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FEATURE ARTICLE

ANALYZING SEMANTIC PROCESSING USING EVENT-RELATED BRAIN POTENTIALS

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This work was performed between 1994-1996, while the first author was a member of Dr. Neville's lab at Department of Cognitive Science, University of California, San Diego.

EDITOR'S NOTE

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ANALYZING SEMANTIC PROCESSING USING EVENT-RELATED BRAIN POTENTIALS

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Abstract

The brain's electrical response to violations of semantic or syntactic structure differs as a function of the type of violation. Recent event-related potential (ERP) studies have shown that violations of different syntactic structures elicit distinct brainwave patterns. Whether this is true for semantic violations, which canonically generate an N400, has not yet been systematically explored. This study performs an analysis of the semantic domain by examining ERPs recorded from eighteen young adults as they read sentences containing three classes of semantic violations: improbability, hyponymy, and negative polarity. Improbability anomalies elicited a robust N400 effect. By contrast, neither hyponymy nor negative polarity violations elicited an N400. Hyponymy anomalies elicited a sustained left anterior negativity that began at 500 msec post-onset while negative polarity elicited a small anterior negativity between 300-500 msec. Furthermore, although the three classes violate specific semantic properties, ERPs for all three classes included a late posterior positivity similar to that reported in studies of syntactic violations. Onset of the positivity varied for each class: improbability 540 msec, hyponymy 380 msec, negative polarity 500 msec. These data show that ERP responses in the semantic domain yield results as rich as those reported for syntactic violations. In addition, the results suggest a re-evaluation of the syntax-semantics dichotomy made at the neural level by past ERP studies that have used the N400 as a specific marker of semantic violation and the late positivity as a specific marker of syntactic processing.

INTRODUCTION

Language users synthesize pieces of linguistic information -- phonological, morphological, syntactic, semantic, and pragmatic -- in seeking to achieve the most fundamental and crucial aspects of language communication: the conveyance of thought and the comprehension of meaning. The study of linguistic meaning, or semantics, explores the nature of meaning and strives to understand the role meaning plays in the human communication process, and more generally, in human cognition. It is in this spirit that the present study aims to widen our understanding of semantic processing by approaching the task from a neurobiological perspective. In particular, by using the technique of event-related potentials, we offer an examination of the underlying neural processes associated with the processing of different types of semantic information.

The task of trying to describe and understand the dynamics involved in semantic organization is, of course, no easy feat. One approach that language researchers have taken in constructing a systematic method for studying the structure and logic of the semantic properties of language is by analyzing anomalous sentences (e.g., Cruse, 1986). Analyzing and categorizing semantic anomalies provides for a systematic approach to sorting out the relationship between concepts represented by lexical items and sentences and allows for the formulation of criteria in evaluating the well-formedness of expressions. The following are some examples of categories of violations of semantic relationships that have been distinguished by linguistic theory (e.g., Kempson, 1977; Cruse, 1986; Larson, 1990):

<u>Antonyms</u>:
*Jim rushed slowly to the door.
*It is cold today, but it is hot.

<u>Contradiction</u>:
*Fred is a bachelor and his wife makes great pies.
*Jane is a strict vegetarian and she eats lots of meat everyday.

<u>Hyponymy</u>:
*Susie never eats dessert, so after dinner she always likes to have some cake.
*It was not an animal that we saw in the woods but a grizzly bear.

<u>Improbability</u>:
*The throne was occupied by a pipe-smoking alligator.
*My grandmother baked chocolate chip cookies in the engine.

Negative Polarity:
*Tina liked the movie at all.
*Cliff believes that he has ever seen that woman before.

Pleonasm:
*A female mother took her children to the park.
*He was murdered illegally.

Zeugma:
*Jim caught a cold and a fish.
*Arthur and his driver's license expired last Thursday.

These sentences above illustrate that semantic differences can be systematically mapped out by identifying distinct classes of relationships that describe interactions between lexical semantic properties within a sentence. With that achieved, the investigation of semantic processing can be approached in a methodical manner.

In trying to shed light on the nature of semantic processing, cognitive neuroscientists have taken advantage of recent advances in measuring tools and imaging techniques in seeking explanations and understanding of semantic aspects of language processing at a biological level. Several positron emission tomography (PET) studies have implicated the left prefrontal and left inferior temporal regions in the brain during semantic tasks such as semantic categorization, lexical search, and word recognition (Demonet, Chollet, Ramsay, Cardebat, Nespoulous, Wise, Rascol, and Frackowiak, 1992; Sakurai, Momose, Iwata, Watanabe, Ishikawa, and Kanazawa, 1993; Kapur, Rose, Liddle, Zipursky, Brown, Stuss, Houle, and Tulving, 1994; Klein, Milner, Zatorre, Meyer, and Evans, 1995). Likewise, functional magnetic resonance imaging (FMRI) studies have also reported activation in the left prefrontal and left temporal regions during similar semantic encoding processes (Bellemann, Spitzer, Brix, Kammer, Loose, Schwartz, and Guckel, 1995; Demb, Desmond, Wagner, Vaidya, Glover, and Gabrieli, 1995).

However, while PET and FMRI studies are particularly good at providing spatial information regarding the location of neural structures responsible for particular cognitive processes, the important temporal properties of these processes are not as informatively supplied. The scalp recording technique of event-related potentials (ERPs), by contrast, provides a fine temporal resolution of neural processes occurring on the order of milliseconds and proves to be an important tool by which rapid and natural linguistic processes can be examined as they unfold online. ERPs are averaged, patterned voltage changes in the ongoing electroencephalogram (EEG) of the brain that are sensitive and time-locked to sensory, motor, and cognitive processes (Hillyard and Picton, 1987). Characteristics of ERPs useful for analysis and comparison between different cognitive processes include the amplitude of a potential, its onset (latency), polarity, and distribution across the scalp. Under the assumption that distinct ERP patterns index nonidentical patterns of brain activity, ERP language studies have utilized linguistically-defined categories to direct a systematic exploration into the cerebral organization and processing of language.

ERP Research in Language

A series of ERP language studies within the past 16 years has been performed to examine the nature of online language comprehension. Kutas and Hillyard (1980a, 1980b, 1980c) first observed that contextually inappropriate words at the end of a sentence (e.g., "I take my coffee with cream and *dog*") elicit a large negative potential that onsets around 250 msec and peaks around 400 msec following the presentation of the inappropriate word. This so-called N400 was bilaterally distributed, was most pronounced over centro-parietal regions of the scalp, and tended to be larger over the right than the left hemisphere. The N400 has since been reliably recorded in subsequent studies involving the evaluation of semantic content and information. But while the N400 was first observed within the context of semantic violations, subsequent studies have shown that the N400 is not a manifestation of semantic violation detection per se. The amplitude of the N400 is modulated by an array of semantic integration factors such as word frequency, the cloze probability of a target word, the degree of semantic relatedness between a target word and the word that best completes the sentence, the degree of semantic priming for a target word, and prior contextual cues and constraints (Kutas and Hillyard, 1984; Kutas, Lindamood, and Hillyard, 1984; Holcomb and Neville, 1990; Van Petten and Kutas, 1990; also see Kutas and Van Petten, 1990 and Kutas and Kluender, 1994 for thorough overview).

While much of the early ERP work in language was devoted to the investigation of the relationship between the N400 and semantic processing, more recent ERP studies have examined the processing of syntactic variations in language. The range of syntactic structures investigated to date include violations of verb subcategorization, phrase structure, specificity constraints, subjacency constraints, verb number and gender agreement, and the processing of long-distance dependencies (Kutas and Hillyard, 1983; Neville, Nicol, Barss, Forster, and Garrett, 1991; Osterhout and Holcomb, 1992; Hagoort, Brown, and Groothusen, 1993; Kluender and Kutas, 1993; Münte, Heinze, and Mangun, 1993; Rösler, Pütz, Friederici, and Hahne, 1993; Friederici, Pfeifer, and Hahne, 1993; Osterhout, Holcomb, and Swinney, 1994). Interestingly, the ERP results for the processing of these syntactic structures have yielded a diverse range of brainwave patterns that are distinct from the semantic N400. While the electrophysiological correlates reported for syntactic processes are not very homogeneous, the common findings reduce generally to a late posterior positive wave that onsets about 500 msec following the onset of the target word (labeled P600 by Osterhout and Holcomb, 1992; labeled Slow Positive Shift (SPS) by Hagoort et al., 1993; Neville et al., 1991; Osterhout et al., 1994) and various anterior negativities (tending to be lateralized to the left hemisphere) that have been reported to occur some time between the range of 125 msec to 700 msec (Kutas and Hillyard, 1983; Neville, Nicol, Barss, Forster, and Garrett, 1991; Kluender and Kutas, 1993; Münte, Heinze, and Mangun, 1993; Rösler, Pütz, Friederici, and Hahne, 1993; Friederici, Pfeifer, and Hahne, 1993).

A review of the previous ERP work in language processing shows that while the processing of different violations of syntactic structures has been examined, the range of different semantic distinctions has not been as systematically explored. As was discussed earlier, in the same manner that syntactic substructures are defined by linguistic theory, semantic variations are also methodically distinguished. Under the general umbrella of "contextually inappropriate" violations, most semantic ERP studies in the past have focused mainly on the "improbability" type associated with the N400 -- e.g., "He spread the warm bread with *socks*." However, semantic/contextual inappropriateness can be fine-tuned to encompass still more specific and different structures, most of which have not yet been studied. It remains uncertain whether the processing of different semantic categories is associated with different brainwave patterns, and if so, how those patterns would relate to language-related ERP components that have been discussed in past studies. This study takes a step to widening our understanding of semantic processing by evaluating ERP responses elicited during the processing of different categories of semantic violations.

The Present Study

Three semantic categories distinguished by semantic theory were evaluated in the present ERP study: hyponymy, negative polarity, and improbability.

Hyponymy (HP)

Hyponymy describes the lexical relation corresponding to the inclusion of one class in another (Cruse, 1986). X is said to be a hyponym of Y if f(X) entails f(Y), but f(Y) does not necessarily entail f(X) [where f( ) is an indefinite expression] (Cruse, 1986). For example, "This is a *dog*" unilaterally entails "This is an *animal*." However, "This is an *animal*" does not necessarily entail "This is a *dog*." Similarly, "This is a *scarlet* flower" entails "This is a *red* flower," but a flower that is red does not necessarily have to be scarlet. Hyponymy violations breach the (X --> Y) relationship, or its logical equivalence (~Y --> ~X), where X (a subordinate) resides on a lower level in a taxonomic hierarchy than Y (a superordinate). In the present study, sentences used in the hyponymy category violate the (~Y --> ~X) relationship:

*I dislike all fruits and I enjoy eating lots of <u>apples</u> at lunch.
*Norman never drinks any alcohol and he always enjoys a glass of <u>whisky</u> after each meal.

It should be noted that although the subordinate member (e.g., "apples") designates the point where semantic incoherence is first perceived in the test sentences, the subordinate member in many of the sentences does not have to be the "violation" of the sentence. Semantic incoherence often could be attributed to other sentential variables such as the choice of conjunction used. For example, "I dislike all fruits and I enjoy eating lots of apples at lunch" could be interpreted to be anomalous because of the conjunction *and*; that is, "I dislike all fruits *but* I enjoy eating lots of apples at lunch" could be a semantically coherent counterpart to the anomalous sentence. Nonetheless, it is still only after encountering the subordinate member of the sentence that an anomalous reading is first perceived (see appendix I for sample sentences).

Negative Polarity (NP)

In English, sentences containing a negative element (e.g., *not*) often facilitate the use of so-called negative polarity words such as *ever* and *any* (or phrases such as *give a damn*, *drink a drop*) within the scope of the sentence. Because the use of these words appears to be sensitive to the negative contextual environment, the appearance of negative polarity items in non-

negative contexts often yields odd readings. For example,
Max believes that he has not *ever* seen that painting.
*Max believes that he has *ever* seen that painting.

The ballet dancer did not trip over *any* wires on the stage.
*The ballet dancer tripped over *any* wires on the stage.

Like the sentences above, violations of negative polarity in the current study present the negative polarity items *ever*, *any*, and *yet* in unfitting non-negative contexts that are better suited for their positive polarity counterparts *never*, *some*, and *already*:

*The student worries that he will <u>ever</u> pass the difficult exam.
*Jack listened at the door and heard <u>any</u> music inside the room.
*Since John had left <u>yet</u>, we decided to meet him at the restaurant.

It should be noted that while the distribution of negative polarity items originally had been described in syntactic terms -- that negative polarity items occurred only within the scope of negative sentential elements (Klima, 1964; Baker, 1970), linguists have subsequently pointed out that negative polarity items are not just sensitive to simple negations. Contexts triggering polarity sensitive items include questions, comparatives, conditionals, particular determiners, clauses headed by universal quantifiers, etc. To account for the complex dynamics involved in polarity sensitivity, current linguistic theories now offer semantically definable accounts of the phenomenon by contending that semantic and pragmatic factors interact to create usage restrictions on the type of sentential constructs compatible with negative polarity items (Fauconnier, 1975; Ladusaw, 1980; Israel, 1994; van der Wouden, 1994; Barss, personal communication). The present study explores the negative polarity phenomenon from such a semantic standpoint (though in all fairness, it should be mentioned that there are current theories which maintain that negative polarity has both semantic as well as syntactic ramifications (e.g., Linebarger, 1987).

Improbability (IM)
Violation sentences of this category are similar to those used in past N400 studies. Improbability sentences contain inappropriate words embedded in sentence contexts such that what is yielded are descriptions of circumstances or events unlikely to occur in the real world. This category was included mainly to serve as a comparison with the other semantic categories:
*An angry crowd of <u>sponges</u> protested for free speech.
*The car on the bridge traveled from one side of the <u>salad</u> to the other.

RESULTS

Behavioral Study

A pilot behavioral study was run on 12 different subjects prior to the ERP study to ascertain that deviant points in the violation sentences were immediately apparent and that control sentences were perceived as "good" sentences. Subjects were instructed to read the word-by-word presentation and respond by a button press (button hand counterbalanced) *as soon as* they read a word that made the sentence sound strange in any way (see methods section for presentation details). Subjects were instructed to respond as quickly and as accurately as possible. Reaction times were collected in this study to evaluate the time course of anomaly detection. The averaged reaction times (measured from target word onset) for each sentence type are as follows: hyponymy: 789 msec (sd = 248); negative polarity: 1363 msec (sd = 514); improbability: 932 msec (sd = 201).

Overall in the behavioral experiment, control sentences containing anomaly-detection responses (false alarms) by more than 4 of the 12 subjects were discarded and new replacement sentences were created for the ERP experiment. Experimental sentences in which the deviant word was not detected (misses) by at least 10 of the 12 subjects were also discarded and replaced in the ERP experiment.

A second behavioral study was run with replacement sentences (in place of those discarded) to ascertain once again that sentences were perceived as they were intended (control vs violation). Results from this study were satisfactory and will not be presented.

ERP Study

Behavior
Subjects detected control sentences with an accuracy of 95.14% and deviant sentences with an accuracy of 96.74%.

ERP

Mean voltage measures relative to baseline voltage were subjected to ANOVAs with repeated measures over 20 msec intervals beginning from the onset of the comparison point and ending 1100 msec post-stimulus. Three or more consecutive 20 msec intervals revealing significant results were subjected to ANOVA with repeated measures over the latency window encompassing those contiguous intervals. The first 20 msec-block within this larger window was taken as the indicator of the onset of the effect.

An omnibus ANOVA on 3 levels of sentence type (hyponymy vs negative polarity vs improbability), 2 levels of condition (control vs deviant), 2 levels of hemisphere (left vs right), 5 levels of anterior-posterior (frontal vs anterior temporal vs central temporal vs parietal vs occipital), and 2 levels of laterality (medial vs lateral) applied to the mean amplitude measure over a 1100 msec epoch showed that there were differences between the different sentence types [sentence type $F(2,34)=17.15$, $p<.001$; condition $F(1,17)=7.55$, $p<.02$; sentence type x anterior-posterior $F(8,136)=6.52$, $p<.01$; sentence type x laterality $F(2,34)=33.34$, $p<.001$; sentence type x anterior-posterior x laterality $F(8,136)=15.34$, $p<.001$]. To tease out the different sentence type effects, 20 msec ANOVAs were applied to each of the separate semantic categories on 2 levels of condition (control vs deviant), 2 levels of hemisphere (left vs right), 5 levels of anterior-posterior (frontal vs anterior temporal vs central temporal vs parietal vs occipital), and 2 levels of laterality (medial vs lateral).

Effects of Improbability Violations

An early difference between the conditions showed that deviant words elicited a slightly larger negativity in the left hemisphere between 160-220 msec [condition x hemisphere $F(1,17)=6.02$, $p<.03$] (Figure 2). More importantly, consistent with prior research, deviants of the improbability category elicited a large negative potential that onset around 320 msec and reached maximal amplitude around 400 msec (N400) [mean amplitude between 320-500: condition $F(1,17)=25.83$, $p<.001$]. Peak of the maximal amplitude *difference* between improbability controls and deviants occurred around 430 msec. Consistent with prior reports is also the bilateral distribution of the N400, with the largest negativity at medial central temporal and medial parietal sites [condition x laterality $F(1,17)=8.34$, $p<.01$; condition x anterior-posterior x laterality $F(4,68)=7.05$, $p<.01$]. The posterior N400 in these data also tended to be more prolonged in the left hemisphere [condition x hemisphere x anterior-posterior x laterality $F(4,68)=3.68$, $p<.01$].

In the current study, a widely distributed, large, sustained positive potential was also recorded in response to the deviant words relative to the controls. This positivity began around 540 msec (which is 40 msec into the presentation of the word following the comparison word). The ANOVA taken from 540-1000 msec revealed that the positivity was largest over posterior regions (parietal and occipital) and larger over medial than lateral electrode sites [condition $F(1,17)=6.09$, $p<.05$; condition x anterior-posterior $F(4,68)=10.44$, $p<.01$; condition x laterality $F(1,17)=14.81$, $p<.001$; condition x anterior-posterior x laterality $F(4,68)=14.05$, $p<.001$]. In this same time window, lateral anterior sites (frontal and anterior temporal) remained negative. Indeed, follow-up statistical analysis for just the frontal and anterior temporal areas revealed a significant sustained negativity at the lateral sites [condition x laterality $F(1,17)=14.07$, $p<.001$].

A midline site ANOVA (Fz, Cz, Pz; see Figure 1) yielded no significant differences of sentence type between 160-220 msec. Analysis between 320-500 msec indicated a main effect of condition [$F(1,17)=17.45$, $p<.001$] and an interaction between condition and anterior-posterior [$F(2,34)=5.66$, $p<.03$] reflecting the larger N400 effect at Cz and Pz. Similarly, analysis between 540-1000 msec pointed to a main effect of condition [$F(1,17)=14.13$, $p<.001$] but found no significant differences of anterior-posterior position.

Effects of Hyponymy Violations

Twenty msec measures for the hyponymy condition indicated condition interactions beginning at 380 msec. Mean amplitude measures taken between 380-1000 msec yielded an array of effects: condition $F(1,17)=7.77$, $p<.02$; condition x hemisphere $F(1,17)=14.32$, $p<.001$; condition x anterior-posterior $F(4,68)=32.29$, $p<.001$; condition x hemisphere x anterior-posterior $F(4,68)=13.66$, $p<.001$; condition x laterality $F(1,17)=41.98$, $p<.001$; condition x hemisphere x laterality $F(1,17)=4.80$, $p<.05$; condition x anterior-posterior x laterality $F(4,68)=17.11$, $p<.001$]. To more effectively tease out whether these significant effects were contributed by the apparent sustained anterior negativity or the sustained posterior positivity (see Figure 3), separate 20 msec ANOVAs were performed for anterior (frontal, anterior temporal, central temporal) and posterior sites (central temporal, parietal, occipital).

Over anterior regions, deviant words in the hyponymy category elicited a negativity that onset about 500 msec and continued through the recording epoch. An area voltage measure between 500-1000 msec showed that the negativity was largest over left lateral (frontal and anterior temporal) electrode sites (mean amplitude for sites over the right hemisphere were actually positive) [condition x hemisphere $F(1,17)=24.71$, $p<.001$, condition x anterior-posterior $F(2,34)=18.25$, $p<.001$, condition x laterality $F(1,17)=33.82$, $p<.001$, condition x anterior-posterior x laterality $F(2,34)=23.12$, $p<.001$]. The onset of the negativity was seen as early as 380 msec for the left lateral frontal electrode (F7).

Over posterior regions, deviant words elicited a large, sustained positivity arising around 380 msec post-onset relative to the control words. This positivity within the area 380-1000 msec occurred maximally over parietal and occipital areas, tended to be larger over medial than lateral sites, and was slightly larger over the right than the left hemisphere [condition $F(1,17)=20.59$, $p<.001$; condition x hemisphere $F(1,17)=6.05$, $p<.03$; condition x anterior-posterior $F(2,34)=23.14$, $p<.001$; condition x hemisphere x anterior-posterior $F(2,34)=16.25$, $p<.001$; condition x laterality $F(1,17)=53.00$, $p<.001$; condition x hemisphere x laterality $F(1,17)=8.56$, $p<.01$; condition x anterior-posterior x laterality $F(2,34)=32.36$, $p<.001$].

Midline sites exhibited a greater positivity at Cz and Pz than Fz within the 380-1000 msec epoch [condition $F(1,17)=20.75$, $p<.001$; condition x anterior-posterior $F(2,34)=34.80$, $p<.001$].

Effects of Negative Polarity Violations

The negative polarity condition elicited a small, symmetrical negative potential between 300-500 msec over anterior regions of the scalp (most prominent at frontal and anterior temporal sites) [condition x anterior-posterior $F(4,68)=8.55$, $p<.01$] (Figure 4).

As in the improbability and hyponymy conditions, a late positivity was also recorded for the deviant words in the negative polarity condition relative to the control words. A mean amplitude measure taken between 500-1000 (coincident with the presentation of the word following the comparison word) revealed a wide, bilateral distribution of this positive potential which was maximal over medial, posterior (parietal & occipital) regions [condition $F(1,17)=15.17$, $p<.001$; condition x anterior-posterior $F(4,68)=34.44$, $p<.001$; condition x laterality $F(1,17)=12.74$, $p<.01$; condition x anterior-posterior x laterality $F(4,68)=13.79$, $p<.001$].

Midline measures between 300-500 msec revealed a condition x anterior-posterior interaction [$F(2,34)=6.70$, $p<.02$] indicating a negativity at Fz but not at Cz or Pz. Measures between 500-1000 msec showed that the late positivity increases in amplitude as it shifts posteriorly [condition $F(1,17)=18.56$, $p<.001$; condition x anterior-posterior $F(2,34)=32.82$, $p<.001$].

Difference Wave Comparisons

A difference wave mean amplitude comparison (deviant minus control) performed between 300-500 msec for the 3 conditions yielded a main sentence type effect [$F(2,34)=18.62$, $p<.001$], a sentence type x anterior-posterior interaction [$F(8,136)=6.01$, $p<.01$], a sentence type x laterality interaction [$F(2,34)=8.77$, $p=.001$], and a sentence type x anterior-posterior x laterality interaction [$F(8,136)=4.99$, $p=.001$].

Planned pairwise comparisons indicated a main sentence type effect between the hyponymy and negative polarity conditions [$F(1,17)=7.20$, $p<.02$]. This difference reflects the anterior negativity seen in the negative polarity category which is absent in the hyponymy category.

Comparison between the hyponymy and improbability categories yielded a main sentence type effect [$F(1,17)=31.83$, $p<.001$]. Differences between the two sentence types reflect the N400 negativity seen in the improbability condition, largest at medial posterior sites, contrasted to the absence of an N400 in the hyponymy condition. [sentence type x anterior-posterior $F(4,68)=6.23$, $p<.03$; sentence type x laterality $F(1,17)=17.04$, $p<.001$; sentence type x anterior-posterior x laterality $F(4.68)=10.04$, $p<.001$]. This difference also tended to be larger in the left than the right hemisphere [sentence type x hemisphere x anterior-posterior x laterality $F(4,68)=3.08$, $p<.05$]. Furthermore, because of the earlier onset of the positive effect, the hyponymy mean amplitude for the difference measured in the 300-500 msec window was more positive than that of the improbability condition.

Pairwise analysis for negative polarity and improbability from 300-500 msec yielded the anticipated result that the mean voltage of the difference potential was significantly more negative for the improbability condition, especially in the posterior region since the negative effect seen in the negative polarity condition was confined to anterior electrode sites [sentence type $F(1,17)=12.82$, $p<.01$; sentence type x anterior-posterior $F(4,68)=11.89$, $p<.01$]. This difference also tended to be slightly larger at medial than lateral sites and over the left than the right hemisphere [sentence type x laterality $F(1,17)=5.39$, $p<.05$; sentence type x hemisphere x anterior-posterior x laterality $F(4,68)=3.14$, $p<.05$].

To evaluate sentence type differences of the late positivity, a difference wave mean amplitude measure in the 540-1000 msec window was performed. An overall ANOVA of the three sentence types yielded no significant differences.

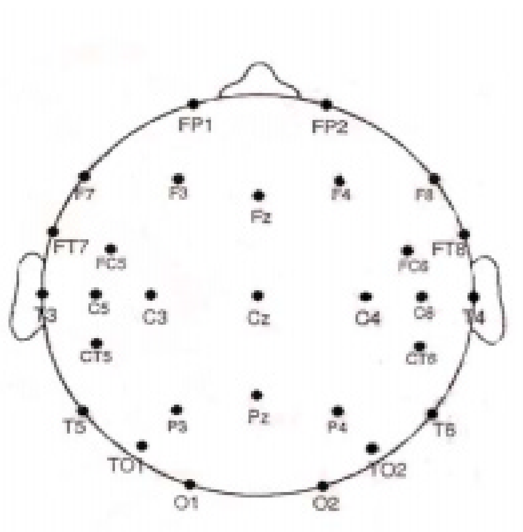

Figure 1.

Summary of Main Results

The comparison words in the deviant sentences of all three semantic categories elicited a widely distributed, bilateral positive shift that was greatest over medial posterior areas compared to control sentences. The onset of the positivity (determined by 20 msec window measures) varied depending on the category: improbability 540 msec, hyponymy 380 msec, negative polarity 500 msec.

Consistent with past findings, deviant words in the improbability category elicited a widely distributed negativity that onset around 320 msec and peaked around 400 msec (N400). This negativity was most pronounced over medial posterior areas.

In contrast to the improbability category, no N400 effect was observed in the hyponymy category. However, beginning around 500 msec, a sustained negativity confined to the left, anterior region was observed. This effect was most pronounced over the lateral electrode sites at F7 and FT7.

Again, no N400 effect was observed in the negative polarity category. The deviant words of this category did, however, produce a small anterior negativity between 300-500 msec compared to control words. This negativity was most pronounced over frontal electrode sites.

DISCUSSION

This study aimed to achieve a better understanding of linguistic (semantic) processing by examining the neural activities associated with the processing of different categories of semantic violations. This study has shown that different ERP patterns are elicited for the three semantic categories tested: improbability, hyponymy, and negative polarity. In particular, the N400 effect that was replicated in the improbability category was not recorded in the ERPs for either the hyponymy or negative polarity categories. Furthermore, the ERP responses recorded for these semantic categories resemble those that have been reported in both semantic *and* syntactic studies.

Negativities

While the negativity produced by the improbability sentences corresponds to the N400 reported in past semantic ERP studies, the anterior negativities observed in the hyponymy sentences as well as the negative polarity sentences resemble anterior negativities that have been reported in past syntactic ERP studies:

- Kutas and Hillyard (1983) reported a negativity between 300-600 msec with a somewhat more frontal distribution to their verb tense and number agreement violations.
- Neville et al. (1991) reported in their phrase structure violations an enhanced N125 at left anterior sites followed by a negativity between 300-500 msec (though maximal over temporal and parietal areas and lateralized to the left hemisphere).
- Osterhout and Holcomb (1992) reported an anterior negativity over the left hemisphere between 300-500 msec preceding a late positivity (P600) in main clause auxilary verbs of garden-pathed sentences.
- Kluender and Kutas (1993) reported an enhanced negativity between 300-500 msec at left anterior sites to the processing of unbounded dependencies.
- Münte, Heinze, and Mangun (1993) reported a negativity between 300-600 msec, maximal at frontal sites, to syntactic word-pair violations.
- Rösler et al. (1993) reported an anterior-maximal negativity between 400-700 msec for German verb subcategorization violations.
- Friederici et al. (1993) reported in their auditory processing study an anterior-maximal

negativity peaking around 400 msec to phrase structure violations in German.

- Münte and Heinze (1994) reported an anterior negativity between 250-500 msec to violations of case inflection in a sentence reading task as well as an anterior negativity between 300-600 msec to syntactic violations in a word-pair paradigm.

One theory suggesting a potential link between some of the anterior negativities in past studies is put forth by Kluender and Kutas (1993) in their study on the processing of long-distance (filler-gap) dependences. A left anterior negativity (LAN) between 300-500 msec was reported in the ERPs of their study to sentences requiring the holding of a filler in working memory and the subsequent retrieval of it for gap assignment (e.g., What did he wonder who he could coerce ___ INTO ___ this time?). Attributing the LAN to a tax on working memory capacity in linguistic contexts involving some kind of role-filling memory search, Kluender and Kutas (1993; Kluender, personal communication) suggest that similar processing/parsing strategies involving working memory load may underlie the generation of the left anterior negativities reported in past studies (e..g, Neville, 1991; Osterhout and Holcomb 1992). To lend support to the connection between the anterior negativity and working memory capacity, a recent study by King and Kutas (1995) on the processing of object and subject relative sentences showed that thematic role assignments that required more difficult processing or that competed with the storage functions of working memory also evoke an anterior negativity (which was more prolonged over left anterior regions).

It is conceivable that the negativities observed in the hyponymy and negative polarity sentences are linked to working memory factors, as both categories involve the processing of negative scope relations. In the case of hyponymy, upon encountering the target subordinate word (e.g., "apple"), subjects might begin a backward search in memory for the negation of the superordinate (e.g., "fruit") to varify that a category had indeed been negated. Likewise, in processing negative polarity target words, subjects might conduct a search for the negative operator that they believe they might have missed earlier in the sentence presentation (Kluender, personal communication). In both cases, involved is the notion of attempting to re-establish a (long-distance) dependency that would call for an added processing load on working memory.

However, two points need addressing in considering the working memory account with the current data. First, the long-distance dependency for negative polarity target words is short. If the negation *not* were to occur in a target sentence, it would occur no more than two or three words away from the target (in sentences with *ever*, the *not* would precede immediately). Language studies demonstrating the effects of working memory load, however, typically have involved dependencies spanning several words or crossing clausal boundaries. This difference does not rule out the possibility of working memory load involvement in the current data, but the extent to which the anterior negativities can be explained by working memory tax seems less powerful. A second consideration is that the morphology of the ERPs for hyponymy (left sustained anterior negativity) and negative polarity (anterior negativity between 300-500 msec) are noticeably different. A unified working memory theory applied to this study would have to account for the differences observed in the morphology of the brainwaves for the two categories.

Applying the working memory capacity theory serves as a starting point in generating plausible interpretations of the current data. Naturally, it must be borne in mind that, at this stage, we have at best a preliminary guess as to what is going on. More research is required to test and modify the hypothesis.

Positivities

Although the three categories tested in this study violate specific semantic properties, the ERPs for all three categories included a posterior positivity similar to the late positivity reported in studies of syntactic violations:

- Neville et al. (1991) recorded a sustained positivity maximal over occipital sites starting around 500 msec to phrase structure violations, and violations of subjacency in the same study produced a widely distributed positivity that onset at 500 msec.
- Osterhout and Holcomb (1992) reported a posterior positivity (P600) to verb subcategorization violations.
- Hagoort et al. (1993) also reported a centro-parietal-maximal slow positive shift (SPS) that onset about 500 msec to violations of Dutch noun-verb agreement and phrase structure.
- Rösler et al. (1993) reported a tendency for German subcategorization violations to evoke some late positivity over the parietal region.
- Friederici et al. (1993) reported a late posterior positivity that onsets about 600 msec to morphological errors in the auditory speech processing of German.

Previous studies have considered the late positivity as a specific index of syntactic processing elicited by parsing strategies (Osterhout and Holcomb, 1992; Hagoort et al., 1993; Osterhout et al., 1994). However, Münte and Heinze (1994) described a similar long-lasting positive shift that was maximal over parietal regions associated with semantically, syntactically, and orthographically incongruent words. Furthermore, in assessing the existence of a syntax specific ERP component, Coulson, King, and Kutas (1995) performed probability manipulations on syntactic violations of noun-verb number agreement and pronoun case marking. Results of that study suggested that the Syntactic Positive Shift is related to the Late Positive Component (LPC), a domain-general ERP component in the P300 family that is sensitive to the expectancy of task-relevant events (Duncan-Johnson and Donchin, 1977; Hillyard and Picton, 1987). Together with the results of the present study, accumulating evidence challenges the claim of a syntax-specific late positivity.

It is worth mentioning, however, that this study required end-of-sentence judgment responses from the subjects. As mentioned above, because preparation and decision-making on task-relevant stimuli often elicit a late positivity in the ERP responses, it would be important to investigate in a follow-up study whether the late positivities reported here are indeed a manifestation of linguistic processing or whether they are simply task-induced.

Design considerations

Two points from the present study require comment. The first concerns the comparison of the negative polarity ERPs to the other two categories. As is noted in the methods section, the comparison words in the negative polarity category are closed-class adverbs (i.e., ever, any, yet), whereas comparison words for improbability sentences are open-class nouns. Research has shown that the processing of open-class words and closed-class words (content vs function) results in qualitatively different ERP responses (Neville, Mills, and Lawson, 1992). In particular, an N280 response associated with closed-class word processing has been reported to be localized over left, anterior regions of the scalp (Neville et al., 1992). Whether this open-closed class difference occurs as a function of semantic versus grammatical class, the degree of meaningful content, imageability, etc. is not yet understood. So in making the contrast between the ERP results collected for negative polarity and improbability and hyponymy, one must bear in mind the possibility that the results may to some degree reflect differences elicited as a function of word class. However, this consideration does not discount the fact that violation of negative polarity constitutes a semantic one.

The second qualification addresses the design of the study. The same sentence stem was used for each set of control and deviant sentences (e.g., "I dislike all fruits and I enjoy eating lots of _____ at lunch" [vegetables vs apples]). Subjects recognized quickly that once they had seen one sentence, the next presentation with the same stem will be the corresponding sentence of the opposite type (control or deviant). Subject debriefing indicated that hyponymy sentences were particularly susceptible to this expectancy confound. Subjects reported that viewing the repeated superordinate word (e.g., fruits) gave way to the expectation of a predictable type of subordinate member (e.g., apple). For example, when subjects viewed for a second time the sentence beginning "Norman never drinks any alcohol and he always ...", the word "alcohol" prompted them to anticipate a completion by some kind of alcoholic beverage if they remember having previously read the control, or anticipate some kind of non-alcoholic beverage if they had previously read the deviant sentence. This type of expectancy was evident in all three sentence categories, but hyponymy sentences (superordinate words) tended to provide a more blatant recognition cue for the subjects.

To remedy the possibility of an expectancy-effect confound, presentation of the stimuli was tailored so that in half of the sentences for each category, the control sentence was presented before its corresponding deviant sentence; in the other half, the deviant sentence was presented before the control (sentences still randomly intermixed). Anticipation effects from the subjects would then be taken into account for both the control and the deviant sentences such that any confounding effects would be averaged out in the final data analysis. To ascertain that the final ERP results were not influenced by these sentence stem expectancies, an additional split analysis was performed on the ERP data so that only sentence stems presented for the first time were compared to each other. Such a comparison ensured that expectancy effects would be filtered out of the data. Assuringly, results from the split analysis yielded identical effects as the comprehensive analysis for both the hyponymy and improbability categories. Results for negative polarity bordered on marginal significance in the split analysis. However, it should be noted that a split analysis considerably reduces the power of the data.

GENERAL DISCUSSION

Data from this study show that ERP responses in the semantic domain yield results as rich as those reported for syntactic violations. This suggests that a unified theory assigning ERP indexes to syntactic or semantic processes cannot be achieved as of yet. As was discussed above, some ERP studies have made the syntax-semantics dichotomy at the neural level by using the N400 as a specific marker of semantic violation and the late positivity as a specific marker of syntactic processing. Evidence presented so far suggests that the late positivity is not sensitive to only the processing of syntactic structures; the presents study shows that late positivities are elicited by semantic violations as well. Similarly, this study suggests that the N400 is not a lone ERP marker for semantic processing. It is quite notable that as of yet, no study of syntactic violations has been able to elicit an N400 and the elicitation of an N400 has consistently been associated with the operation of semantic integration processes. However, it would be misguided to hold that all semantic processes therefore must conversely produce an N400. The current study has provided evidence that this is not the case. Violations of linguistically-defined semantic categories like hyponymy and negative polarity do not elicit an N400 effect. Non-N400 ERP responses can be and are associated with other types of semantic processes. It follows, then, that operations that do not produce an N400 effect do not by default correspond exclusively to syntactic processes or suggest that no semantic processing has taken place.

Many ERP sentence processing studies, the present one included, are carried out testing linguistic distinctions (e.g., syntax vs semantics) that are theoretically motivated. These distinctions provide for a systematic exploration of the investigation of human language processing, and research employing such distinctions have provided much valuable insight into the workings of a highly complex domain. However, depending on the theory to which one subscribes, a different degree of separation between syntax and semantic is assumed, and interpretation of brain activities associated with the processing of specific structures is often guided by such assumptions. Since one of the common goals of ERP language research is to discover whether empirical evidence exists for making a syntax-semantics distinction at the neural level, we must not begin the search by having already made our own syntactic and semantic assignments to the brain responses. Much more evidence needs to be gathered from all levels of linguistic processing so that supporting information showing reliable differences or convergence in the ERP patterns can be assembled to address the issue of domain-specificity of language in the brain. At this stage, however, available ERP data do not provide enough evidence to allow for the neural differentiation between the two linguistic domains.

Much progress has been made to advance our understanding of the neural processes and mechanisms underlying language processing, and much exploration awaits. A fruitful source of knowledge for ERP research lies simply in investigating the processing of additional linguistic structures. Whether they will eventually be accounted for by language-unique explanations or more fundamental cognitive processes, brainwave patterns emerging from different linguistic processes will provide a key link to constructing a unified theory of the biological basis of language, and consequently, a more insightful and illuminating understanding of the human brain can be achieved.

METHODS

Subjects

Behavioral

Twelve native monolingual English speakers (6 female) with normal or corrected-to-normal vision participated in the experiment for university credit. The mean age was 20 years (range 18-29 years). Handedness for these subjects was not assessed.

ERP

Eighteen native monolingual English speakers (9 female) with normal or corrected-to-normal vision participated as paid volunteers. The mean age was 22 years (range 18 - 30 years). All subjects were right-handed according to self-report, and seven subjects reported having left-handed relatives in their immediate families.

Materials

Stimuli for the experiment consisted of a total of 240 sentences. One hundred twenty experimental sentences were divided into three categories: 40 hyponymy (HP), 40 negative polarity (NP), and 40 improbability (IM). The sentences were of variable length (grand mean = 13.65 words, sd = 2.92; HP mean = 16.23, sd = 2.17; NP mean = 12.43, sd = 2.47; IM mean = 12.30, sd = 2.24), and in all three categories, the deviant word occurred in sentence medial position (words prior to onset: HP mean = 12.55, sd = 1.99; NP mean = 6.13, sd = 2.11; IM mean = 7.90, sd = 2.38). Deviant words were designed to be evident immediately upon their presentation, and due to the nature of the categories, deviant words of the hyponymy and improbability categories were nouns and deviants of the negative polarity category were closed-class adverbs. One hundred twenty corresponding sentences using the same sentence stem as each of the experimental sentences were used as controls -- in each case, the deviant words were simply replaced with words that yielded proper and meaningful English sentences (negative polarity sentences replaced with positive polarity words). The control and deviant words of each category did not significantly differ in mean frequency (mean: HPcontrol = 30.50, HPdeviant = 25.17, $F(1,78) = .262$, $p > .05$; NPcontrol = 858.55, NPdeviant = 694.05, $F(1,78) = 2.060$, $p > .05$; IMcontrol = 38.25, IMdeviant = 37.85, $F(1,78) = .002$, $p > .05$).

Procedure

Subjects were tested in a single session that lasted between 2 and 2.5 hours. They sat comfortably 57" in front of a 23-inch monitor and viewed the sentence stimuli on the screen. The 240 sentences were randomly intermixed and presented one word at a time by an IBM-PC computer. Subjects were instructed to read the sentences for meaning and were told that some sentences may look similar to one another and that there may be repeated presentations of some sentences (although there were none). No sentence was presented more than once in the experiment. Subjects were presented with 6 practice trials prior to the experiment. ERPs were not collected during the practice and no practice sentences were presented in the actual experiment. Sentences were presented in 4 blocks of 60 trials each. At the signal of the subject's button press, a rectangular border appeared on the computer screen (subtending 5 x 3 degrees visual angle) for 1000 msec. Subjects in the ERP experiment were instructed not to blink or move while the border was illuminated. Each word was presented for 300 msec and was followed by a 200 msec interval, yielding a total stimulus-onset asynchrony (SOA) of 500 msec. The words subtended a visual angle of 0.5 - 2.0 degrees horizontally and 0.5 degrees vertically. Sentence terminal words appeared with a period and the rectangular border was extinguished 1000 msec following the terminal word of the sentence. Subjects in the ERP experiment were asked to respond at this point by pressing one of two response buttons (labeled "good" and "bad") to indicate whether or not the sentence "made good sense." Subjects in the behavioral experiment were instructed to respond as soon as a word that made the sentence sound strange in any way was detected during the sentence presentation. The response hand for good/bad was counterbalanced across all subjects. Subjects initiated each subsequent trial by an additional button press.

ERP Recording

The electroencephalogram (EEG) was recorded from 29 electrodes mounted in an elastic cap (Electro-Cap); see Figure 1. Standard International 10-20 electrode locations include: Fz, Cz, Pz, Fp1, Fp2, F3, F4, F7, F8, C3, C4, T3, T4, T5, T6, P3, P4, O1, O2. Nonstandard electrode placements over traditional language areas are: anterior central -- FC5, FC6 (50% of arc between C3(4) and F7(8)); central -- C5, C6 (50% of arc between C3(4) and T3(4)); anterior temporal -- FT7, FT8 (50% of arc between F7(8) and T3(4)); central temporal -- CT5, CT6 (50% of arc between C3(4) and T5(6)); temporal occipital -- TO1, TO2 (50% of arc between O1(2) and midpoint of arc connecting P3(4) and T5(6)). Vertical eye movements and blinks were monitored by the electro-oculogram (EOG) recorded from an electrode placed below the right eye, and horizontal eye movements were recorded via a right-to-left bipolar montage at the external canthi. Activity in the left mastoid was recorded during the experiment, and all online recordings were referenced to the right mastoid. All recordings were re-referenced to averaged mastoids in the final data averaging. The EEG was amplified with Grass 7P511 amplifiers (3dB cutoff, bandpass of 0.01 to 100 Hz) and digitized online at a sampling rate of 250 Hz.

Data Analysis

ERP averages were formed for each of the three semantic categories (hyponymy, negative polarity, improbability), beginning 100 msec prior to the onset of the comparison word and ending 2000 msec after word onset. Trials containing excessive eye movement, muscle artifact, and amplifier blocking were rejected (approximately 6% across all conditions).

Mean amplitude measurements of the ERPs were computed relative to the baseline voltage. Electrodes were grouped in the following way for all statistical analysis: frontal -- F3(4) & F7(8), anterior temporal -- FC5(6) & FT7(8), central temporal -- C3(4) & T3(4), parietal -- P3(4) & T5(6), and occipital -- O1(2) & TO1(2). The following electrodes were additionally grouped as medial: F3(4), FC5(6), C3(4), P3(4), O1(2). The following electrodes were grouped as lateral: F7(8), FT7(8), T3(4), T5(6), TO1(2). Separate analyses were performed for the midline sites Fz, Cz, and Pz. ERP measures associated with each sentence type were subjected to ANOVA with repeated measures on two levels of condition (deviant vs control), 2 levels of hemisphere (left vs right), 5 levels of anterior-posterior (frontal, anterior temporal, central temporal, parietal, occipital), and 2 levels of laterality (medial vs lateral). The Geisser-Greenhouse correction was applied to all repeated measures with greater than 1 degree of freedom.

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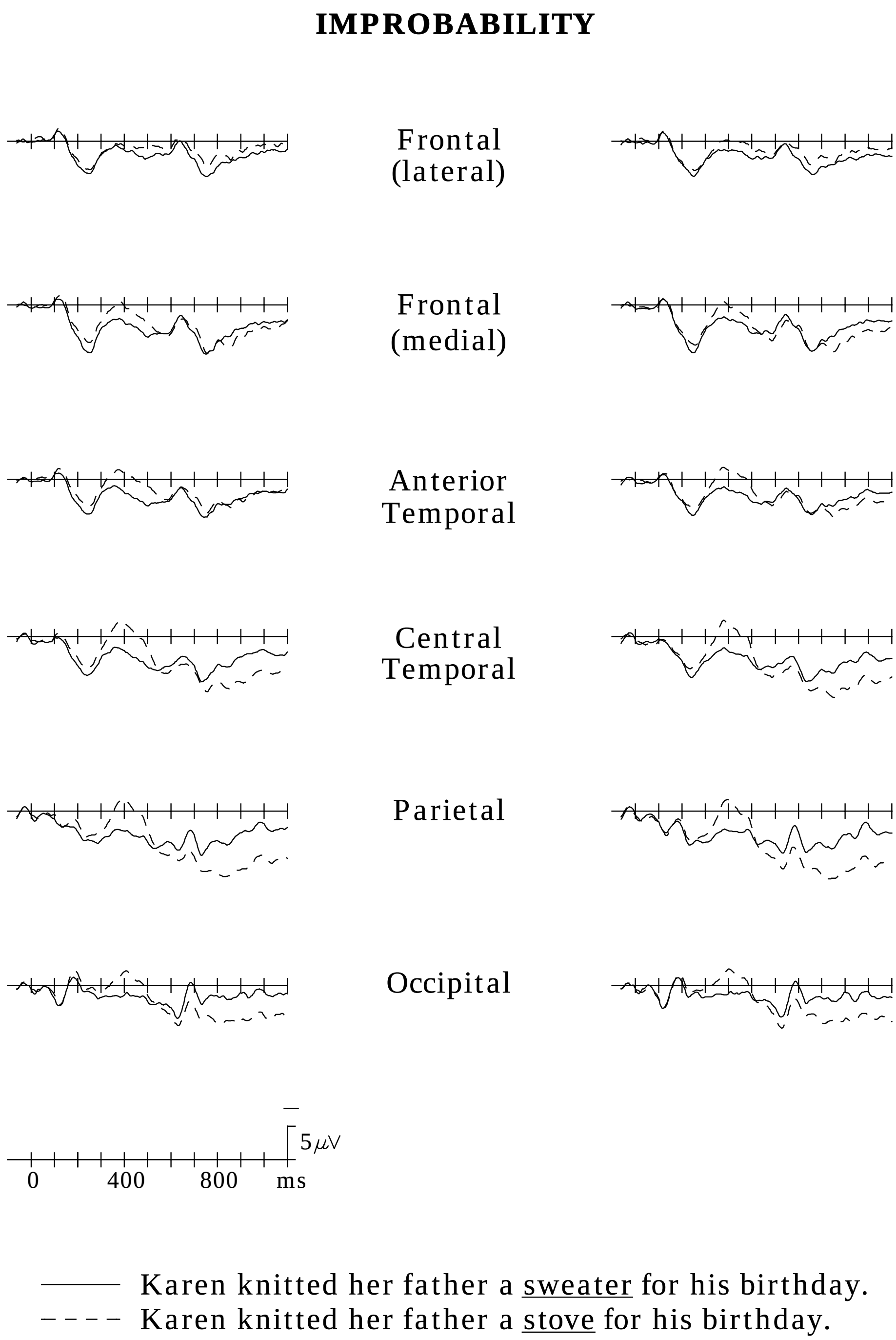
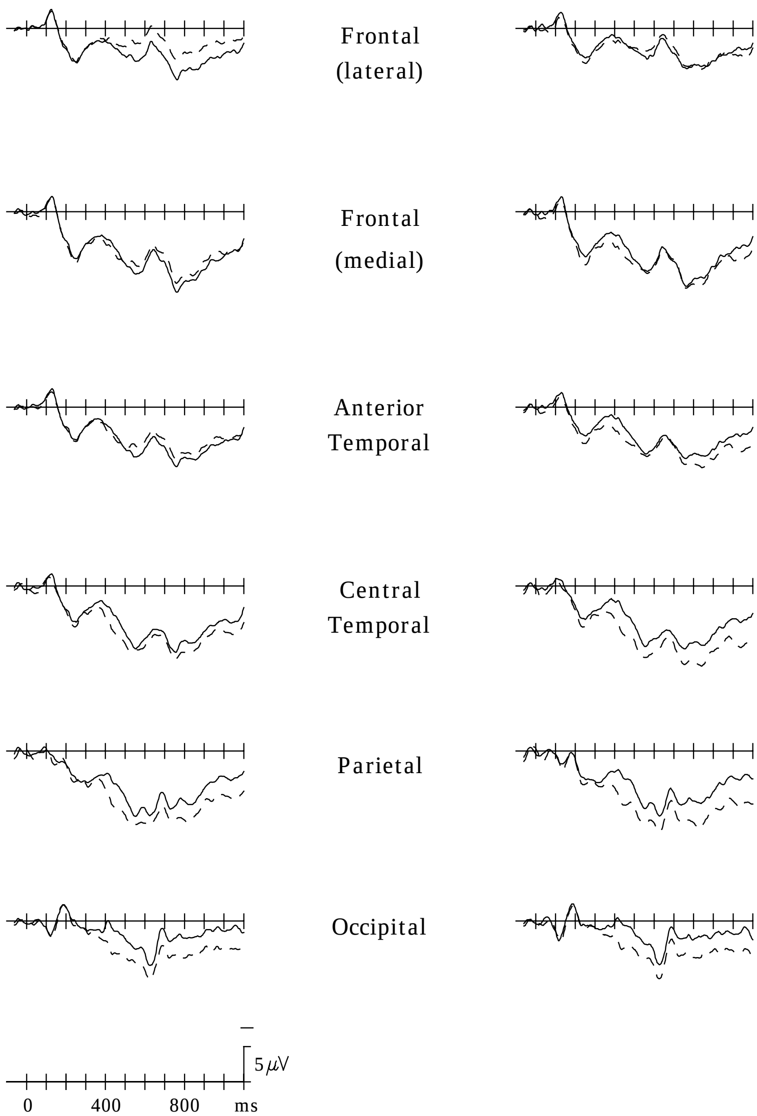

IMPROBABILITY
Frontal (lateral)
Frontal (medial)
Anterior Temporal
Central Temporal
Parietal
Occipital
5μV
0
400
800
ms
Karen knitted her father a sweater for his birthday.
Karen knitted her father a stove for his birthday.

Figure 2.

HYPONYMY



______ Jane does not eat any meat at all, and instead, she eats lots of <u>rice</u> and vegetables.

_ _ _ _ Jane does not eat any meat at all, and instead, she eats lots of <u>beef</u> and vegetables.

Figure 3.

NEGATIVE POLARITY

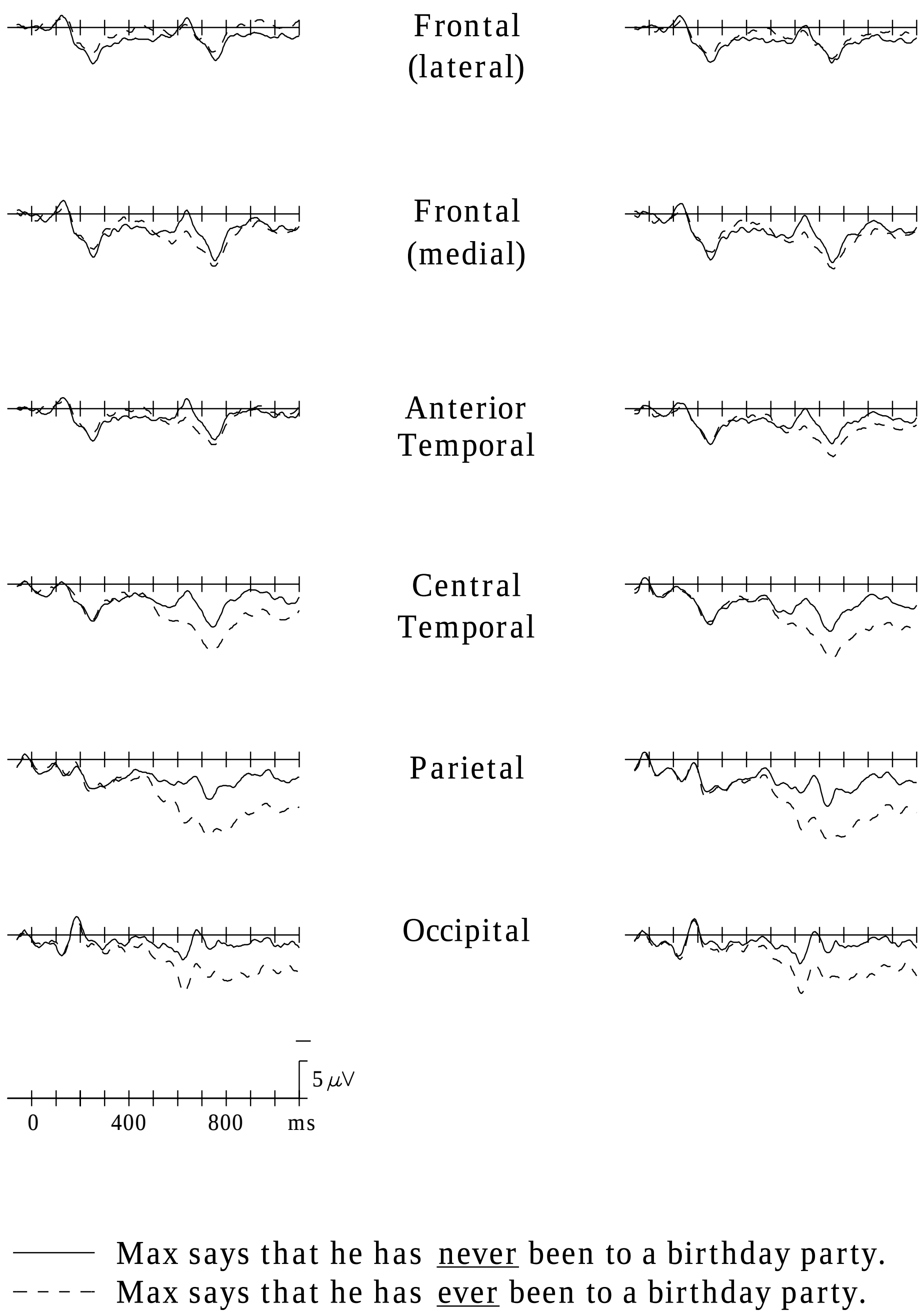


Figure 4.

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