality	**0.776**	**0.433**	**1.142**	**0.315**
Congruence*Caudality*Laterality*Verticality	**2.979**	**0.076**	**2.138**	**0.144**
Position*Caudality*Laterality*Verticality	**2.958**	**0.081**	**0.148**	**0.841**
Congruence*Position*Caudality*Laterality*Verticality	**0.123**	**0.822**	**0.731**	**0.456**

N400 window (340–420ms)	**Half 1**		**Half 2**	
	F value	**p value**	**F value**	**p value**
Congruence	7.311	0.0117	17.57	0.0003
Position	1.249	0.2735	17.665	0.0003
Caudality	1.828	0.1875	12.239	0.0016
Laterality	4.532	0.0425	0.11	0.7432
Verticality	1.831	0.1858	0.467	0.5161
Congruence*Position	4.245	0.0491	2.296	0.1414
Congruence*Caudality	8.656	0.0066	13.365	0.0011
Position*Caudality	10.065	0.0037	35.564	0.0001
Congruence*Laterality	4.923	0.0351	3.51	0.0719
Position*Laterality	0.401	0.5317	0.17	0.6830
Caudality*Laterality	0.401	0.5318	2.07	0.1617
Congruence*Verticality	26.361	0.0001	39.566	0.0001
Position*Verticality	13.617	0.0006	33.243	0.0001
Caudality*Verticality	4.061	0.0353	7.647	0.0024
Laterality*Verticality	8.195	0.0018	1.56	0.2236
Congruence*Position*Caudality	18.729	0.0002	2.747	0.1090
Congruence*Position*Laterality	3.12	0.0886	13.55	0.0010
Congruence*Caudality*Laterality	0.016	0.9001	0.866	0.3603
Position*Caudality*Laterality	2.634	0.1162	1.099	0.3039
Congruence*Position*Verticality	8.754	0.0040	4.324	0.0371
Congruence*Caudality*Verticality	24.155	0.0001	8.519	0.0021
Position*Caudality*Verticality	2.739	0.0889	6.729	0.0046
Congruence*Laterality*Verticality	1.211	0.2956	0.021	0.9409
Position*Laterality*Verticality	2.355	0.1226	4.264	0.0357
Caudality*Laterality*Verticality	5.994	0.0101	2.788	0.0835
Congruence*Position*Caudality*Laterality	0.353	0.5572	12.122	0.0017
Congruence*Position*Caudality*Verticality	10.038	0.0012	0.362	0.6023
Congruence*Position*Laterality*Verticality	1.071	0.3383	1.497	0.2355
Congruence*Caudality*Laterality*Verticality	5.364	0.0188	1.063	0.3414
Position*Caudality*Laterality*Verticality	5.078	0.0168	0.461	0.6155
Congruence*Position*Caudality*Laterality*Verticality	0.032	0.9286	2.053	0.1530

LPC window (580–800ms)	**Half 1**		**Half 2**	
	F value	**p value**	**F value**	**p value**
Congruence	1.425	0.243	0.012	0.915
Position	25.013	0.000	30.613	0.000
Caudality	17.519	0.000	1.342	0.257
Laterality	0.033	0.857	2.223	0.148
Verticality	24.555	0.000	38.542	0.000
Congruence*Position	0.55	0.465	3.07E-05	0.996
Congruence*Caudality	9.449	0.005	4.652	0.040
Position*Caudality	13.927	0.001	13.359	0.001
Congruence*Laterality	4.21	0.050	6.678	0.016
Position*Laterality	0.164	0.689	6.153	0.020
Caudality*Laterality	1.119	0.299	1.135	0.296
Congruence*Verticality	12.204	0.001	25.61	0.000
Position*Verticality	9.975	0.003	30.615	0.000
Caudality*Verticality	0.82	0.429	1.838	0.171
Laterality*Verticality	4.157	0.032	2.01	0.159
Congruence*Position*Caudality	0.003	0.955	0.835	0.369
Congruence*Position*Laterality	1.232	0.277	25.158	0.000
Congruence*Caudality*Laterality	0.21	0.650	0.049	0.826
Position*Caudality*Laterality	0.013	0.911	8.266	0.008
Congruence*Position*Verticality	4.052	0.045	8.001	0.004
Congruence*Caudality*Verticality	2.307	0.126	0.361	0.679
Position*Caudality*Verticality	22.31	0.000	8.059	0.001
Congruence*Laterality*Verticality	0.895	0.388	1.908	0.174
Position*Laterality*Verticality	7.969	0.006	5.24	0.018
Caudality*Laterality*Verticality	0.164	0.807	3.896	0.041
Congruence*Position*Caudality*Laterality	0.716	0.405	11.406	0.002
Congruence*Position*Caudality*Verticality	0.581	0.499	1.49	0.237
Congruence*Position*Laterality*Verticality	1.21	0.291	0.993	0.356
Congruence*Caudality*Laterality*Verticality	1.861	0.172	1.323	0.274
Position*Caudality*Laterality*Verticality	1.939	0.167	1.087	0.331
Congruence*Position*Caudality*Laterality*Verticality	0.187	0.773	0.459	0.589

Bibliography

Anderson, J. E., & Holcomb, P. J. (1995). Auditory and visual semantic priming using different stimulus onset asynchronies: an event-related brain potential study. *Psychophysiology, 32*(2), 177-190.

Bentin, S. (1987). Event-related potentials, semantic processes, and expectancy factors in word recognition. *, 31*(2), 308-327.

Besson, M., & Macar, M. (1986). Visual and auditory event-related potentials elicited by linguistic and non-linguistic incongruities. *Neurosci Lett, 63*(2), 109-114.

Breton, F., Ritter, W., Simson, R., & Vaughan, H. G. (1988). The N2 component elicited by stimulus matches and multiple targets. *, 27*(1), 23-44.

Brunswick, N., & Rippon, G. (1994). Auditory event-related potentials, dichotic listening performance and handedness as indices of lateralisation in dyslexic and normal readers. *Int J Psychophysiol, 18*(3), 265-275.

Chung, G., Tucker, D. M., West, P., Potts, G. F., Liotti, M., Luu, P., & Hartry, A. L. (1996). Emotional expectancy: brain electrical activity associated with an emotional bias in interpreting life events. *Psychophysiology, 33*(3), 218-233.

Connolly, J. F., Stewart, S., & Phillips, N. (1990). The effects of processing requirements on neurophysiological responses to spoken sentences. *Brain Lang, 39*(2), 302-318.

Crosson, B. (1999). Subcortical mechanisms in language: lexical-semantic mechanisms and the thalamus. *Brain Cogn, 40*(2), 414-438.

Curran, T., Tucker, D. M., Kutas, M., & Posner, M. I. (1993). Topography of the N400: Brain electrical activity reflecting semantic expectation. *Electroencephalography and Clinical Neurophysiology, 88*(3), 188—209.

Deacon, D., Breton, F., Ritter, W., & Vaughan, H. G., Jr. (1991). The relationship between N2 and N400: Scalp distribution, stimulus probability, and task relevance. *Psychophysiology, 28, 185-200.*

Dien, J. (1998a). Addressing misallocation of variance in principal components analysis of event-related potentials. *Brain Topography, 11*(1), 43—55.

Dien, J. (1998b). Issues in the application of the average reference: Review, critiques, and recommendations. *Behavioral Research Methods, Instruments, and Computers, 30*.

Dien, J., Frishkoff, G. A., & Tucker, D. M. (2000). Differentiating the N3 and N4 electrophysiological semantic incongruity effects. *Brain & Cognition, 43*, 148-152.

Donchin, E., & Coles, M. G. H. (1988). Is the P300 component a manifestation of context updating? *Behavioral and Brain Sciences, 11*, 357-374.

Duncan-Johnson, C. C. (1981). P300 latency: A new metric of information processing. *Psychophysiology, 18*(3), 207-215.

Duncan-Johnson, C. C., & Donchin, E. (1977). On quantifying surprise: The variation of event-related potentials with subjective probability. *Psychophysiology, 14*(3), 456-467.

Duncan-Johnson, C. C., & Donchin, E. (1979). The time constant in P300 recording. *Psychophysiology, 16*, 53-55.

Fischler, I., Childers, D. G., Achariyapaopan, T., & Perry, N. W. (1985). Brain potentials during sentence verification: Late negativity and long-term memory strength. *Neuropsychologia, 22*(559–568).

Frishkoff, G., Davey, C., & Tucker, D. M. (2000, in preparation-a). Neural correlates of the N400 effect: Mapping equivalent dipoles through time.

Frishkoff, G. A., Dien, J., Hough, M., & Tucker, D. M. (2000, in preparation-b). Componential Analysis of the N400 Response to Semantic Anomaly.

Holcomb, & Neville. (1991). Natural speech processing: An analysis using event-related brain potentials. *Psychobiology, 19*(4), Dec 1991.

Holcomb, P. J. (1988). Automatic and attentional processing: An event-related brain potential analysis of semantic priming. *, 35*(1), 66-85.

Holcomb, P. J., Coffey, S. A., & Neville, H. J. (1992). Visual and auditory sentence processing: a developmental analysis using event-related potentials. *Developmental Neuropsychology, 8*(2 &3), 203—241.

Johnson, B. W., & Hamm, J. P. (2000). High-density mapping in an N400 paradigm: evidence for bilateral temporal lobe generators. *Clin Neurophysiol, 111*(3), 532-545.

Kleiman, G. M. (1980). Sentence frame contexts and lexical decisions: Sentences acceptability and word-relatedness effects. *Memory and Cognition, 8*, 336—344.

Kutas, M., & Hillyard, S. A. (1980a). Event-related potentials to semantically inappropriate and surprisingly large words. *Biological Psychology, 11*, 99—116.

Kutas, M., & Hillyard, S. A. (1980b). Reading senseless sentences: Brain potentials reflect semantic incongruity. *Science, 207*, 203—205.

Kutas, M., & Hillyard, S. A. (1980c). Reading between the lines: Event-related brain potentials during natural sentence processing. *Brain and Language, 11*, 354-373.

Kutas, M., & Hillyard, S. A. (1983). Event-related brain potentials to grammatical errors and semantic anomalies. *, 11*(5), 539-550.

Kutas, M., & Hillyard, S. A. (1984). Brain potentials during reading reflect word expectancy and semantic association. *, 307*(5947), 161-163.

Kutas, M., Lindamood, T. E., & Hillyard, S. A. (1984). Word expectancy and event-related brain potentials during sentence processing. In S. Kornblum & R. J. (Eds.), *Preparatory states and processes* (pp. 217-237). Hillsdale: Erlbaum.

Kutas, M., McCarthy, G., & Donchin, E. (1977). Augmenting mental chronometry: The P300 as a measure of stimulus evaluation time. *Science, 197*, 792-795.

Kutas, M., Van Petten, C., & Besson, M. (1988a). Event-related potential asymmetries during the reading of sentences. *Electroencephalogr Clin Neurophysiol, 69*(3), 218-233.

Kutas, M., Van Petten, C., & Besson, M. (1988b). Event-related potentials asymmetries during the reading of sentences. *Electroencephalography and Clinical Neurophysiology, 69*, 218-233.

Mandler, J. (1992). How to build a baby: II. Conceptual primitives. *Psychological Review, 99*, 587-604.

Munte, T. F., Szentkuti, A., Wieringa, B. M., Matzke, M., & Johannes, S. (1997). Human brain potentials to reading syntactic errors in sentences of different complexity. *Neurosci Lett, 235*(3), 105-108.

Naatanen, R., & Gaillard, A. W. K. (Eds.). (1983). *The Orienting Reflex and the N2 Deflection of the Event-Related Potential (ERP)*. Amsterdam: North-Holland.

Neville, H. (1991). Syntactically Based Sentence Processing Classes: Evidence from Event-Related Brain Potentials. *Journal of Cognitive Neuroscience, 3*(2), 151—165.

Neville, H. J. (1985). Brain potentials reflect meaning in language. *TINS, 8*(3), 91-92.

Neville, H. J., Kutas, M., Chesney, G., & Schmidt, A. L. (1986). Event-related brain potentials during initial encoding and recognition memory of congruous and incongruous words. *Journal of Memory and Language, 25*.

Osterhout, L. (1997). On the brain response to syntactic anomalies: manipulations of word position and word class reveal individual differences. *Brain Lang, 59*(3), 494-522.

Polich, J. (1985). Semantic categorization and event-related potentials, *26*(2), 304-321.

Polich, J., Vanasse, L., & Donchin, E. (1980). Category expectancy and the N200. *Psychophysiology, 18, 142. (Abstract).*

Rugg, M. D., & Coles, M. G. H. (1995). *Electrophysiology of Mind: Event-Related Brain Potentials and Cognition*. New York: Oxford University Press.

Squires, N. K., Squires, K. C., & Hillyard, S. A. (1975). Two varieties of long-latency positive waves evoked by unpredictable auditory stimuli in man. *Electroencephalography and Clinical Neurophysiology*(39), 387—401.

Tucker, D. M. (1993a). Emotional experience and the problem of vertical integration: Discussion of the special section on emotion. *Neuropsychology, 7*, 500-509.

Tucker, D. M. (1993b). Spatial sampling of head electrical fields: the geodesic sensor net. *Electroencephalogr Clin Neurophysiol, 87*(3), 154-163.

Tucker, D. M. (2000, in press). Motivational Control of Memory: Hierarchic Anatomy and Physiological Mechanisms. In G. Gainotti (Ed.), *Handbook of Neuropsychology* .

Tucker, D. M., & Dien, J. (2000, in preparation). Analyzing Superposition: Principal Component Analysis of the N400 Effect.

Tucker, D. M., Liotti, M., Potts, G. F., Russell, G. S., & Posner, M. I. (1994). Spatiotemporal analysis of brain electrical fields. *Human Brain Mapping, 1,* 134-152.

Tucker, D. M., & Luu, P. (1998). Cathexis revisited. Corticolimbic resonance and the adaptive control of memory. *Ann N Y Acad Sci, 843*, 134-152.

Van Burkum, J. A., Hagoort, P., & Brown, C. M. (1999). Semantic integration in sentences and discourse: Evidence from the N400. *Journal of Cognitive Neuroscience, 11*(6), 657–671.

Van Petten, C. (1993). A comparison of lexical and sentence-level context effects in event-related potentials. *Language and Cognitive Processes, 8*(4), 485—531.

Van Petten, C. (1995). Words and sentences: event-related brain potential measures. *Psychophysiology, 32*(6), 511-525.

Van Petten, C., & Kutas, M. (1990). Interactions between sentence context and word frequency in event- related brain potentials. *Mem Cognit, 18*(4), 380-393.

Weisbrod, M., Kiefer, M., Winkler, S., Maier, S., Hill, H., Roesch-Ely, D., & Spitzer, M. (1999). Electrophysiological correlates of direct versus indirect semantic priming in normal volunteers. *Cognitive Brain Research, 8*(3), 289–298.

Woody, C. D. (Ed.). (1967). *Characterization of an Adaptive Filter for the Analysis of Variable Latency Neuroelectric Signals*. (Vol. 5): Pergamon Press.