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Brain Potentials Elicited by Garden-Path Sentences: Evidence of the Application of Verb Information During Parsing

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Event-related potentials were recorded from 13 scalp locations while participants read sentences containing a syntactic ambiguity. In Experiment 1, syntactically disambiguating words that were inconsistent with the "favored" syntactic analysis elicited a positive-going brain potential (P600). Experiment 2 examined whether syntactic ambiguities are resolved by application of a phrase-structure-based minimal attachment principle or by word-specific subcategorization information. P600 amplitude was a function of subcategorization biases rather than syntactic complexity. These findings indicate that such biases exist and can influence the parser under certain conditions and that P600 amplitude is a function of the perceived syntactic well-formedness of the sentence.

One set of fundamental questions about language comprehension concerns the psychological processes underlying the syntactic analysis of sentences. It is generally (although not universally) agreed that comprehenders rapidly assign syntactic structure in real time, that is, on a word-by-word basis (Frazier, 1987; Frazier & Rayner, 1982; Marslen-Wilson, 1980; Rayner, Carlson, & Frazier, 1983). However, there is far less agreement concerning the means by which the comprehension system accomplishes this task. Two distinct approaches dominate the recent literature. One approach, the structure-driven model, holds that initial decisions concerning sentence structure are determined by reference to knowledge concerning possible constituent structures (often characterized as a set of phrase structure rules) combined with knowledge of the major syntactic categories of words in the sentence (e.g., noun, verb, preposition; for a review, see Frazier, 1987). A second approach, the lexically driven model, holds that initial hypotheses about sentence structure are driven by knowledge of the complement-taking properties of verbs in the sentence (Fodor, 1978; Ford, Bresnan, & Kaplan, 1982; Holmes, 1984; Holmes, Stowe, & Cupples, 1989; Tanenhaus, Boland, Garnsey, & Carlson, 1989; Tanenhaus & Carlson, 1989).[1]

These two parsing models make distinct claims concerning the processor's response to syntactic ambiguity (situations in which two well-formed syntactic analyses are available for a sentence fragment). Consider Sentence 1:

The judge believed *the defendant* (Sentence 1)
(a) and threw out the charges.
(b) was lying.

The proper syntactic analysis of the noun phrase *the defendant* is temporarily uncertain; the noun could act as the direct object of the verb, as in Continuation a (Figure 1A), or as the subject of a clausal complement, as in Continuation b (Figure 1B). A phrase-structure-driven parser would attempt to resolve the uncertainty by applying strategies based on the comprehender's knowledge of phrase structure constraints. Frazier and associates (Frazier, 1978; Frazier & Rayner, 1982) have proposed one such strategy, the *minimal attachment principle.* A minimal attachment parser initially constructs the simplest structure (as defined by the number and depth of phrase structure nodes) consistent with the phrase structure rules of the language. In support of this model, Frazier and Rayner (1982; see also Clifton & Frazier, 1989; Ferreira & Clifton, 1986; Frazier, 1978; Rayner et al., 1983; Rayner & Frazier, 1987) measured readers' eye movements as they read sentences similar to Sentence 1. A minimal attachment parser would initially assign the object role to the ambiguous noun phrase because the direct object interpretation is syntactically simpler than the clausal complement analysis. Given a direct object analysis, Continuation b cannot be attached to the previously computed structure and, in this case, the parser is forced to reanalyze the sentence to derive the correct syntactic analysis. Frazier and Rayner noted increased eye fixations when the sentence ended in a clausal complement, as in

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[1] The parsing models contrasted in this article are not the only models currently being debated in the literature. The recent literature includes less extreme proposals concerning the interaction between lexical and structural knowledge (cf. Frazier, 1989) that our data do not address. Also, we did not investigate the influence of discourse-based factors on the parsing process, so we were unable to evaluate recent discourse-driven parsing models (cf. Altmann, Garnham, & Dennis, 1992).

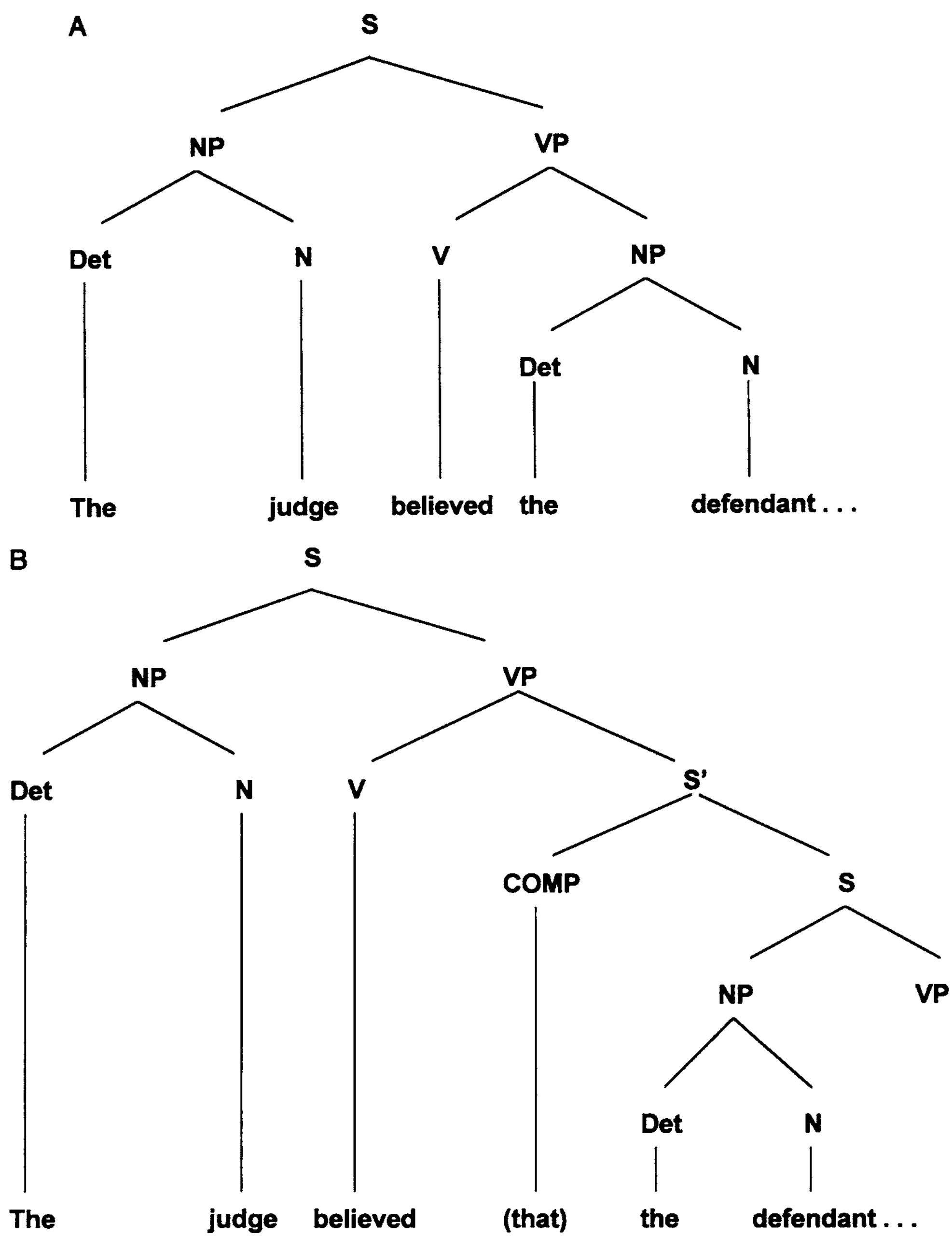

Figure 1. Two possible syntactic interpretations of the word string *The judge believed the defendant.* (A) A simple active interpretation; (B) a complement clause interpretation. S = subject; NP = noun phrase; VP = verb phrase; Det = determiner; N = noun; V = verb; S' = sentential complement.

Continuation b, suggesting that readers had difficulty when faced with disambiguating information inconsistent with a minimal attachment analysis.

In contrast, a lexically driven parser would rely on verb subcategorization (or other argument-taking properties) from the verb to determine which analysis to pursue first (Clifton, Frazier, & Connine, 1984; Fodor, 1978; Ford et al., 1982; Holmes, 1984; Holmes et al., 1989). The syntactic path initially attempted in Sentence 1 would be determined by lexical biases associated with the verb *believe.* If the verb is biased toward a transitive use, then the direct object role will be initially assigned to the noun phrase *the defendant.* Conversely, an intransitively biased verb causes the parser to assign the subject-of-the-complement-clause role to the noun phrase *the defendant.* Evidence consistent with these predictions has been reported by Mitchell and Holmes (1985; see also Holmes, 1987), who used a self-paced reading task in which phrase-sized segments were sequentially presented. Large increases in reading times for sentences similar to Sentence 1 were observed when readers encountered a clausal complement, Continuation b, but only when the main verb was biased toward a transitive use.

One time-honored means for adjudicating between the minimal attachment and the lexically driven parsing models is to observe situations in which the two models would predict opposing analyses. For example, a minimal attachment parser would initially pursue the syntactically simpler direct-object analysis in Sentence 1, whereas a lexically driven parser would pursue the clausal complement analysis because the verb *believe* in Sentence 1 is biased toward intransitive use (as determined by production norms; Connine, Ferreira, Jones, Clifton, & Frazier, 1984). Correspondingly, a minimal attachment parser would experience a garden-path effect on encountering Continuation b, whereas a lexically driven parser would experience a garden-path effect on encountering Continuation a. Several recent studies have examined the processing response to this type of ambiguity. Ferreira and Henderson (1990) reported longer reading times to disambiguating material that was inconsistent with the minimal attachment analysis, regardless of the verbs' subcategorization properties (see also Mitchell, 1989). However, Holmes et al. (1989) found that reading times increased for disambiguating material that was inconsistent with the verb's subcategorization biases, indicating that detailed verb-specific knowledge is applied rapidly during parsing. Conflicting findings such as these have prevented a consensus view concerning the use of verb information during processing.

In our research, we addressed this issue by recording event-related brain potentials (ERPs) elicited during the comprehension of sentences containing local syntactic ambiguity. ERPs are voltage changes in the ongoing electroencephalogram (EEG) that are time locked to the onset of a sensory, motor, or cognitive event (Hillyard & Picton, 1987). ERPs consist of positive and negative voltage peaks (or components) distributed over time. Early ERP components are primarily determined by aspects of the physical stimulus and remain relatively insensitive to changes in the psychological state of the subject. However, later occurring components appear to be sensitive to cognitive variables, such as changes in the meaningfulness of the stimuli or changes in task requirements (for a review, see for example, Hillyard & Picton, 1987). The value of this approach lies in the fact that ERPs are an on-line, multidimensional, millisecond-by-millisecond reflection of processing activity that do not require simultaneous performance of some behavioral decision task (as one must do with, for example, word-by-word grammaticality judgments) during language comprehension.

Earlier work has demonstrated that certain ERP components are sensitive to relevant aspects of language comprehension. In a set of pioneering studies, Kutas and Hillyard (1980a, 1980b, 1980c) found that contextually inappropriate words (e.g., "John buttered his bread with *socks*") elicit a large-amplitude negative component with a peak around 400 ms subsequent to the onset of the word (the N400 component). Subsequent studies have indicated that the amplitude of the N400 is a function of the "semantic fit" between the target word and preceding context even when the target word is contextually appropriate. For example, N400 amplitude is negatively correlated with the cloze value of the target word (Kutas & Hillyard, 1984). Although the precise cognitive events underlying the N400 are not known, it has been suggested that N400 amplitude is inversely related to the amount of lexical or semantic priming impinging on the representation of the target word (Fischler & Raney, 1991; Holcomb & Neville, 1990). Another view is that N400 amplitude reflects the build-up of semantic constraints imposed by preceding context (Kutas, Van Petten, & Besson, 1988; Van Petten & Kutas, 1990, 1991).

ERPs also appear to be sensitive to certain types of syntactic anomaly. However, the brain response to a variety of syntactic anomalies is distinct from that to semantically anomalous words. Violations (or apparent violations) of verb subcategorization, phrase structure, number and gender agreement, and subjacency constraints elicit a late positive-going wave (labeled *P600* by Osterhout & Holcomb, 1992; Hagoort, Brown, & Groothusen, 1993; McKinnon & Osterhout, 1993; Neville, Nicol, Barss, Forster, & Garrett, 1991; Osterhout, 1990; Osterhout & Holcomb, 1992, 1993; Osterhout & Mobley, 1993; for a review, see Osterhout, in press). Typically, the positive-going activity elicited by these anomalies has an onset around 500 ms after presentation of the anomalous word, and differences in the waveforms elicited by anomalous words and nonanomalous control words are largest over midline and posterior regions. Furthermore, the P600 effect appears to be elicited by the anomaly that results from syntactic garden-path effects (Osterhout & Holcomb, 1992, 1993). Osterhout and Holcomb (1992) examined the response to syntactically disambiguating words that followed a simple active-reduced relative clause ambiguity (e.g., "The broker persuaded *to* . . ."). Disambiguating words that forced a relative clause analysis of the sentence (the word *to* in the previous example) elicited a positive-going wave similar to that elicited by outright violations of syntactic constraints. These data not only indicate that ERPs are sensitive to language-related events, but they also allow one to speculate that ERPs are sensitive to the linguistic level (e.g., syntactic vs. semantic) of these events. Indeed, several authors have suggested that the N400 and P600 effects are elicited as a function of the linguistic level of the anomaly (Hagoort et al., 1993; Osterhout, in press; Osterhout & Holcomb, 1992, 1993).

Our research was designed to directly contrast predictions of the minimal attachment and lexically driven parsing models. In Experiment 1, we examined the response to direct object–clausal complement ambiguities such as that in Sentence 1. The goal was to determine whether the P600 would be elicited by syntactically disambiguating information that is inconsistent with a direct object analysis under conditions in which both a minimal attachment parser and a lexically driven parser would initially attempt the direct object analysis. In Experiment 2, we directly contrasted predictions stemming from the minimal attachment and lexically driven parsing models concerning when and where the P600 component, as a marker of garden pathing, would be elicited during the comprehension of sentences containing syntactic uncertainty. Specifically, we examined situations in which a minimal attachment parser and a lexically driven parser would pursue opposing parse paths in cases of direct object–clausal complement ambiguity.

Experiment 1

Two sentence types were presented in Experiment 1, as exemplified by the sentences in Appendix A. Both sentence types were grammatical; each contained a clausal complement, with a postverbal noun phrase acting as the subject of the clausal complement. However, the absence of an overt complementizer in Sentence 2 in Appendix A rendered the proper syntactic role of the postverbal noun phrase temporarily ambiguous between direct object and subject-of-the-clause roles. A minimal attachment parser would initially (and erroneously) assign the direct object role to the ambiguous noun phrase in such sentences because the direct object analysis is syntactically simpler than the clausal complement analysis (see Figure 1). Because the verb *charge* is biased toward transitive usage, a lexically driven parser would also erroneously pursue the direct object analysis. Hence, both parsing models predict that the parser will experience syntactic anomaly when it encounters the disambiguating region (*was lying*) of Sentence 2. If so, and if the P600 acts as an electrophysiological marker of the syntactic anomaly resulting from garden paths, then the auxiliary verbs in Sentence 2 should elicit a P600 effect relative to ERPs elicited by the same words in Sentence 1.

Method

Participants

Twelve right-handed, native English-speaking Tufts University undergraduates (9 women and 3 men) with normal or corrected-to-normal vision participated for pay. Ages ranged from 17 to 33 years ($M = 24$ years).

Materials

Sixty sentences were created. Two versions of each sentence were formed, as exemplified by the sentences in Appendix A. A list of these materials is provided in Appendix B. Matrix verbs in these sentences were biased toward use with a direct object, as determined by the Connine et al. (1984) norms. Sentence type was counterbalanced across two stimulus lists such that only one version of each sentence appeared on each stimulus list. Thirty exemplars of each sentence type appeared on each list. In addition to the 60 experimental sentences, 150 filler sentences were added to each list, some of which were part of a second experiment not described in this article. Thirty of these were ungrammatical, and another 30 were semantically implausible. Fillers were constructed such that verbs used in the experimental sentences appeared approximately equally often in verb–noun phrase (direct object) and verb–sentential complement (clausal complement) constructions across all the materials.

Procedure

Sentences were presented in a word-by-word manner, with individual words presented centered on a CRT screen for 300 ms and with 350 ms separating words. We used a 650-ms stimulus onset asynchrony (SOA) between words so that we could examine an extended period of ERP activity in response to each word, uncontaminated by the ERP to the subsequent word. Sentence-ending words appeared with a period. A 1,450-ms blank screen interval followed each sentence-ending word, after which a prompt appeared asking participants to decide whether the previous sentence was acceptable or unacceptable. Participants responded by pressing one of two buttons. They were tested in one session lasting approximately 2 hr, during which they were seated in a comfortable chair situated in a sound-attenuating chamber. Instructions indicated that participants were to carefully read each sentence as it was presented and to judge whether the sentence was acceptable or unacceptable. Acceptable sentences were defined as semantically coherent and grammatically correct; unacceptable sentences were defined as those that were semantically incoherent or bizarre or that were judged as being ungrammatical. Respondents were provided with a few examples of syntactically and semantically anomalous sentences. No sentences presented during the experiment were used as examples. Participants were asked if they understood the criteria for acceptability, and additional examples were provided as needed. A short practice session of about six or seven sentences preceded the experiment.

Recording System

EEG activity was recorded from 13 scalp locations, using tin electrodes attached to an elastic cap (Electrocap International). Electrode placement included International 10–20 system locations (Jasper, 1958) over homologous positions over the left and right occipital (O1 and O2, respectively) and left and right frontal (F7 and F8, respectively) regions and from frontal (Fz), central (Cz), and parietal (Pz) midline sites. In addition, several nonstandard sites over posited language centers were used, including Wernicke's left area and its right hemisphere homologue (WL and WR: 30% of the interaural distance lateral to a point 13% of the nasion–inion distance posterior to Cz); posterior temporal left and right (PTL and PTR: 33% of the interaural distance lateral to Cz); and anterior temporal left and right (ATL and ATR: one half the distance between F7 and T3 and between F8 and T4). Vertical eye movements and blinks were monitored by means of an electrode placed beneath the left eye, and horizontal eye movements were monitored by an electrode positioned to the right of the right eye. The 15 channels of EEG were referenced to an electrode placed over the left mastoid bone and were amplified with a bandpass of 0.01 to 100 Hz (3-dB cutoff) by a Grass Model 12 amplifier system. Activity over the right mastoid bone was actively recorded on a 16th channel to determine whether there would be any effects of the experimental variables on the mastoid recordings. No such effects were observed in any of the data.

Data Analysis

Continuous analog-to-digital conversion of the EEG and stimulus trigger codes was performed on-line by a Data Translation 2801-A board and an AT-compatible computer at a sampling frequency of 200 Hz. Trials characterized by excessive eye movement (vertical or horizontal) or amplifier blocking were rejected. In Experiment 1, 29% of the trials were rejected.[2] In all cases, rejected trials were evenly

[2] The relatively high rate of trial rejections resulted from the use of long (2,400 ms) epochs. Also, the grand averages reported were not response contingent; that is, all artifact-free trials for a particular condition were entered into the grand average, regardless of the participant's response on that trial. We adopted this strategy because we did not know what the relationship would be between the participant's delayed, end-of-sentence responses and the on-line processing responses to the critical words. However, we also computed response-contingent averages, and these did not differ in any important respect from the reported averages.

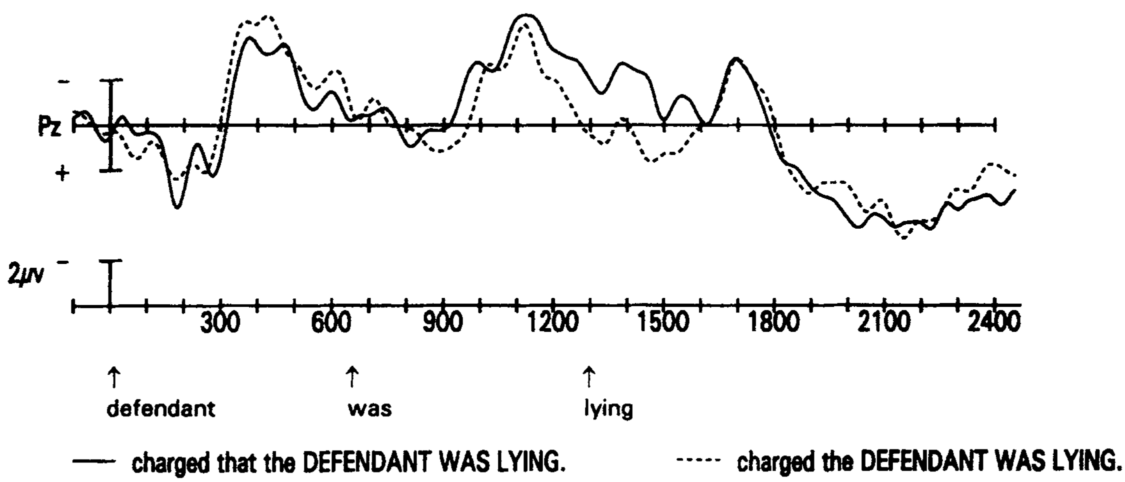

Figure 2. Grand average event-related brain potentials (averaged over participants and items) to the final three words in unreduced and reduced sentences in Experiment 1 recorded over parietal (Pz) site. Onset of the postverbal noun (e.g., *defendant*) is at 0 ms (vertical calibration bar). Onsets of subsequent words are indicated with an arrow. Each mark on the horizontal axis represents 100 ms. Negative voltage is plotted up.

distributed across treatment conditions. ERPs were quantified by computer as the mean voltage within a latency range following presentation of words of interest, relative to a prestimulus baseline that was made up of the 100 ms of activity preceding the epoch of interest. Data acquired at midline and lateral sites were treated separately during data analyses to allow for quantification of hemispheric differences. Two-way analyses of variance (ANOVAs) with repeated measures on sentence type and three levels of electrode position (frontal, central, and parietal) were performed on midline data. Three-way ANOVAs with repeated measures on sentence type, five levels of electrode position, and two levels of hemisphere (left and right) were performed on data from lateral sites. To protect against excessive Type I error due to violations of the assumption of equal variances of differences between conditions of within-subject variables, we applied the Huynh-Feldt (1976) correction when evaluating effects with more than one degree of freedom.

Results and Discussion

Acceptability Judgments

Sentences with and without overt complementizers were judged to be acceptable on 91% and 73% of the trials, respectively. This difference was statistically reliable, $F(1, 11) = 10.32, p < .01, MS_e < 1$.

Event-Related Brain Potentials

In this and all subsequent analyses, the general shapes of the obtained waveforms were similar to earlier reports of ERPs to language stimuli (e.g., Kutas & Hillyard, 1980a, 1980b, 1980c; Neville, Kutas, Chesney, & Schmidt, 1986). A clear positive–negative–positive complex was visible in the first 250 ms after presentation of a word. The first positive component (P1) was largest over occipital regions, reflecting the visual nature of the task. The negative component (N1) was largest over occipital and frontal sites and tended to have a peak latency around 200 ms. The second positive component (P2) was largest over midline central and frontal locations with a peak around 250 ms. A large-amplitude negative deflection with a centro-posterior distribution and a peak amplitude around 400 ms (N400) was also clearly visible in the ERPs to most of the words.

ERPs to the final three words in each sentence type (e.g., *defendant was lying*), recorded over Pz, are shown in Figure 2. This extended epoch allowed us to investigate ERPs elicited by the postverbal noun (e.g., *defendant;* this word was in the syntactically ambiguous region of the reduced sentences), the auxiliary verb (which acted as the syntactically disambiguating word in reduced sentences), and sentence-final verbs. Mean voltages for all electrode sites within a window between 500–800 ms subsequent to presentation of auxiliary verbs are shown in Table 1. ERPs to postverbal nouns showed few differences across sentence types, except that at some electrode sites (Cz and Pz) N400 amplitudes to nouns in the reduced sentences were larger than those elicited by the same words in the unreduced sentences. A midline ANOVA on mean amplitudes within a 350–450-ms window subsequent to presentation of these nouns revealed a significant interaction between sentence type and electrode site, $F(2, 22) = 4.62, p < .05, MS_e = 3$. No reliable differences were observed at lateral sites. Small differences between conditions were also evident between 500 and 600 ms following presentation of postverbal nouns. These differences were not reliable.

Of more theoretical interest were ERPs to auxiliary verbs, which acted as syntactically disambiguating words in the reduced sentences. Inspection of Figure 2 shows that the auxiliary verbs in the reduced sentences elicited a positive-going deflection most notable between about 500 and 800 ms subsequent to presentation of these words, relative to ERPs to the same words in the unreduced sentences. Although this effect was largest posteriorly and at midline sites, the greater positivity to reduced sentences was evident at most sites.

Table 1
Mean P600 Amplitude in Microvolts (500–800 ms) in Experiment 1

	Electrode site												
Sentence	O1	WL	PTL	ATL	F7	O2	WR	PTR	ATR	F8	Fz	Cz	Pz
Reduced	−0.19	0.73	0.39	0.53	0.31	−0.43	−0.77	−0.34	0.11	0.22	0.15	0.01	−0.34
Unreduced	−0.46	−1.51	−0.83	−0.22	−0.03	−0.47	−1.93	−1.54	−0.29	−0.46	−1.40	−1.46	−2.74
Difference	0.27	2.24	1.22	0.75	0.34	0.04	1.16	1.20	0.40	0.66	1.55	1.47	2.40

Note. O1 = left occipital; WL = Wernicke's left area; PTL = posterior temporal left; ATL = anterior temporal left; F7 = left frontal region; O2 = right occipital; WR = Wernicke's right area; PTR = posterior temporal right; ATR = anterior temporal right; F8 = right frontal region; FZ = frontal midline site; CZ = central midline site; PZ = parietal midline site.

Analyses were performed on mean voltages within three latency windows: 200–350, 350–450, and 500–800 ms. (These windows were chosen because they roughly correspond to the latency ranges of the N1–P2 complex, the N400 component, and the P3/P600 slow-wave components typically reported in cognitive ERP studies.) In the 200–350- and 350–450-ms windows, neither the midline nor the lateral ANOVAs revealed any reliable differences between sentence types. In the 500–800-ms window, ERPs elicited by the auxiliary verbs in reduced sentences were reliably more positive going at midline sites than those elicited by the same words in sentences with overt complementizers, $F(1, 11) = 8.91, p = .01, MS_e = 6$. At lateral sites, the main effect for sentence type was marginally significant, $F(1, 11) = 3.58, p = .08, MS_e = 10$. The temporal and distributional characteristics of the positive-going activity elicited by the auxiliary verbs in reduced sentences were similar to previous reports of the P600 effect (Osterhout & Holcomb, 1992, 1993).

Earlier work (Osterhout & Holcomb, 1992, 1993) has indicated that final words in sentences typically judged to be unacceptable elicit an N400-like effect, relative to final words in sentences typically judged to be acceptable. Differences in N400 amplitude to final words in the current experiment were noticeable at anterior sites (e.g., Fz, Cz, ATL, PTL) but not at posterior sites (e.g., Pz, WL, WR). ANOVAs were performed on mean amplitude within a 350–450-ms window time locked to presentation of the final words. The midline ANOVA revealed a reliable interaction between sentence type and electrode site, $F(2, 22) = 4.08, p < .05, MS_e = 3$. The anterior distribution of this effect might be due in part to the temporal overlap of the P600 effect elicited by the auxiliary verbs in the reduced sentences and the N400 elicited by the final words in these sentences. That is, the positive-going activity elicited by auxiliary verbs in reduced sentences extended into the temporal window associated the N400 elicited by sentence-final words and might have obscured differences in N400 amplitude, particulary at posterior sites.

These observations are consistent with previous claims that the P600 is an electrophysiological marker of syntactic anomaly and provide further evidence that syntactically disambiguating information elicits the P600 effect when that information is inconsistent with the "preferred" syntactic analysis; that is, the P600 appears to act as an electrophysiological marker of the garden-path effect. These results also indicate that garden-path effects (as indexed by the P600) are obtainable in instances of direct object–clausal complement ambiguities. However, because the verbs in these sentences were biased toward use with a direct object, the data from Experiment 1 did not allow us to discriminate between the minimal attachment and lexically driven parsing models; both models predict that the parser will initially pursue the direct object analysis under the conditions existing in Experiment 1. In Experiment 2, we observed situations in which the minimal attachment parser and the lexically driven parser would pursue opposing syntactic analyses when faced with direct object–clausal complement ambiguities.

Experiment 2

Four sentence types were presented in Experiment 2, as exemplified by Sentences 1–4 in Appendix C. These sentences were similar to the reduced clausal complement sentences presented in Experiment 1 in that each sentence contained a clausal complement (*the patient was lying*) but no overt complementizer. However, in these sentences we manipulated the subcategorization properties associated with the matrix verbs.[3] Specifically, the verb *hope* in Sentence 1 is intransitive; the verb *force* in Sentence 2 is transitive; the verb *believe* in Sentence 3 can be used either intransitively or transitively but shows a statistical bias toward intransitive usage (according to the production norms reported by Connine et al., 1984); and the verb *charge* in Sentence 4, which also can be used intransitively or transitively, is biased toward transitive usage. Hence, in Sentences 3 and 4, there is temporary uncertainty concerning the correct syntactic role of the postverbal noun phrase *the patient.* As in Experiment 1, the ambiguity is between a direct object role and a subject-of-the-complement-clause role.

[3] Although some prominent theories of grammar (e.g., generalized phrase structure grammar theory) continue to couch verb-complement constraints in terms of subcategorization frames (thereby emphasizing the "syntactic" aspect of such relations), other frameworks (e.g., Jackendoff, 1987) tend to favor "predicate-argument" structures and thematic roles, emphasizing the "semantic" quality of such phenomena. Similarly, some recent work in psycholinguistics has emphasized the influence of thematic roles during sentence processing (e.g., Tanenhaus, Carlson, & Trueswell, 1989). In our research, the relevant aspect of such relations concerns their implications for the analysis of sentence constituent structure; hence, verb-complement constraints are treated as syntactic constraints.

The question of interest again concerns how readers assign a grammatical role to the postverbal noun phrase *the patient.* A parser applying a strong version of the minimal attachment principle, in which all verb subcategorization information is ignored during the first-pass parse of a sentence (e.g., Ferreira & Henderson, 1990; Frazier, 1989), would incorrectly assign the direct object role to the postverbal noun phrase in all of the sentences shown in Appendix C. This follows from the claim that the direct object analysis is syntactically simpler than the clausal complement analysis. Weaker versions of the minimal attachment parser are conceivable. For example, the parser might normally apply knowledge of verb subcategorization when making syntactic decisions but might rank phrase structure biases over lexical biases when neither phrase structure constraints nor verb subcategorization constraints uniquely determine the correct analysis. Such a parser would correctly assign the subject-of-the-clause role to the postverbal noun phrase for Sentence 1 in Appendix C because the intransitive verb *hope* is rarely used with a direct object. In contrast, the transitive verb *force* would lead the parser to assign the direct object role in Sentence 2. In Sentences 3 and 4, the correct syntactic role for the postverbal noun phrase remains indeterminate even after application of phrase structure and verb subcategorization constraints. Hence, the parser, applying the minimal attachment principle, would erroneously assign the direct object role to the noun phrase.

A lexically driven parser would rely on verb subcategorization constraints and biases in making parsing decision, even in cases of syntactic indeterminacy. Hence, the intransitive verb *hope* would lead the parser to correctly assign the subject-of-the-clause role to the noun phrase *the patient* in Sentence 1. The transitive verb *force* would lead the parser to assign the direct object role to the noun phrase in Sentence 2. The verb *believe* is biased toward use without a direct object, so the parser would correctly assign the subject-of-the-clause role in Sentence 3. The verb *charge* is biased toward use with a direct object, causing the parser to erroneously assign the object-of-the-verb role to the noun phrase in Sentence 4.

Method

Participants

Twelve right-handed native English-speaking Tufts University undergraduates (6 women and 6 men) participated for course credit. None had participated in Experiment 1. Ages ranged from 18 to 21 years (M = 19 years).

Materials

One hundred twenty experimental sentences were constructed, with four versions of each sentence. The four sentence types reflected a manipulation of the matrix verb: Verb types included intransitive verbs, transitive verbs, intransitively biased verbs, and transitively biased verbs (see Appendix C for examples). Verb bias ratings were obtained from published norms (Connine et al., 1984). Five exemplars of each verb class were used repetitively—intransitive: *agree, hope, think, insist, decide;* transitive: *buy, discuss, follow, include, force;* intransitively biased: *believe, know, promise, remember, guess;* and transitively biased: *hear, forget, understand, see, charge.*[4] The intransitively biased verbs selected were used with clausal complements on 66% of the responses collected in the sentence completion task reported by Connine et al. (1984), and the transitive bias verbs were used with a direct object noun phrase on 68% of the responses. The experimental sentences described were counterbalanced across four stimulus lists, with one version of each sentence appearing on each list. In addition to these experimental items, 60 grammatical and 60 ungrammatical filler sentences were added to each list. All of these sentences included a verb from the above list in a transitive environment. There were 30 filler sentences in each of four sentence types: sentences with a transitive verb (grammatical); sentences with an intransitive verb (ungrammatical); grammatical sentences with a biased verb (15 with transitive bias); and ungrammatical sentences with a biased verb (15 with transitive bias). In this last group, ungrammaticality was caused by a missing determiner or scrambled word order. The anomaly always occurred after the matrix verb–noun phrase sequence. Within each list, each verb appeared with a noun phrase complement and a clausal complement in approximately equal numbers across all experimental and filler sentences. The entire set of experimental sentences is presented in Appendix D.

Procedure

All procedures were identical to those used during Experiment 1.

Results and Discussion

Acceptability Judgments

Sentences containing intransitive, transitive, intransitively biased, and transitively biased verbs were judged to be acceptable on 91%, 4%, 84%, and 66% of the trials, respectively, $F(3, 33) = 188, p < .0001, MS_e = 8$. These data are consistent with the claim that verb subcategorization biases are used during sentence comprehension because participants appeared to have more difficulty understanding sentences in which verbs were used with less preferred complements. However, these data do not indicate when during sentence processing the verb information has its effect.

Event-Related Brain Potentials

Sentences containing intransitive and transitive verbs. Twenty-one percent of all trials were rejected as a result of an artifact. Rejections were randomly distributed across treatment conditions. Figure 3 displays grand average ERPs to the final three words (*patient was lying*) in sentences containing intransitive and transitive verbs. Table 2 shows mean amplitude within a

[4] The repetitive use of verbs was the result of the paucity of certain categories of verbs in Connine, Ferreira, Jones, Clifton, and Frazier's (1984) norms combined with the necessity of large numbers of stimuli for signal-averaging purposes. Because each verb was used approximately equally often across all materials in a transitive and intransitive form, it is unlikely that readers were predicting structure on the basis of verb use within this experimental environment. Also, repeated use of a small set of verbs (and especially repetitive use of these verbs in equal proportions of transitive and intransitive environments) could be expected to mitigate differences in subcategorization biases, thereby introducing a bias against finding reliable differences between conditions.

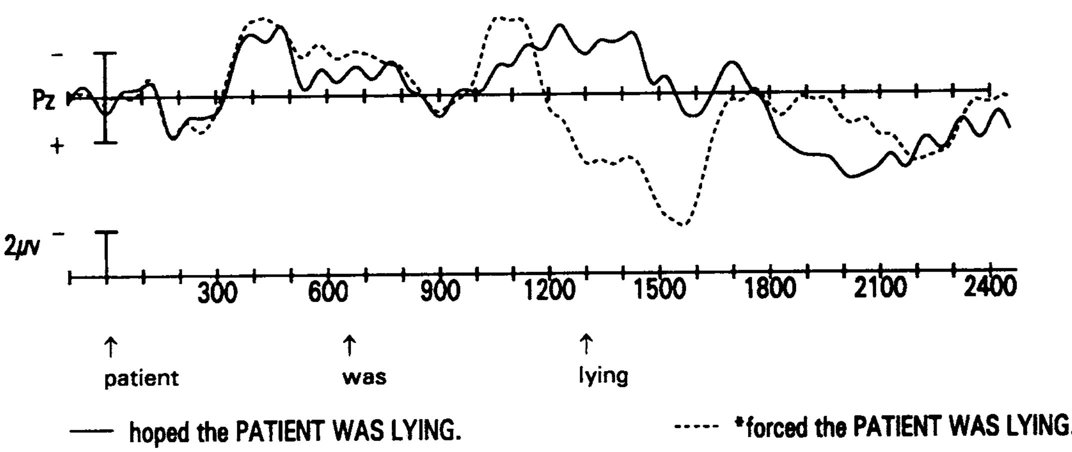

Figure 3. Grand average event-related brain potentials (across all participants and items) from the parietal (Pz) site to the final three words in sentences containing an intransitive or a transitive verb as presented in Experiment 2.

window between 500 and 800 ms subsequent to presentation of auxiliary verbs. As in Experiment 1, the extended epoch allowed us to investigate ERPs elicited by the postverbal noun (e.g., *patient*), the auxiliary verbs, and the sentence-final verbs. Although small differences were evident in the response to the postverbal nouns, ANOVAs performed on mean amplitudes within 200–350-ms, 350–450-ms, and 500–800-ms windows did not reveal any reliable differences between conditions. Responses to the auxiliary verbs in each sentence type were of primary interest; it is here that the sentences containing transitive verbs become ill-formed. Inspection of Figure 3 reveals a biphasic response to the anomalous auxiliary verb in sentences containing a transitive verb, relative to the same words in sentences containing an intransitive verb. Specifically, a negative-going potential with a peak amplitude around 400 ms was followed by a large positive-going wave with an onset around 500 ms. Both effects were largest at posterior regions. Windows of 350–450 and 500–800 ms were chosen to quantify the negative- and positive-going components, respectively. Within the 350–450-ms window, the response to auxiliary verbs following transitive verbs was significantly more negative going than that following intransitive verbs at lateral sites, $F(1, 11) = 6.33$, $p < .05$, $MS_e = 24$, and marginally more negative at midline sites, $F(1, 11) = 3.95$, $p = .07$, $MS_e = 15$. The reliability of this negative-going wave was probably diminished by its apparent temporal overlap with the positive-going component, particularly at midline sites where the positivity was largest. Within the 500–800-ms window, ERPs elicited by the auxiliary verbs in sentences containing transitive verbs were significantly more positive going than those elicited in sentences containing intransitive verbs at midline sites, $F(1, 11) = 16.64$, $p < .01$, $MS_e = 8$. Furthermore, differences between conditions were largest posteriorly—Sentence Type × Electrode Site interaction: midline, $F(2, 22) = 3.30$, $p = .05$, $MS_e = 5$; lateral, $F(4, 44) = 2.96$, $p < .05$, $MS_e = 4$.

Examinations of ERPs to sentence-ending words were complicated by the continuation of differences in ERPs to auxiliary verbs across sentence type. Specifically, it was difficult to determine an appropriate baseline for comparing ERPs with sentence-final words, given that the P600 elicited by the

Table 2
Mean P600 Amplitude in Microvolts (500–800 ms) in Experiment 2

	Electrode site												
Sentence	O1	WL	PTL	ATL	F7	O2	WR	PTR	ATR	F8	Fz	Cz	Pz
Transitive	0.63	0.85	1.06	0.86	0.46	0.58	0.78	1.06	0.88	0.30	1.29	1.69	1.98
Intransitive	−0.76	−1.11	−0.30	−0.51	1.31	−0.86	−1.04	−0.16	0.58	1.01	0.57	−1.56	−2.35
Difference	1.39	1.96	1.36	1.37	−0.85	1.44	1.82	1.22	0.30	−0.71	0.72	3.25	4.33
Transitively biased	0.97	0.62	0.78	0.68	0.50	0.74	0.35	0.95	1.25	0.90	0.48	1.16	1.55
Intransitively biased	−0.91	−0.68	−0.21	0.59	1.37	−0.89	−0.92	−0.05	0.72	1.58	1.55	0.32	−1.21
Difference	1.88	1.30	0.99	0.09	−0.87	1.63	1.27	1.00	0.53	−0.68	−1.07	0.84	2.76

Note. O1 = left occipital; WL = Wernicke's left area; PTL = posterior temporal left; ATL = anterior temporal left; F7 = left frontal region; O2 = right occipital; WR = Wernicke's right area; PTR = posterior temporal right; ATR = anterior temporal right; F8 = right frontal region; FZ = frontal midline size; CZ = central midline site; PZ = parietal midline site.

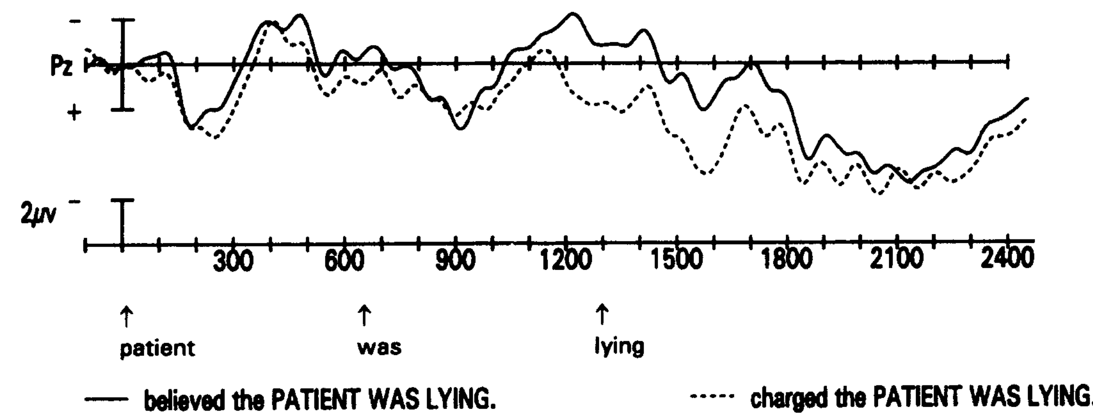

Figure 4. Grand average event-related brain potentials (across all participants and items) from the parietal (Pz) site to the final three words in sentences containing an intransitively biased or a transitively biased verb as presented in Experiment 2.

auxiliary verbs following transitive verbs resulted in large differences in waveforms just prior to presentation of the sentence-final words. No reliable differences were found within the 350–450-ms window, suggesting that there were no significant differences in N400 amplitude across sentence types. However, as in Experiment 1, this conclusion is tempered by the possibility that differences in N400 amplitude to sentence-final words might have been obscured by the large positive-going activity elicited by the preceding auxiliary verbs in sentences containing transitive verbs. Clear differences were observable later in the epoch to sentence-final words. Specifically, ERPs to final words in sentences containing intransitive verbs elicited a large slow positivity, beginning about 500 ms subsequent to presentation of the sentence-final word. This slow-wave positivity is typically observed at the end of well-formed sentences (cf. Friedman, Simson, Ritter, & Rapin, 1975; Osterhout & Holcomb, 1992). This end-of-sentence positivity was greatly reduced in the (ungrammatical) sentences containing transitive verbs, as indicated by ANOVAs on mean amplitude within a window of activity from 500 to 800 ms after presentation of the sentence-final words—midline: $F(1, 11) = 16.26, p < .01, MS_e = 10$; lateral: $F(1, 11) = 30.64, p < .001, MS_e = 11$.

Sentences containing intransitively and transitively biased verbs. ERPs to the final three words in sentences containing biased verbs are shown in Figure 4. Small differences in ERPs to the postverbal noun were again evident. Analyses were performed on mean voltages within windows of 200–350 ms, 350–450 ms, and 500–800 ms subsequent to presentation of these nouns. The only significant effect was an interaction between sentence type and electrode site in the midline ANOVA on mean voltage within the 500–800-ms window, $F(2, 22) = 6.21, p < 01, MS_e = 5$. Visual inspection of the ERPs indicated that this interaction reflected the fact that ERPs to transitively biased sentences were slightly more negative going at Pz and slightly more positive going at Fz within this window. This interaction was not reliable at lateral sites.

As in previous analyses, ERPs elicited by the auxiliary verbs are of the most interest because it is here that evidence of garden pathing would be predicted if the parser erroneously attaches the postverbal noun phrase as an object of the verb. Inspection of Figure 4 reveals that the auxiliary verbs elicited a monophasic positive-going wave with an onset around 500 ms in sentences with transitively biased verbs, relative to ERPs elicited by the same words in sentences containing intransitively biased verbs. Differences between conditions were largest at posterior sites, both over midline and over lateral sites. ANOVAs on mean amplitude within 500–800 ms subsequent to presentation of the auxiliary verbs showed these differences to be reliable—Sentence Type × Electrode Site interaction: midline, $F(2, 22) = 5.99, p < .01, MS_e = 3$; lateral, $F(4, 44) = 3.80, p < .01, MS_e = 3$. ERPs to sentence-final verbs differed only within the 350–450-ms window—Sentence Type × Electrode Site interaction: midline, $F(2, 22) = 6.29, p < .01, MS_e = 3$; lateral, $F(4, 44) = 4.69, p < .01, MS_e = 2$. This difference resulted from the continuation of the positive-going activity elicited by the auxiliary verbs in sentences containing a transitively biased verb.

Analyses involving all sentence types. Analyses involving ERPs to all four sentence types were also performed. Because differences in the response to the auxiliary verbs across sentence type were largest at Pz, and because we wanted to reduce the quantity of data analyses, we restricted our analyses to data acquired at Pz. For unknown reasons, the peak amplitude of the P2 component elicited by the postverbal nouns was greater for sentences with biased verbs than for sentences with "pure" intransitive and transitive verbs, $F(1, 11) = 5.28, p < .05, MS_e = 3$. To equate the waveforms prior to the critical regions in the sentence (i.e., the auxiliary verbs), we used a poststimulus baseline of activity between 150 and 250 ms subsequent to presentation of the postverbal noun.[5] Figure 5 shows ERPs elicited by the final three words in each of the four sentence types. Difference waves, formed by subtracting ERPs elicited by sentences containing an intransitive verb from the ERPs to sentences containing one of the other three types of verbs, are shown in Figure 6. Visual inspection of the

[5] Analyses performed with a prestimulus baseline did not differ qualitatively from those reported.

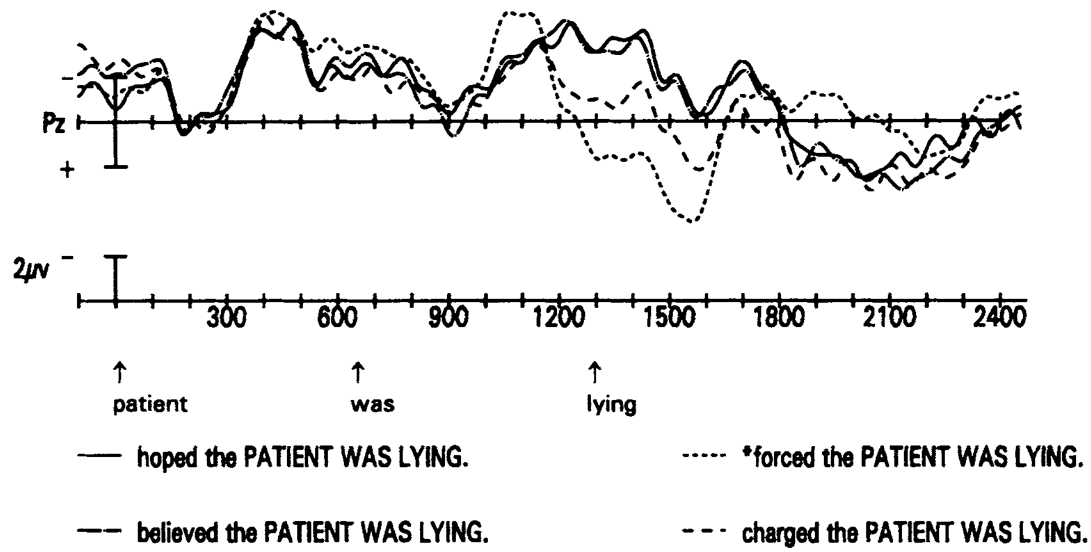

Figure 5. Grand average event-related brain potentials (across all participants and items) from the parietal (Pz) site to the final three words in all four sentence types presented during Experiment 2. A poststimulus baseline made up of activity elicited between 150 and 250 ms subsequent to presentation of the postverbal noun was used.

ERPs elicited by postverbal nouns did not reveal any noticeable differences between sentence types. Analyses on mean amplitude within windows of 200–350, 350–450, and 500–800 ms showed no reliable differences.

Figures 5 and 6 both indicate that auxiliary verbs in sentences containing a transitive verb elicited a larger N400 component than did auxiliary verbs in the other sentences. However, an ANOVA on mean amplitude within a 350–450-ms window subsequent to onset of the auxiliary verbs did not indicate reliable differences between sentence types, $F(3, 33) = 1.94$, $p = .14$, $MS_e = 7$. These figures also reveal that although auxiliary verbs in sentences containing transitive verbs and in sentences containing transitively biased verbs elicited P600s, the P600 effect was largest in sentences containing transitive verbs. An ANOVA on mean voltage between 500 and 800 ms time locked to presentation of the auxiliary verbs revealed a significant effect for sentence type, $F(3, 33) = 8.81$, $p < .001$, $MS_e = 5$. Planned comparisons were then performed on mean amplitudes for each pair of sentence types in the form of one-tailed t tests by using a modified Bonferroni correction for multiple comparisons (following the suggestions of Keppel, 1982; see also Osterhout & Holcomb, 1992). Under this

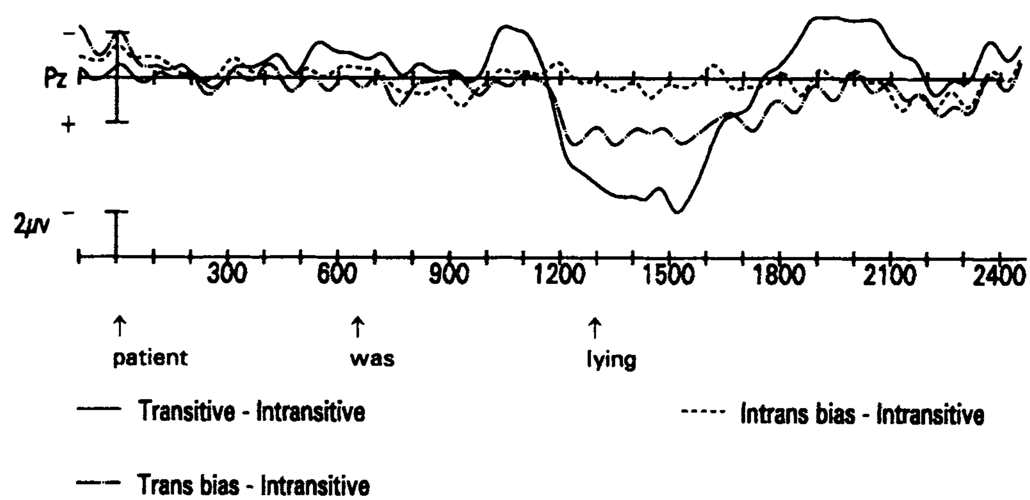

Figure 6. Difference waves (from the parietal [Pz] site) formed by subtracting event-related potentials (ERPs) to the final three words in sentences containing intransitive verbs from ERPs elicited by the final three words in sentences containing transitive, transitively (trans) biased, or intransitively (intrans) biased verbs.

procedure, we used an alpha level of .04 for all comparisons. ERPs to auxiliary verbs in sentences containing transitive verbs were reliably more positive going than ERPs in sentences containing intransitive, $t(11) = 5.44, p < .001$, intransitively biased, $t(11) = 4.64, p < .001$, and transitively biased verbs, $t(11) = 2.06, p = .03$. As in the earlier analyses, the critical comparisons involved sentences containing biased verbs. ERPs to auxiliary verbs in sentences with transitively biased verbs were reliably more positive going than those in sentences with intransitively biased verbs, $t(11) = 2.46, p < .02$, and intransitive verbs, $t(11) = 1.84, p = .04$. In contrast, ERPs to auxiliary verbs in sentences containing intransitively biased verbs did not differ from those to auxiliary verbs in sentences containing pure intransitive verbs, $t(11) = 0.19$.

Although the auxiliary verbs in sentences containing either a pure transitive verb or a transitively biased verb elicited a P600 effect, P600 amplitude was largest following transitive verbs. One plausible explanation for this difference is the possible existence of greater between-subjects variance in the mental representation of verb subcategorization for the transitively biased verbs than for the transitive verbs. If such variance exists, then the between-subjects variance in P600 amplitude to auxiliary verbs in sentences containing transitively biased verbs should be greater than the variance in P600 amplitude to auxiliary verbs in sentences with transitive verbs. To assess this possibility, we performed the Box (1954) test of homogeneity of variance on mean voltage within the 500–800-ms window following presentation of auxiliary verbs in each sentence type. With an alpha level of .10, we found no significant differences between any pairs of means, $F(11, 11) < 2.00$, in all comparisons.[6]

Cross-experiment analyses. In Experiment 1, the overt complementizer in the unreduced sentences unambiguously indicated to the parser that the postverbal noun phrase was the subject of a clausal complement. In Experiment 2, the presence of an intransitive verb similarly indicated that the noun phrase was the subject of a clausal complement. We wanted to determine whether these two types of information would be equally effective at preventing garden pathing, that is, erroneous assignment of the direct object role to the postverbal noun phrase. The lexically driven parsing model predicts that both types of information should be equally effective at preventing the garden path, whereas the minimal attachment parsing model predicts that overt complementizers will be much more effective than intransitive verbs. To assess these predictions, we compared P600 amplitude elicited by auxiliary verbs in two pairs of sentences with each other: the sentences from Experiment 1, which appeared with and without an overt complementizer and which always contained a transitively biased verb; and the sentences from Experiment 2, which contained an intransitive or a transitively biased verb. Both parsing models predict that the parser will erroneously assign the direct object role to the noun phrase in a sentence without an overt complementizer when that sentence contains a transitively biased verb. If overt complementizers were more effective than intransitive verbs at preventing the parser from assigning the erroneous direct object role, then the reduction in P600 amplitude elicited by auxiliary verbs (relative to the P600 elicited in reduced sentences with transitively biased verbs) should be greater when the sentence contains an overt complementizer than when the sentence contains an intransitive verb. The mean reduction in P600 amplitude to auxiliary verbs at site Pz (within a window between 500 and 800 ms) was 2.40 μV in sentences containing an overt complementizer and 2.28 μV in sentences containing an intransitive verb. An ANOVA on data acquired at Pz with a between-subjects variable of sentence pair and a within-subject variable of sentence type showed a significant main effect for sentence type, $F(1, 22) = 8.50, p < .01$, $MS_e = 7$, but no interaction between sentence pair and sentence type, $F(1, 22) = 0.005$. These data are consistent with the claim that overt complementizers and intransitive verbs were roughly equally effective in preventing the parser from assigning the erroneous direct object role to the postverbal noun phrase.[7]

General Discussion

In two experiments, we recorded ERPs while participants read sentences containing a local syntactic ambiguity. In Experiment 1, syntactically disambiguating words that were inconsistent with the preferred syntactic analysis elicited an ERP component previously associated with syntactic anomaly (P600). This finding is consistent with previous claims that the P600 is an electrophysiological marker of the garden-path effect (Osterhout & Holcomb, 1992, 1993). The goal of Experiment 2 was to determine whether readers rely primarily on phrase structure biases (minimal attachment) or on lexical subcategorization biases in deciding which syntactic analysis to pursue. The P600 was elicited as a function of the subcategorization properties associated with verbs rather than as a function of syntactic complexity. Specifically, words that indicated a violation of verb subcategorization or verb subcategori-

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[6] A reviewer raised the possibility that differences across sentence types in P600 amplitude to auxiliary verbs might have resulted from within-subject variation rather than between-subjects variation. Unfortunately, we have no means for computing within-subject variance to investigate this possibility. However, if there had been differences in variance either between or within subjects across conditions, then one reasonable expectation would be that differences in P600 amplitude to auxiliary verbs should exist between sentences containing pure intransitive and biased intransitive verbs (similar to those observed between pure transitive and transitively biased verb sentences). This follows from the fact that more variance would exist for the intransitively biased condition than for the pure intransitive condition, such that some readers (or some readers on some trials) would have had a transitive bias for some of the intransitively biased verbs. This would not have been likely to occur with regularity in the pure intransitive condition. However, the waveforms elicited by auxiliary verbs following pure intransitive and intransitively biased verbs were nearly identical.

[7] This cross-experiment comparison involves a comparison of different participants; hence, caution is called for in interpreting this analysis. In particular, the absolute differences in P600 amplitude across experiments might be influenced by overall amplitude variation between groups. However, the effect of applying a normalizing procedure in this case would be to show a larger P600 amplitude reduction in sentences containing intransitive verbs than in sentences containing overt complementizers, which is contrary in direction to the hypothesized difference we were testing.

zation biases elicited the P600. Furthermore, P600 amplitude was larger to violations of verb subcategorization than to violations of verb subcategorization biases.

Verb Information and Parsing

Our findings add to a growing literature demonstrating the application of verb-specific knowledge during the on-line processing of sentences (Clifton et al., 1984; Ford et al., 1982; Garnsey, Tanenhaus, & Chapman, 1989; Holmes et al., 1989; Mitchell & Holmes, 1985; Tanenhaus, Boland, et al., 1989; Trueswell, Tanenhaus, & Kello, 1993). At first glance, therefore, these data appear to favor the lexically driven parser model (Fodor, 1978; Ford et al., 1982; Holmes et al., 1989). However, before accepting this interpretation we need to consider several alternative interpretations that are consistent with the minimal attachment model, that is, a model in which the parser's initial syntactic analyses are governed by a syntactic simplicity metric rather than by verb subcategorization information. We consider three such possibilities.

First, the parser might have initially assigned the direct object (minimal attachment) role to postverbal noun phrases in all four sentence types in Experiment 2 but rapidly performed a check on the semantic/pragmatic plausibility of the resulting verb–direct object combination (for similar notions, see, e.g., Clifton, Speer, & Abney, 1991; Rayner et al., 1983). The parser could have reanalyzed sentences after detection of implausibility before encountering the syntactically disambiguating auxiliary verb. However, to account for the apparent absence of P600 activity to auxiliary verbs in sentences containing an intransitive or intransitively biased verb, this interpretation entails that readers systematically (and with equal frequency) detect implausibility at the postverbal nouns in these two sentence types. This interpretation seems unlikely given the results of a recent study by Osterhout (1990), who examined the ERP response to nouns in prepositional phrases that could modify either the matrix verb or the object of the verb. Each sentence was created such that the preferred attachment resulted in an anomalous interpretation. For example, when reading the sentence "The thief stabbed the man *with the cash* last night," there is an apparent preference to initially attach the prepositional phrase to the verb. Such an analysis results in semantic and pragmatic anomaly. Correspondingly, the nouns in these prepositional phrases elicited large-amplitude N400s, relative to nonanomalous controls. Thus, if readers were systematically detecting semantic/pragmatic implausibility in sentences containing an intransitive or intransitively biased verb in Experiment 2, and if they used this implausibility as a basis for reparsing the sentence prior to encountering the auxiliary verb, then the postverbal nouns in sentences with intransitive or intransitively biased verbs should have elicited larger N400s than in sentences with transitive or transitively biased verbs. We did not observe any such systematic increases in N400 amplitude.

A second alternative interpretation of our data hinges on the fact that the precise cognitive events underlying the P600 are unknown. One possibility is that P600 amplitude reflects the "cost of reprocessing" following a garden path rather than syntactic anomaly engendered by a garden path. Consistent with this possibility, Feirrera and Henderson (1990, 1991) suggested that verb subcategorization information helps the parser recover from a garden path rather than preventing the garden path from occurring. They claimed that the initial parse through a sentence is governed by the minimal attachment principle. In our research, P600 amplitude elicited by syntactically disambiguating auxiliary verbs might have been a function of the cost associated with deriving the clausal complement analysis after having initially pursued the syntactically simpler direct object analysis. If verb information guides reanalysis after a garden path, then the parser could more easily derive the clausal complement analysis following an intransitive or intransitively biased verb than following a transitive or transitively biased verb, thereby accounting for the larger P600s to auxiliary verbs in sentences containing transitive or transitively biased verbs relative to auxiliary verbs in sentences containing intransitive or intransitively biased verbs.

However, given reasonable assumptions, this interpretation also predicts differences in N400 amplitude to postverbal nouns in the four sentence types presented in Experiment 2. Any analysis that assigns a direct object role to the postverbal noun in sentences with intransitive verbs (e.g., "The doctor hoped the patient") would seemingly engender semantic anomaly before the auxiliary verb. Conversely, a direct object analysis in sentences containing a transitive verb (e.g., "The doctor believed the patient") would be fully coherent. Therefore, if the parser was in fact initially assigning the direct object role to postverbal noun phrases in all four sentence types, one reasonable expectation is that nouns in sentences containing an intransitive verb would have produced larger N400s than the same nouns in sentences containing a transitive verb. No such difference in N400 amplitude was observed.

A further indication of whether this interpretation is correct can be obtained by examining relative differences in P600 amplitude across sentence types and experiments. A minimal attachment parser would avoid a garden path in the sentences containing a complementizer (because the direct object analysis of the postverbal noun phrase is blocked) but would encounter a garden path in reduced sentences containing an intransitive verb (because the parser is presumed to ignore verb subcategorization information). A minimal attachment parser would also be garden pathed in reduced sentences with a transitively biased verb. Thus, assuming that some reanalysis is always more costly than no reanalysis, the following predictions emerge concerning P600 amplitudes elicited by auxiliary verbs in the sentences presented in our research. Auxiliary verbs in sentences with a complementizer should elicit no P600 because the parser is not garden pathed in these sentences; auxiliaries in reduced sentences with a transitively biased verb should elicit a large P600 because the parser is garden pathed and the needed alternative analysis is inconsistent with verb subcategorization biases; and auxiliaries in reduced sentences with an intransitive verb should elicit a P600 intermediate in amplitude between the first two types of sentences because the parser is garden pathed and the alternative analysis is consistent with verb subcategorization information. One implication of these predictions is that differences in P600 amplitude should be larger between unreduced sentences with an overt complementizer and reduced sentences with transitively biased verbs (the sentences presented in Experiment 1) than between reduced sentences with intransitive verbs and reduced sentences with transitively biased verbs (two types of sentences presented in Experiment 2). However, differences in P600 amplitude elicited by the auxiliary verbs were statistically equivalent in the two comparisons. One could interpret this finding as an indication that overt complementizers and intransitive verbs are approximately equally effective at preventing garden paths, as predicted by the lexically driven parser model.

A third alternative interpretation invokes the notion of a "lexical filter" operating on the output of a minimal attachment parser. It has recently been proposed that the parser initially constructs minimal attachment structures but that structures that are inconsistent with lexical constraints are then rapidly "filtered out" (Frazier, 1987; Mitchell, 1989; but see Trueswell et al., 1993). We cannot rule out this possibility. However, if such a device is working, then the filter is sensitive not only to transitivity constraints but also to transitivity biases. Furthermore, our results (for the reasons outlined above) indicate that the filter is probably not responding to the semantic/pragmatic plausibility of the initial parse in deciding whether to attempt a second analysis (cf. Clifton et al., 1991).

Thus, we believe that the most parsimonious account of our data is that given the comprehension environment used, the parser can use verb subcategorization information to resolve local ambiguities during its first pass through a sentence. We do not know whether similar results will be observed in situations involving faster presentation rates, different tasks for the reader to perform during comprehension, or different proportions of garden-path sentences. In particular, one could criticize our methodology in that word-by-word presentation (at a rate of one word every 650 ms) is far removed from the usual manner of reading. Current work in our laboratory is aimed at replicating the findings reported in this article with continuous natural speech as stimuli. It is worth noting that in a previous study in which participants listened to natural speech stimuli, apparent violations of verb subcategorization elicited a positive-going wave with an onset between 50 and 300 ms after the onset of the anomaly. This finding appears to indicate that verb subcategorization information is rapidly applied even under more naturalistic comprehension situations (Osterhout & Holcomb, 1993).

Our research, then, has demonstrated that verb subcategorization biases do exist and have processing relevance under certain comprehension situations. As noted by Holmes et al. (1989), however, we do not currently have a detailed understanding of why these verb biases exist. A more perspicacious treatment of these issues might well introduce notions of semantic or thematic properties of verbs to account for verb biases and their influence on the parsing process (cf. Jackendoff, 1987; Levin & Rappaport, 1986; Shapiro, Zuriff, & Grimshaw, 1987).

Event-Related Brain Potentials and Sentence Processing

The experiments reported here provide additional evidence that syntactic anomaly elicits the P600 effect (cf. Neville et al., *1991*; Osterhout, *1990*; Osterhout & Holcomb, 1992, 1993; Osterhout & Mobley, 1993). These findings also indicate that the P600 is elicited regardless of whether the anomaly results from an outright violation of the lexical, argument-taking properties of verbs (as in the sentences containing transitive verbs in Experiment 2) or from parsing strategies used by the comprehender (as in the reduced sentences containing transitively biased verbs in Experiments 1 and 2).

Of particular interest is the observation that the P600 effect to auxiliary verbs was of greater amplitude in sentences containing a transitive verb than in sentences containing a transitively biased verb. One seemingly plausible explanation for this variation is the probable existence of greater between-subjects variance in the representation of verb subcategorization for transitively biased verbs than for transitive verbs. This would have produced more variance in P600 amplitude to auxiliary verbs following transitively biased verbs than following transitive verbs and would have resulted in a reduced P600. However, variances in P600 amplitude did not significantly differ across conditions. A more provocative possibility is that P600 amplitude is sensitive to the syntactic fit between a sentence constituent and preceding sentence structure in a manner analogous to the way that N400 amplitude is a function of the semantic fit between a word and preceding context (Kutas & Hillyard, 1984). Indeed, the sentence completion task used by Connine et al. (1984) to determine verb subcategorization preferences is directly analogous to the cloze task used to determine cloze probabilities for sentence-final nouns (Fischler & Bloom, 1979). One speculation consistent with our data is that P600 amplitude is a function of syntactic expectations engendered by preceding context, just as N400 amplitude has been claimed to be a function of semantic expectations.

A second (related) explanation for the amplitude variation in the P600 reintroduces the notion of cost of reprocessing, but under a lexically driven parsing account (as opposed to the structure-driven account previously discussed). Under this account, the postverbal noun is assigned the direct object role following transitive and transitively biased verbs. The subsequent auxiliary verb indicates that this is the wrong analysis, forcing the parser to search for an alternative analysis. Because an alternative analysis is present for sentences containing transitively biased verbs but is not present for sentences containing transitive verbs, one could claim that P600 amplitude is a function of the ease with which an alternative analysis can be constructed.

An intriguing but unexpected outcome of Experiment 2 was that auxiliary verbs in sentences with a transitive verb elicited a biphasic response. These words elicited a negative-going component between 300 to 500 ms, followed by a positive-going component beginning around 500 ms (P600). Given its scalp distribution (largest at posterior sites and in the right hemisphere), polarity, and temporal characteristics, this negative-going activity might be related to the N400 effect elicited by semantically inappropriate words (Kutas & Hillyard, 1980a, 1980b, 1980c). Auxiliary verbs in sentences with transitively biased verbs elicited a P600, but not an N400. These observations present a challenge to previous claims that N400 and P600 are elicited as a function of anomaly type (Hagoort et al., 1993; Osterhout & Holcomb, 1992, 1993). One conceivable explanation notes differences in the severity of the anomaly in these two sentence types. The auxiliary verbs in sentences with a transitive verb rendered these sentences ungrammatical, hence, uninterpretable. Ungrammaticality induced by these words (i.e., the inability to form a coherent syntactic representation of the sentence) might have rapidly engendered semantic anomaly (i.e., an inability to form a coherent message-level representation of the sentence), leading to the occurrence of both the P600 and the N400 within the same epoch of EEG. In contrast, the auxiliary verbs in sentences with transitively biased verbs simply forced the parser to reanalyze the sentence to derive the less preferred syntactic analysis for the sentence. Given the alternative analysis, the sentence was fully interpretable at both the syntactic and the semantic levels. Correspondingly, the temporary parsing difficulty resulted in momentary syntactic anomaly (and the P600 effect), but not semantic anomaly (and the N400 effect), because semantic anomaly was avoided as a result of the availability of a grammatical analysis of the sentence. However, if this interpretation is correct, then the relative onsets of the N400 and P600 seem paradoxical. N400 onset occurred around 300 ms after onset of the auxiliary verb, whereas P600 onset was around 500 ms. Hence, the putative response to semantic anomaly precedes the response to syntactic anomaly when the interpretation entails that the semantic anomaly in these sentences occurred after (and as a result of) syntactic anomaly. One possible explanation hinges on the cost of reprocessing interpretation of the P600. If the P600 effect reflects reprocessing engendered by the garden path rather than the processes directly involved in computing the initial syntactic analysis, then the relative onsets of the N400 and P600 effects are much less puzzling.

A final issue concerns the relationship between the P600 and the P300 family of positivities. The P300 component is elicited by unexpected task-relevant stimuli (Donchin, 1979, 1981; Duncan-Johnson & Donchin, 1977; Johnson, 1988, 1989, 1993; Ritter & Vaughan, 1969; Ruchkin, Johnson, Canoune, Ritter, & Hammer, 1990). Furthermore, the amplitude of the P300 is often proportional to the unexpectedness of the stimulus. One could claim that in our research, P600 amplitude was a function of syntactic expectations derived from verb subcategorization information (e.g., expectations concerning possible verbal complements). Currently, it is unclear whether the P600 is neurally and functionally distinct from the P300 family. Current work in our laboratory is aimed at determining whether the P300 and P600 are manifestations of a similar or identical set of neural and cognitive events. However, the veracity of our claim that P600 is elicited by syntactic anomaly does not critically hinge on the question of the relation between P300 and P600 or, more generally, on the language specificity of the P600. The relevant claim, supported here and elsewhere (Hagoort et al., 1993; Neville et al., 1991; Osterhout, 1990; Osterhout & Holcomb, 1992, 1993), is that the amplitude of the P600 appears to be sensitive to certain cognitive and neural processes involved in the determination of constituent structure during sentence processing. It is this sensitivity to relevant cognitive processes that allows investigators to use ERPs in general, and the P600 in particular, as tools for examining the on-line comprehension of language.

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Appendix A

Examples of Sentences Presented During Experiment 1

The underlined region is syntactically ambiguous and the double-underlined region is the syntactically disambiguating region.

The lawyer charged that the defendant was lying. (1)
(unreduced clausal complement sentence)

The lawyer charged the defendant was lying. (2)
(reduced clausal complement sentence)

Appendix B

Experimental Sentences Presented During Experiment 1

The auditors understood (that) the deficit had increased.
The police charged (that) the criminal would return.
The agent heard (that) the actress would arrive.
The lawyer charged (that) the claims were false.
The pilot forgot (that) the weather had worsened.
The actress heard (that) the law was unfair.
The girl saw (that) the bank had closed.
The captain saw (that) the ship was safe.
The shopper charged (that) the merchandise was stolen.
The secretary understood (that) the visitor was anxious.
The student heard (that) the decision was wrong.
The investor forgot (that) the newspaper had failed.
The pilot forgot (that) the flight was delayed.
The doctor saw (that) the boy would heal.
The senator charged (that) the secretary was lying.
The consultant heard (that) the contract was inadequate.
The general understood (that) the decision was risky.
The officer charged (that) the driver was drunk.
The waitress saw (that) the customers would leave.
The students heard (that) the war was unfair.
The mailman forgot (that) the dog was unleashed.
The employer understood (that) the workers would improve.
The professor saw (that) the student would succeed.
The sailor saw (that) the ship was leaving.
The gambler charged (that) the game was fixed.
The cook heard (that) the recipe was good.
The professor saw (that) the student had cheated.
The housewife forgot (that) her watch was broken.
The judge understood (that) the charges were dropped.
The banker forgot (that) the accountant was stealing.
The doctor charged (that) the patient was lying.
The workers saw (that) the employer was sincere.
The scientist heard (that) several solutions were possible.
The woman forgot (that) the key was lost.
The woman forgot (that) the profits had disappeared.
The judge understood (that) the testimony was misleading.
The professor charged (that) the student had failed.
The student heard (that) the assignment was insufficient.
The traveler saw (that) the island was deserted.
The soldier understood (that) the decision was unfair.
The doctor heard (that) the patient was insane.
The salesman charged (that) the car was safe.
The critic understood (that) the book was good.
The mechanic saw (that) the car was fixed.
The banker understood (that) the market would collapse.
The lawyer charged (that) the defendant was guilty.
The customer forgot (that) the coffee was bitter.
The writer heard (that) the play would succeed.
The secretary understood (that) the joke was inappropriate.
The plumber charged (that) the housewife was lying.
The thief saw (that) the combination had changed.
The host forgot (that) the guests would arrive.
The coach saw (that) the call was unfair.
The senator heard (that) the bill would pass.
The man understood (that) the fee was excessive.
The actor forgot (that) the girl was married.
The doctor charged (that) the patient was healthy.
The editor forgot (that) the manuscript was lost.
The workers saw (that) the policy had changed.
The officer charged (that) the inheritance was stolen.

Appendix C

Examples of Sentences Presented During Experiment 2

The doctor hoped the patient was lying. (1)
(intransitive verb)

*The doctor forced the patient was lying. (2)
(transitive verb)

The doctor believed the patient was lying. (3)
(intransitively biased verb)

The doctor charged the patient was lying. (4)
(transitively biased verb)

(Appendix D follows on next page)

Appendix D

Experimental Sentences Used in Experiment 2

Each sentence was paired with four verbs, one from each of four verb categories. Verbs are listed in the following order: intransitive, transitive, intransitively biased, transitively biased.

The captain agreed/bought/believed/heard the crew was unhappy.
The banker hoped/discussed/knew/forgot the secretary had called.
The musician thought/followed/remembered/heard the sonata was beautiful.
The mother insisted/included/promised/saw the child would sleep.
The student decided/forced/guessed/understood the answer was incorrect.
The detective thought/bought/knew/charged the criminal was lying.
The physicist insisted/discussed/knew/understood the theory was wrong.
The doctor decided/followed/remembered/forgot the prescription had changed.
The man hoped/included/promised/forgot his wife would return.
The plumber agreed/forced/guessed/saw the faucet was fixed.
The shopper insisted/bought/remembered/charged the bicycle was broken.
The psychiatrist decided/discussed/believed/saw the patient was sane.
The landlord thought/followed/knew/heard the tenant was angry.
The company hoped/included/promised/forgot the customer would arrive.
The detective agreed/forced/guessed/charged the criminal was guilty.
The judge agreed/followed/believed/understood the defendant was guilty.
The professor thought/discussed/knew/understood his lecture was unprepared.
The waitress agreed/bought/remembered/forgot the coffee was bitter.
The salesman insisted/included/promised/saw the car was safe.
The secretary decided/forced/guessed/heard the number had changed.
The reporter decided/bought/believed/heard the story was inaccurate.
The quarterback hoped/discussed/knew/saw the receiver was open.
The traveler agreed/followed/remembered/understood the country was poor.
The grocer thought/included/believed/forgot the customer had shoplifted.
The spy insisted/forced/promised/understood his government was willing.
The woman decided/bought/guessed/charged the merchandise was worthless.
The conductor hoped/discussed/knew/heard the orchestra was good.
The boy thought/followed/remembered/saw the dog was hungry.
The man hoped/forced/promised/forgot the police would arrive.
The accountant insisted/included/guessed/charged the purchases were unneeded.
The doctor hoped/discussed/believed/charged the patient was lying.
The workers insisted/forced/believed/charged the employer was sincere.
The scientist decided/included/knew/heard several solutions were possible.
The woman agreed/bought/remembered/forgot the key was lost.
The woman thought/included/knew/forgot the profits had disappeared.
The judge decided/bought/believed/understood the testimony was misleading.
The professor insisted/followed/remembered/charged the student had failed.
The student agreed/discussed/knew/heard the assignment was insufficient.
The traveler hoped/bought/promised/saw the island was deserted.
The soldier agreed/followed/knew/understood the decision was unfair.
The doctor agreed/followed/guessed/heard the patient was insane.
The salesman insisted/bought/promised/charged the car was safe.
The critic thought/discussed/guessed/understood the book was good.
The mechanic insisted/forced/promised/saw the car was fixed.
The banker thought/followed/guessed/understood the market would collapse.
The lawyer decided/forced/remembered/charged the defendant was guilty.
The customer thought/included/remembered/forgot the coffee was bitter.
The writer hoped/discussed/promised/heard the play would succeed.
The secretary decided/included/guessed/understood the joke was inappropriate.
The plumber insisted/forced/believed/charged the housewife was lying.
The thief insisted/forced/knew/saw the combination had changed.
The host hoped/included/knew/forgot the guests would arrive.
The coach thought/discussed/believed/saw the call was unfair.
The senator agreed/discussed/promised/heard the bill would pass.
The man agreed/included/guessed/understood the fee was excessive.
The actor hoped/followed/remembered/forgot the girl was married.
The doctor decided/forced/remembered/charged the patient was healthy.
The editor decided/bought/believed/forgot the manuscript was lost.
The workers insisted/bought/promised/saw the policy had changed.
The officer insisted/followed/guessed/charged the inheritance was stolen.
The auditors insisted/discussed/believed/understood the deficit had increased.
The police hoped/forced/knew/charged the criminal would return.
The agent thought/followed/promised/heard the actress would arrive.
The lawyer agreed/included/guessed/charged the claims were false.
The pilot agreed/discussed/remembered/forgot the weather had worsened.
The actress thought/discussed/knew/heard the law was unfair.
The girl hoped/forced/remembered/saw the bank had closed.
The captain agreed/bought/promised/ship the ship was safe.

The shopper decided/bought/knew/charged the merchandise was stolen.

The secretary decided/followed/remembered/understood the visitor was anxious.

The student agreed/forced/believed/heard the decision was wrong.

The investor hoped/bought/remembered/forgot the newspaper had failed.

The pilot decided/included/guessed/forgot the flight was delayed.

The doctor hoped/included/promised/saw the boy would heal.

The senator insisted/forced/believed/charged the secretary was lying.

The consultant agreed/discussed/knew/heard the contract was inadequate.

The general insisted/discussed/guessed/understood the decision was risky.

The officer decided/followed/believed/charged the driver was drunk.

The waitress thought/forced/knew/saw the customers would leave.

The students insisted/discovered/believed/heard the war was unfair.

The mailman thought/followed/guessed/forgot the dog was unleashed.

The employer hoped/forced/promised/understood the workers would improve.

The professor agreed/included/guessed/saw the student would succeed.

The sailor thought/bought/remembered/saw the ship was leaving.

The gambler insisted/included/promised/charged the game was fixed.

The cook decided/bought/promised/heard the recipe was good.

The professor decided/forced/knew/saw the student had cheated.

The housewife thought/bought/remembered/forgot her watch was broken.

The judge hoped/included/knew/understood the charges were dropped.

The banker insisted/followed/believed/forgot the accountant was stealing.

The governor agreed/discussed/knew/understood the problem was severe.

The man thought/bought/remembered/forgot his wallet was empty.

The farmer hoped/discussed/knew/saw the corn had grown.

The lawyer insisted/followed/believed/charged the senator was stealing.

The student hoped/included/guessed/forgot the concert was free.

The president insisted/forced/promised/understood the country would survive.

The woman insisted/followed/believed/heard the song was sexist.

The student agreed/bought/guessed/forgot the book was overdue.

The king thought/included/promised/saw the queen would complain.

The coach decided/forced/promised/understood the team would lose.

The activists insisted/discussed/believed/charged the mayor was unjust.

The nurse thought/forced/knew/saw the patient had improved.

The vacationer agreed/bought/remembered/forgot the hotel was old.

The soldier hoped/followed/promised/heard the general would return.

The actress decided/included/guessed/heard the play would succeed.

The general thought/forced/believed/charged the enemy was weak.

The baron insisted/discussed/knew/charged the countess had lied.

The librarian thought/included/remembered/saw the books were unshelved.

The sheriff decided/followed/guessed/understood the hermit was homeless.

The president hoped/discussed/promised/heard the shareholders were willing.

The cook agreed/bought/promised/forgot the food was ready.

The student decided/included/guessed/forgot the answer was unknown.

The operator agreed/forced/knew/understood the caller was correct.

The reporter hoped/bought/believed/saw the story was big.

The prosecution insisted/forced/believed/charged the witness had lied.

The playboy thought/followed/remembered/forgot the woman was penniless.

The driver insisted/discussed/remembered/saw the accident was unavoidable.

The nurse hoped/followed/promised/heard the surgeon would improve.

The executive agreed/bought/guessed/charged the decision was poor.

The mayor agreed/included/knew/understood the situation was serious.

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