Bridging the Gap: Evidence from ERPs on the Processing of Unbounded Dependencies

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Abstract

■ Since the early days of generative grammar, the study of "unbounded dependencies" such as *wh*-questions and relative clauses has occupied a central place in both syntactic theory and language processing research. The problem that such constructions pose is as follows. In a normal *wh*-question, a *wh*-phrase is typically displaced to the left periphery of a clause (*What* did you say ____ to John?); this displaced constituent is often referred to as a "filler." The vacant position (indicated in the previous example by a blank line) where it would ordinarily occur in an "echo" question (You said *what* to John?) is correspondingly referred to as a "gap." Filler and gap are mutually dependent on each other since they share syntactic and semantic information essential for successful sentence interpretation. However, since sentence processing is a sequential operation, a filler cannot be assigned to its gap until some time after it has occurred. In other words, the filler must be held in working memory until such time as filler–gap assignment can take place. The intent of the research reported here was to examine the processing of unbounded dependencies in English as revealed in event-related brain potentials (ERPs). To this end, subjects were shown both grammatical and ungrammatical yes/no-questions (Did you say something to John?) and *wh*-questions. A number of comparisons made at various points in these questions showed that both the storage of a filler in working memory and its subsequent retrieval for filler–gap assignment were associated with an enhanced negativity between 300 and 500 msec poststimulus over left anterior sites. This effect of left anterior negativity (LAN) was independent of and orthogonal to the grammaticality of the eliciting condition. We show how this interpretation coincides with recent studies that demonstrate a correlation between left anterior negativity, working memory capacity, and successful language processing. ■

INTRODUCTION

The human capacity for language and its neural underpinnings present one of the more difficult challenges to the understanding of human cognition. Although cognitive neuroscientists have at times despaired of the seemingly arcane nature of theoretical linguistic inquiry, the investigation of language nonetheless continues to capture the imagination of researchers both within and outside the field of linguistics proper. We believe the question addressed in this study to be of relevance not only for those familiar with current issues in syntactic theory, but also for those who share a more general interest in questions of language and its relation to the brain, and to other cognitive systems. The focus of our investigation is a fundamental and universal property of human language, namely the possibility of displacing a constituent to the beginning of its clause, or to the beginning of an entire utterance, in order to direct the hearer's attention to it. We were interested in finding out what electrophysiological processes are associated with this type of syntactic operation.

In English the most transparent and familiar manifestation of such displacement is the formation of *wh*-questions like

What did you put ____ on the table? (1)

In this example the displaced constituent *what*, commonly referred to as a "filler," is the direct object of the sentence, as indicated by the blank line, commonly referred to as a "gap" (Fodor, 1978). Direct objects in English typically follow the verb, as in

Did you put **the book** on the table? (2)

However, the direct object in (1) does not; instead it appears at the beginning of the clause.[1] Of course such displacement is not limited to the direct objects of verbs; in English it is equally possible to question the object of the preposition *on* in example (2), namely *the table*, yielding

What did you put the book on ____ ? (3)

Here the prepositional object has been fronted from its usual position following the preposition, once again indicated by a gap.

Note that although two completely different constituents have been questioned in these two examples, namely a direct object in (1) and a prepositional object in (3), both questions start out identically.

What did you put . . . ? (4)

This ambiguity demonstrates the computational problem involved in the comprehension of such structures: at the point when the hearer or reader encounters a filler, there is no way of knowing what semantic role (e.g., agent, patient, or goal) or grammatical function (e.g., subject, direct object, or prepositional object) it should be assigned. Such assignment cannot be made until the position in the sentence is located where the displaced constituent would occur if it were not displaced. In other words, aspects of both semantic interpretation and syntactic parsing must be delayed until the gap is located and "filled." If no suitable gap can be found, the filler remains uninterpretable, as shown in (5).[2]

**What* did you put the book on the table? (5)

A gap is similarly uninterpretable without a corresponding filler, as shown in (6).

*Did you put ____ on the table? (6)

For these reasons a mutual relationship of "dependency" is said to exist between filler and gap. It is therefore crucial that the filler in questions like (1) and (3) be held in working memory[3] until an appropriate gap can be located.

Above we stated that a constituent may be displaced (a) to the beginning of its clause or (b) to the beginning of the entire utterance. So far we have had no cause to differentiate between these two possibilities since all the examples we have considered have consisted of only one clause; that is, in every example thus far the beginning of the clause has always been the beginning of the entire utterance as well. This will, however, not be the case when two or more clauses are involved. Take, for example, the following sentence.

[$_{matrix}$ Did you say [$_{embedded}$ you put the book on the table]]? (7)

In this example there are two clauses, the "matrix" clause *Did you say* and the "embedded" clause *you put the book on the table*. If we question one of the constituents in the embedded clause, it may be displaced either to the beginning of its clause, yielding an embedded question,

(a) Did you say [$_{embedded}$ *what* you put ____ on the table]?
(b) Did you say [$_{embedded}$ *what* you put the book on ____]? (8)

or to the beginning of the entire utterance, yielding a matrix question.

(a) [$_{matrix}$ *What* did you say [$_{embedded}$ you put ____ on the table]]?
(b) [$_{matrix}$ *What* did you say [$_{embedded}$ you put the book on ____]]? (9)

The embedded fillers in (8) place essentially the same demands on working memory as the matrix fillers in (1) and (3), since the filler–gap relationship is in each case limited to one clause. The fillers in (9) however make greater demands on working memory since they appear at the beginning of the matrix clause, while the gaps which they fill occur within the embedded clause. Thus the matrix filler must be held in working memory not only for the duration of the matrix clause, but also across the embedded clause boundary indicated by the left bracket.

The use of the term "unbounded dependency" for syntactic operations such as *wh*-question formation derives from this latter interclausal configuration. The dependency between filler and gap is said to be "unbounded" because it is relatively easy to construct examples in which filler and gap are separated from each other by several intervening clause boundaries.

What did she think [he swore [that Mary said [you remembered [you had put the book on ____]]]]? (10)

In light of this example the only constraint on such constructions would appear to be one of working memory capacity. However the well-formedness of an unbounded dependency has been found in part to depend on the type of clause boundary spanned as well. Thus for example if the embedded prepositional object *them* is questioned in each of the following sentences,

(a) Isn't he sure [that the TA explained it to **them** in lab]?
(b) Isn't he sure [if the TA explained it to **them** in lab]?
(c) Isn't he sure [*what* the TA explained ____ to **them** in lab]? (11)

the resultant dependencies vary in their well-formedness (see footnote 2):

(a) *Who* isn't he sure [that the TA explained it to ____ in lab]?
(b) ?*Who* isn't he sure [if the TA explained it to ____ in lab]?
(c) **Who*$_a$ isn't he sure [*what*$_b$ the TA explained ____$_b$ to ____$_a$ in lab]? (12)

(12a) is traditionally considered well-formed, (12b) marginal, and (12c) completely impossible.[4] Much syntactic research has been devoted to the universal characterization of the constraints that govern these facts (Ross, 1968; Chomsky, 1973, 1977, 1981, 1986),[5] and we have elsewhere (Kluender, 1991, 1992; Kluender & Kutas, 1992; Kutas & Kluender, 1992) proposed a processing account of just what it is that causes this three-way distinction.[6] For present purposes, however, we will simply point out that the variability in well-formedness cannot be attributed solely to the type of embedded clause, since the examples in (11) are all fine, nor to the existence of an interclausal dependency alone, since both (10) and (12a) appear to be well-formed.

Our primary concern in the present study was to determine what electrophysiological processes would be associated with the storage of a filler in working memory and its assignment to a gap. To investigate this question we compared event-related brain potentials (ERPs) elicited in response to the various question types exemplified in (11) and (12); we looked for the electrophysiological sign of the filler–gap relationship (a) immediately following the appearance of a filler and (b) immediately following the detection of a gap.[7]

Moreover, we dissociated the mere appearance of a *wh*-filler like *who* or *what* from its storage in working memory by altering the grammatical function of the embedded fillers used. In the above examples we have shown embedded fillers associated only with object gaps, either direct object gaps as in (11c), repeated here as (13),

Isn't he sure [*what* the TA explained ____ to them in lab]? (13)

or prepositional object gaps, as in (14).

Isn't he sure [*who* the TA explained it to ____ in lab]? (14)

However, a filler can also serve as the subject of its clause, as shown in (15).

Isn't he sure [*who* ____ explained it to them in lab]? (15)

Note that although we have indicated the presence of a gap in the embedded subject position in (15), the sentence would be equally interpretable without one.[8] This is because the appearance of the verb *explained* immediately following the embedded filler *who* in (15) unambiguously indicates that *who* is the subject of the embedded clause. Thus even if this filler does enter working memory, it has to be retrieved as soon as the next word is encountered. In (13) and (14), on the other hand, the embedded filler is immediately followed by the subject noun phrase *the TA*. This clearly indicates that the embedded filler cannot be the subject of its clause and will therefore have to be held in working memory pending assignment to an object gap. (13) and (14) thus differ crucially from (15) in that they would be uninterpretable without corresponding gaps (see example 5).

Embedded subject fillers in our materials were always unambiguous, i.e., they were always followed by verbs, as in (15). Half of our stimulus sentences were of this type; the other half contained unambiguous embedded object fillers followed by subject noun phrases (see Materials for further details). This allowed us to compare the electrophysiological record of embedded fillers which either did (object fillers) or did not (subject fillers) need to be held in working memory.

RESULTS

Our objective in this experiment was to track the course of filler–gap dependencies from the time of entry of the filler into working memory to the time of its retrieval and assignment to a gap. We thus looked for electrophysiological indices of the filler–gap relationship immediately following the appearance of fillers and immediately following the detection of gaps. The results are organized according to the linear order of these points of comparison in the stimulus sentences. We begin by discussing comparisons following matrix fillers. Following that, we look at comparisons following embedded fillers in yes/no-questions, in *wh*-questions, and across question types. We then discuss comparisons following embedded direct object gaps in yes/no- and *wh*-questions. Finally, we present a brief summary of these results.

ERPs to Matrix Fillers

In this section we compare the ERPs associated with function words (the personal pronouns *you*, *he*, *she*, and *they*, the possessive pronouns *your*, *his*, *her*, and *their*, and the article *the*) occurring in subject position of the matrix clause in *wh*- and yes/no-questions.

wh-questions: *What* have YOU forgotten [if he dragged her to ____ that weekend]? (16)

yes/no-questions: Have YOU forgotten [if he dragged her to a movie that weekend]? (17)

All matrix *wh*-fillers in our stimulus sentences were associated with prepositional object gaps in the embedded clause (16). Thus in *wh*-questions, the matrix filler had to be held in working memory while the initial function word (capitalized in the above examples) of the matrix subject was being processed. This was not the case in the yes/no-questions, which by definition contain no matrix filler (17). Thus the function words that we used in this case as points of comparison occurred in equivalent positions across question types that either did (*wh*-questions) or did not (yes/no-questions) require fillers to be held in working memory during the processing of this position.

As shown in Figure 1, function words like *you* in (16) were associated with enhanced negativity over left anterior regions between 300 and 500 msec poststimulus relative to equivalent function words like *you* in (17) [question type × anterior/posterior: $F(4,112) = 14.80$, $p < 0.001$]. This interaction of question type × anterior/posterior was however bilateral since it actually reflected

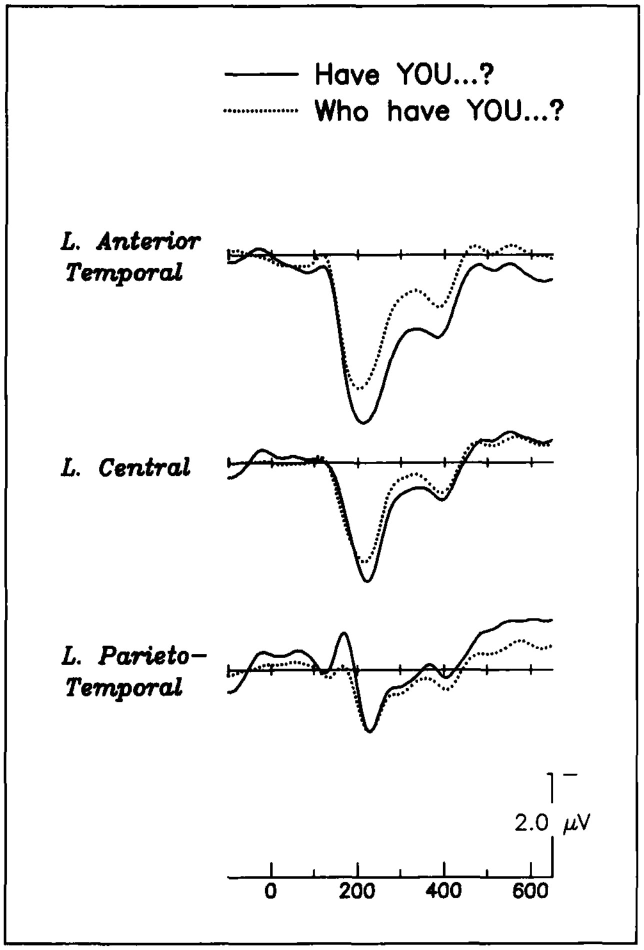

Figure 1. Grand average ERPs (n=30) from three left hemisphere sites in response to function words occurring in matrix subject position of yes/no-questions (solid line) and *wh*-questions (dotted line). Note the increased negativity between 300 and 500 msec associated with the existence of a filler-gap dependency in the *wh*-question condition, represented by the positioning of the dotted tracing closer to baseline than the solid tracing (negative polarity is plotted up in this and all subsequent figures).

two different effects: an increased negativity in response to *wh*-questions seen over left anterior regions (Broca's area), and a bilateral positivity in response to the same condition over temporal sites. ANOVAs restricted to individual electrodes thus showed main effects of sentence type only for Broca's area [$F(1,28) = 19.47, p < 0.001$; right hemisphere homologue of Broca's, $F(1,28) = 1.80$, n.s.], left temporal regions (T5) [$F(1,28) = 17.77, p < 0.001$], and right temporal regions (T6) [$F(1,28) = 16.52, p < 0.001$].

There is an idiosyncrasy of this comparison that warrants further discussion: the initial function word of the matrix subject is the third word of the sentence in *wh*-questions (17) but the second word in yes/no-questions (16). This is of concern since the ERPs to the first word of a sentence differ markedly from the ERPs to subsequent words. For example, previous research (Kutas, 1992) has shown that in the ERPs to sentence-initial words of all kinds, a positive component peaking 200 msec poststimulus (the "P200") is larger in amplitude. Similarly, the amplitude of a negative component peaking 400 msec poststimulus (the "N400")[9] is increased in the ERPs to sentence-initial open-class words. The averages used in the present study also show a larger P200 component in response to first words, but enhanced bilateral frontal negativity instead of an N400, presumably because the sentence-initial words in our study were all function rather than content words (Van Petten & Kutas, 1991a). Since the baseline for any given epoch consisted of the last 100 msec of the previous epoch, this anterior negativity to first words if not resolved by the end of the first epoch could have affected the averages of second words. And it is true of our data that the frontal negativity to first words did continue into the last 100 msec of the first epoch. However, for reasons that we will not go into here, this baseline problem cannot account for the lateral asymmetry of the anterior negativity seen in the ERP to the matrix subjects of *wh*-questions (16).[10]

In summary, a LAN difference was seen in the ERP between 300 and 500 msec poststimulus when *wh*-questions were compared to yes/no-questions at a position early in the matrix clause. Grammaticality was not a factor since at this point in the sentence all stimuli were well-formed. We have therefore hypothesized that this difference is related to the storage of the matrix filler in working memory. We will be confronted with an analogous state of affairs in subsequent comparisons: in each case the eliciting condition will contain a filler-gap dependency that is not present in the control conditions and that requires the storage of a filler in working memory.

ERPs to Embedded Fillers

In the preceding section we reported the effect of matrix *wh*-fillers on the ERP record: a negative component between 300 and 500 msec poststimulus over left anterior regions, the so-called LAN effect. We now turn to the question of what happens in the ERP record when fillers in embedded *wh*-questions presumably enter working memory. We begin by reporting the effect of embedded *wh*-fillers in grammatical yes/no-questions; we then look at the effect of embedded *wh*-fillers in ungrammatical *wh*-questions.

Within Yes/No-Questions

In this section we contrast the ERPs to function words (capitalized) immediately following embedded fillers in yes/no-questions (18 and 19) with the ERPs to function words immediately following embedded *that* complementizers (20) or *if* complementizers (21).

yes/no-*wh* (object):	Have you forgotten [*who* HE dragged ____ to the movie that weekend]?	(18)
yes/no-*wh* (subject):	Have you forgotten [*who* ____ HAD to extricate him from that mess when he was younger]?	(19)
yes/no-*that*:	Have you forgotten [that YOU faxed a copy of that contract to the corporate office on Friday]?	(20)
yes/no-*if*:	Have you forgotten [if HE dragged her to the movie that weekend]?	(21)

The function word used as the point of comparison was always the second word of the embedded clause, either the subject (18, 20, and 21) or the verb (19). Thus while an embedded object filler (18) was always followed by the embedded subject, an embedded subject filler (19) was always followed by the embedded verb. In our stimulus materials it was therefore immediately clear at the point of comparison whether an embedded filler was an object of some kind that had to be held in working memory pending assignment to a gap, or whether it was a subject that did not need to be held in working memory. Since yes/no-questions with embedded *that*-clauses (20) and *if*-clauses (21) contained no fillers whatsoever, these sentence types presumably made no more demands on working memory than yes/no-questions with embedded subject fillers. Therefore if our interpretation of the LAN effect as an index of working memory load is correct, it predicts that the effect should be seen immediately following embedded object *wh*-fillers (18) but not following embedded subject *wh*-fillers (19), *that* complementizers (20), or *if* complementizers (21).

When yes/no-*wh* questions containing embedded object fillers (18) were compared to yes/no–*that* (20) and yes/no–*if* (21) questions, the function words immediately following embedded object fillers were associated with a LAN effect relative to equivalent function words in the yes/no–*that* and yes/no–*if* questions (see Fig. 2) [complement type × anterior/posterior: $F(8,224) = 3.48, p < 0.02$; yes/no–*wh* vs. yes/no–*that*/*if*, $F(4,112) = 5.17, p < 0.01$; yes/no–*if* vs. yes/no–*that*, $F(4,112) = 0.67$, n.s.]. The same was not true of yes/no–*wh* questions containing embedded subject fillers (19), however [complement type × anterior/posterior: $F(8,224) = 1.77$, n.s.; yes/no–*wh* vs. yes/no–*that*/*if*, $F(4,112) = 2.67, p < 0.078$]. Although there was again no three-way interaction of complement type × anterior/posterior × hemisphere in this comparison, ANOVAs restricted to the left hemisphere yielded a significant interaction of complement type × anterior/posterior in yes/no–*wh* questions with embedded object fillers [$F(8,224) = 4.38, p < 0.002$; yes/no–*wh* vs. yes/no–*that*/*if*, $F(4,112) = 7.26, p < 0.002$; yes/no–*if* vs. yes/no–*that*, $F(4,112) = 1.21$, n.s.] while ANOVAs restricted to the right hemisphere did not [$F(8,224) = 1.53$, n.s.; yes/no–*wh* vs. yes/no–*that*/*if*, $F(4,112) = 3.15, p < 0.051$; yes/no–*if* vs. yes/no–*that*, $F(4,112) = 0.26$, n.s.].

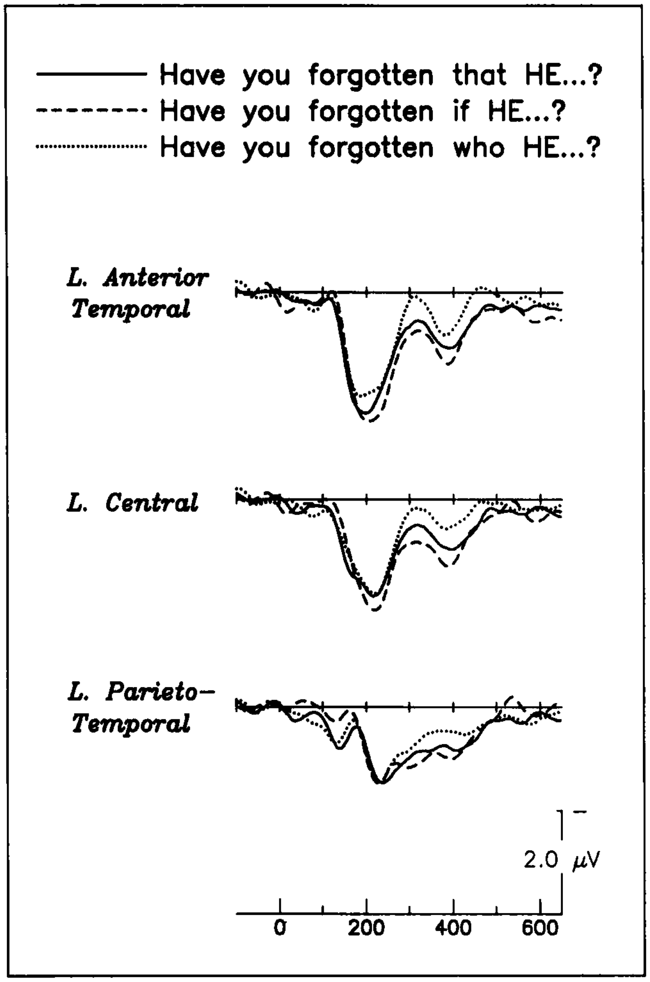

Figure 2. Grand average ERPs (n=30) recorded at three left hemisphere sites to function words (capitalized) immediately following *that* complementizers (solid line), *if* complementizers (dashed line), and object *wh*-fillers (dotted line) embedded in matrix yes/no-questions. Note the similarity of this effect to that seen in Figure 1.

There are two important points to note here. First, the prediction that embedded object fillers but not embedded subject fillers would be associated with enhanced negativity over left anterior regions was confirmed. This in turn provides further evidence consistent with the hypothesis that the LAN effect indexes the storage of a filler in working memory. Second, since the conditions under comparison were all fully grammatical, the LAN difference could not be due to perceived degrees of grammaticality among them. Recall that the same was true of the matrix clause comparisons previously reported. This point will become crucial in the following section when we look at the effects of embedded *wh*-fillers in ungrammatical *wh*-questions.

Within Wh-Questions

In this section we contrast the ERPs to function words (capitalized) immediately following embedded fillers in ungrammatical *wh*-questions (henceforth *wh*–*wh* questions, 22 and 23) with the ERPs to function words in analogous positions in grammatical *wh–that* (24) and marginal *what–if* (25) questions.[11]

wh–wh (object): **Who*$_a$ has she forgotten [*what*$_b$ THE boss referred ___$_b$ to ___$_a$ for further study]? (22)

wh–wh (subject): **What*$_a$ have you forgotten [*who*$_b$ ___$_b$ HAD to extricate him from ___$_a$ when he was younger]? (23)

wh–that: *Who* has she forgotten [that THE boss referred that matter to ___ for further study]? (24)

wh–if: ?*Who* has she forgotten [if THE boss referred that matter to ___ for further study]? (25)

The function word used as the point of comparison in these sentences was, just as in yes/no-questions, the second word of the embedded clause, either the first word of the subject phrase (*the*: 22, 24, and 25) or the first word of the verb phrase (*had*: 23). Thus embedded subject fillers (23) were again identifiably marked as such by virtue of the fact that they were always followed by the embedded verb, while embedded object fillers (22) were always followed by the embedded subject.

However, this comparison differed from that previously reported for yes/no-questions in that all conditions contained matrix *wh*-fillers heading long-distance dependencies into the embedded prepositional object gap position. In other words, in all the conditions under comparison, filler–gap dependencies from the matrix clause into the embedded clause were being maintained at the point of comparison, and all conditions were thus equivalent in this regard. In addition, however, half of the *wh–wh* condition questions contained embedded object fillers that headed dependencies into the embedded direct object position (22). This subset of stimulus sentences thus required the entry of a second filler into working memory at the point of comparison. The same was not true of the *wh–that* (24) and *wh–if* (25) conditions, which contained no dependencies in the embedded clause, or of *wh–wh* questions with embedded subject fillers (23), in which the embedded filler could be immediately assigned to its gap. Therefore questions like (22) required the maintenance of two simultaneous filler–gap dependencies at a point in the sentence where the other conditions (23, 24, and 25) required the maintenance of only one. Consequently our interpretation of the LAN effect as an index of fillers being held in working memory predicts that the questions with embedded direct object fillers (22) should be dissociated from the other conditions in the LAN effects that they produce.

A pattern of results very similar to that observed in yes/no-questions was seen in these comparisons, as predicted: a LAN difference was elicited by function words immediately following object fillers in embedded *wh*-clauses (22) relative to the same position in embedded *that*-clauses (24) and *if*-clauses (25) (see Fig. 3) [complement type × anterior/posterior × hemisphere: $F(8,224) = 2.69$, $p < 0.016$; *wh–wh* vs. *wh–that/if*, $F(4,112) = 4.07, p < 0.009$; *wh–if* vs. *wh–that*, $F(4,112) = 0.71$, n.s.]. As in yes/no-questions, the ERPs to function words following subject fillers in embedded *wh*-clauses (23) did not differ significantly from the ERPs to the same position in embedded *that*-clauses (24) or *if*-clauses (25) [complement type × anterior/posterior × hemisphere: $F(8,224) = 0.46$, n.s.; *wh–wh* vs. *wh–that/if*, $F(4,112) = 0.34$, n.s.].

Thus once again there was a dissociation between embedded subject fillers and embedded object fillers: the entry of an embedded object filler into working memory was marked by a LAN effect in our data, while no such effect was seen in the case of embedded subject fillers, which could be immediately assigned to the hypothesized adjacent gap. This difference can have nothing to do with the ungrammaticality of the *wh–wh* condition since embedded subject and embedded object fillers are *both* ungrammatical in this condition. However,

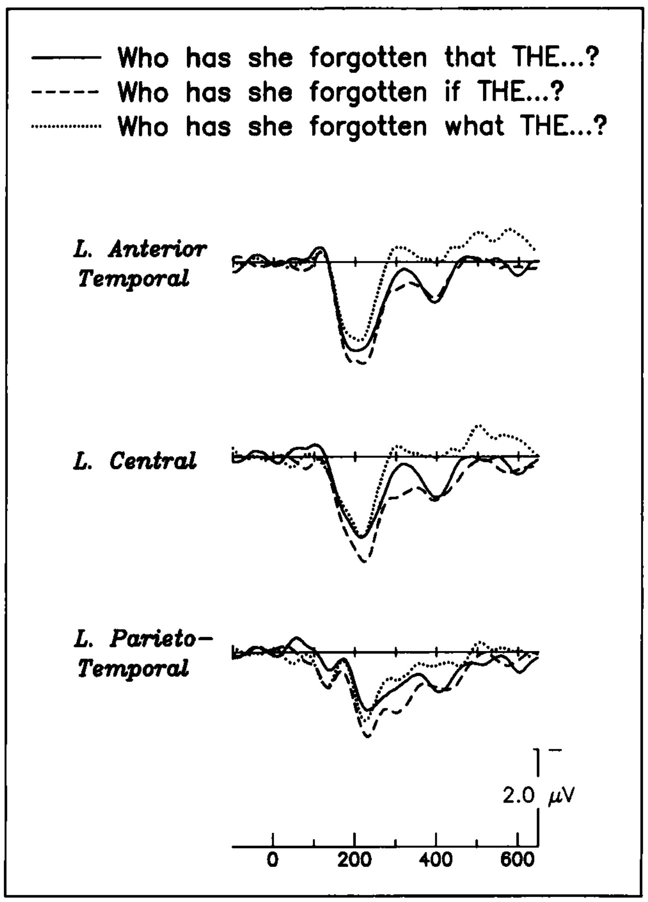

Figure 3. Grand average ERPs (n=30) recorded at three left hemisphere sites in response to function words (capitalized) immediately following *that* complementizers (solid line), *if* complementizers (dashed line), and object *wh*-fillers (dotted line) embedded in matrix *wh*-questions. Note the similarity in distribution of the effect in this figure to that seen in Figure 2.

only the latter elicited a LAN effect, while the former did not differ significantly from the *wh–that* and *wh–if* conditions at this position. Furthermore, recall that a similar LAN effect was seen at the beginning of the embedded clause in the fully grammatical yes/no-*wh* condition following embedded object fillers. The effect is thus clearly orthogonal to grammaticality, and these comparisons lend further credence to the hypothesis that the LAN effect was due to the storage of a filler in working memory pending assignment to a gap.

Across Question Types

We previously reported that matrix clause subjects elicit a LAN effect when they follow matrix *wh*-fillers heading dependencies into the embedded prepositional object position. So far we have reported that embedded clause subjects similarly elicit a LAN effect when they follow an embedded *wh*-filler heading a dependency into the embedded direct object position. Thus whenever the storage of a *wh*-filler in working memory has been required by one condition but not the other(s), we have seen a LAN difference in the ERP. This leads to the prediction that at the second word (capitalized) of the embedded clause in matrix *wh*-questions (26, 28, 30, and 32), a LAN effect should be seen relative to the same position in corresponding matrix yes/no-questions (27, 29, 31, and 33).

wh–wh (object):	**What*$_a$ have you forgotten [*who*$_b$ HE dragged ____$_b$ to ____$_a$ that weekend]?	(26)
yes/no–*wh* (object):	Have you forgotten [*who* HE dragged ____ to the movie that weekend]?	(27)
wh–wh (subject):	**What*$_a$ have you forgotten [*who*$_b$ ____$_b$ HAD to extricate him from ____$_a$ when he was younger]?	(28)
yes/no–*wh* (subject):	Have you forgotten [*who* ____ HAD to extricate him from that mess when he was younger]?	(29)
wh–that:	*Who* has she forgotten [that THE boss referred that matter to ____ for further study]?	(30)
yes/no–*that*:	Have you forgotten [that YOU faxed a copy of that contract to the corporate office on Friday]?	(31)
wh–if:	?*What* have you forgotten [if HE dragged her to ____ that weekend]?	(32)
yes/no–*if*:	Have you forgotten [if HE dragged her to the movie that weekend]?	(33)

This is because matrix *wh*-questions always contain a filler–gap dependency not found in corresponding yes/no-questions, namely the dependency into the prepositional object gap position, and this dependency requires the storage of a filler in working memory.

When the second word of the embedded clause in matrix *wh*-questions (26, 28, 30, and 32) was compared to the same position in matching yes/no-questions (27, 29, 31, and 33), a LAN effect was seen as predicted (see Fig. 4) [question type × hemisphere: *wh–wh* (26 and 28) vs. yes/no–*wh* (27 and 29), $F(1,28) = 7.22, p < 0.012$; *wh–that* (30) vs. yes/no–*that* (31), $F(1,28) = 5.97, p < 0.021$; question type × anterior/posterior × hemisphere: *wh–if* (32) vs. yes/no–*if* (33), $F(4,112) = 3.39, p < 0.04$]. Although there was no interaction of question type × anterior/posterior × hemisphere in the *wh–wh* (26 and 28) vs. yes/no—*wh* (27 and 29) and *wh–that* (30) vs. yes/no–*that* (31) comparisons, in both cases ANOVAs restricted to the left hemisphere showed interactions of question type × anterior/posterior [*wh–wh* vs. yes/no–*wh*, $F(4,112) = 2.71, p < 0.076$; *wh–that* vs. yes/no–*that*, $F(4,112) = 4.39, p < 0.018$], which did not reach significance in ANOVAs restricted to the right hemisphere [*wh–wh* vs. yes/no–*wh*, $F(4,112) = 0.54$, n.s.; *wh–that* vs. yes/no–*that*, $F(4,112) = 1.23$, n.s.].

It is interesting to note that the interaction of question type × hemisphere seen in the *wh–wh* (26 and 28) vs. yes/no–*wh* (27 and 29) comparison was primarily due to subject fillers (28) [$F(1,28) = 4.54, p < 0.042$] rather than to object fillers (26) [$F(1,28) = 2.21$, n.s.]. Furthermore, in the partial ANOVA restricted to the left hemisphere, the interaction of question type × anterior/posterior did not approach significance with either object fillers [$F(4,112) = 1.27$, n.s.] or subject fillers [$F(4,112) = 0.93$, n.s.] alone, but only when both types of filler were taken into consideration.

This is in sharp contrast to our analysis of comparisons

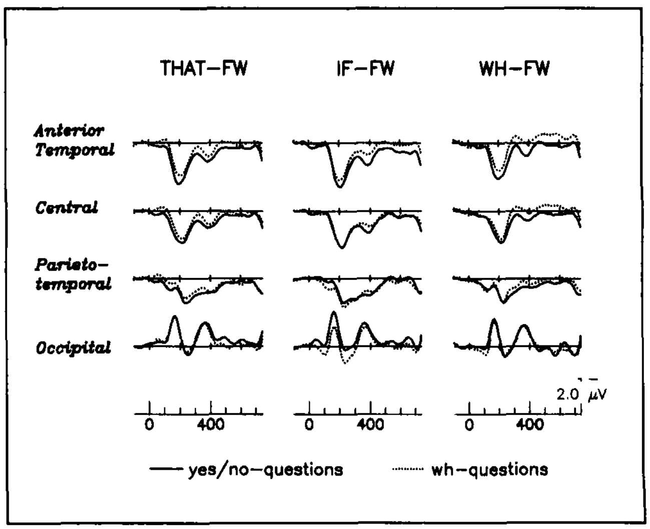

Figure 4. Grand average ERPs (n=30) recorded at four left hemisphere sites in response to the function words immediately following *that* complementizers (left column), *if* complementizers (middle column), and *wh*-fillers (right column) embedded in yes/no-questions (solid line) or *wh*-questions (dotted line).

at the second word of the embedded clause within question types. In those cases, significant LAN differences were unequivocally attributable to embedded object fillers. However, recall that all matrix clause *wh*-questions in our materials (26, 28, 30, and 32) contained fillers separated from the embedded prepositional gaps with which they were associated. Thus the LAN difference seen between *wh*- and yes/no-questions at the second word of the embedded clause reflected the necessity of storing the matrix filler in working memory in *wh*-questions but not in yes/no-questions; the same was true of comparisons early in the matrix clause.[12]

It is important to emphasize once again that the LAN effect seen in these comparisons cannot be due to perceived syntactic deviance. Although it is true that dependencies into *wh*-clauses (26 and 28) are usually considered ungrammatical, and dependencies into *if*-clauses (32) are considered ill-formed by some speakers, the dependencies into *that*-clauses in our stimulus sentences (30) were all well-formed. Still, a LAN effect was elicited at the second word of the embedded clause in all three types of *wh*-questions relative to the same position in corresponding yes/no-questions regardless of these differences in grammaticality.

ERPs to Embedded Gaps

We have looked at the effect of matrix and embedded *wh*-fillers on the ERP record; we now turn to the electrophysiological effect of embedded gaps. In our discussion of the results, we assume that at gap location, fillers must be retrieved from working memory for purposes of gap assignment. Given our interpretation of the LAN effect as an index of working memory load in filler–gap configurations, we were interested in seeing if the effect would appear not only during storage of a filler in working memory pending assignment to a gap, but also upon its retrieval from working memory at gap location. We first look at the filling of embedded direct object gaps in matrix yes/no-questions, and then at the filling of embedded direct object gaps in matrix *wh*-questions.

Within Yes/No-Questions

In this section we contrast the ERP to prepositions (capitalized) immediately following embedded direct object gaps in yes/no–*wh* questions (34) with the ERP to prepositions immediately following direct object noun phrases in yes/no–*that* (36) and yes/no–*if* (37) questions.

yes/no–*wh* (object):	Can't you tell [*what* she intends to drum ____ INTO you by the end of the quarter]?	(34)
yes/no–*wh* (subject):	Can't you remember [*who* ____ tried to scare him INTO selling his property by means of threats]?	(35)
yes/no–*that*:	Can you believe [that he was able to lure them INTO this shady deal with all their experience]?	(36)
yes/no–*if*:	Can't you tell [if she intends to drum this stuff INTO you by the end of the quarter]?	(37)

In yes/no-questions, when a direct object gap immediately preceded the preposition in embedded *wh*-clauses (34), a LAN effect was seen relative to prepositions following lexical noun phrase (NP) direct objects in embedded *that*-clauses (36) and *if*-clauses (37) (see Fig. 5). This effect was largest over Broca's area, but was seen over auditory cortex and Wernicke's area as well [complement type × hemisphere: $F(2,56) = 9.71, p < 0.001$; yes/no–*wh* vs. yes/no–*that*/*if*, $F(1,28) = 12.67, p < 0.001$; yes/no–*if* vs. yes/no–*that*, $F(1,28) = 4.86, p < 0.036$; complement type × anterior/posterior × hemisphere [$F(8,224) = 3.67, p < 0.004$; yes/no–*wh* vs. yes/no–*that*/*if*, $F(4,112) = 6.33$, $p < 0.001$; yes/no–*if* vs. yes/no–*that*, $F(4,112) = 1.39$, n.s.]. Since both interactions included positive differences between 300 and 500 msec over the right hemisphere, an ANOVA restricted to the left hemisphere was also done [complement type × anterior/posterior

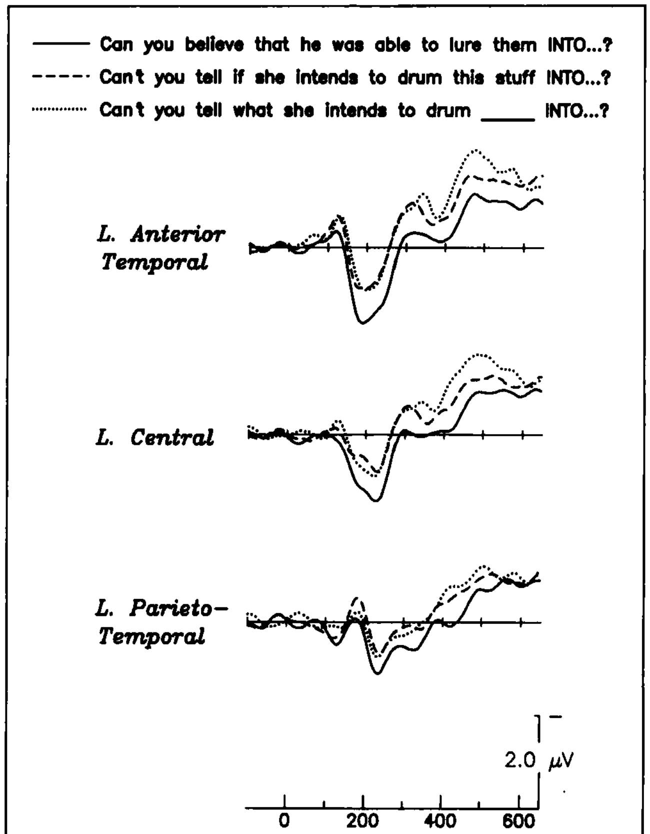

Figure 5. Grand average ERPs (n=30) from three left hemisphere sites in response to prepositions following lexical noun phrases in the yes/no–*that* (solid line) and yes/no–*if* (dashed line) conditions, and to prepositions following object gaps in the yes/no–*wh* condition (dotted line).

[$F(8,224) = 4.58, p < 0.005$; yes/no–*wh* vs. yes/no–*that*/*if*, $F(4,112) = 6.79, p < 0.003$; yes/no–*if* vs. yes/no–*that*, $F(4,112) = 1.55$, n.s.]. Comparisons of the yes/no–*wh* (subject) condition (35) with the yes/no–*that* (36) and yes/no–*that* (37) conditions at the embedded preposition yielded no significant interactions with complement type. This is to be expected, given our hypothesis that left anterior negativity indexes gap-filling at this position, since the prepositions in all three of these conditions were preceded by lexical NP direct objects.

Note that filling the direct object gap in yes/no-questions is an unproblematically grammatical operation, hence the LAN effect seen in this comparison cannot have anything to do with grammaticality. Instead this LAN effect is consistent with an interpretation relating it to the retrieval of the embedded direct object filler from working memory. We will pursue this hypothesis in the next section on the filling of direct object gaps in *wh*-questions.

Within Wh-Questions

In this section we contrast the ERP to prepositions (capitalized) immediately following embedded direct object gaps in *wh–wh* questions (38) with the ERP to prepositions immediately following direct object noun phrases in *wh–that* (40) and *wh–if* (41) questions.

wh–wh (object):	**What*$_a$ did he wonder [*who*$_b$ he could coerce ____$_b$ INTO ____$_a$ this time]?	(38)
wh–wh (subject):	**What*$_a$ can't you remember [*who*$_b$ ____$_b$ had tried to scare him INTO ____$_a$ by means of threats]?	(39)
wh–that:	*What* did he suppose [that he could coerce her INTO ____ this time]?	(40)
wh–if:	?*What* did he wonder [if he could coerce her INTO ____ this time]?	(41)

Just as in yes/no-questions, when a direct object gap immediately preceded the preposition (38), enhanced left hemisphere negativity was seen relative to prepositions following lexical noun phrase (NP) direct objects in embedded *that*-clauses (40) and *if*-clauses (41) (see Fig. 6). In *wh*-questions, this left-hemisphere negativity had a more temporoparietal distribution, largest over auditory cortex and Wernicke's area but visible over Broca's area as well [complement type × anterior/posterior × hemisphere: $F(8,224) = 2.53, p < 0.032$].

However, this interaction included extraneous N400-like differences over the right hemisphere between the *wh–that* (40) and *wh–if* (41) conditions [main effect of complement type: $F(1,28) = 4.47, p < 0.043$; complement type × anterior/posterior × hemisphere: $F(4,112) = p < 0.052$]. To verify that effects following direct object gaps were primarily due to changes over the left hemisphere, and that N400-like effects to lexical NP direct objects in the same latency range of 300 to 500 msec poststimulus

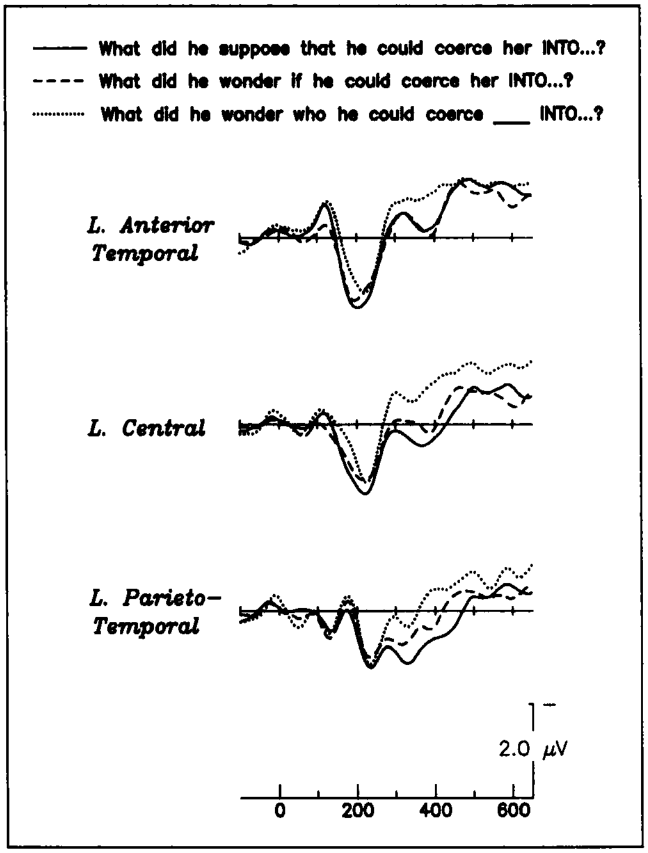

Figure 6. Grand average ERPs (n=30) from three left hemisphere sites in response to prepositions following lexical noun phrases in the *wh–that* (solid line) and *wh–if* (dashed line) conditions, and to prepositions following object gaps in the *wh–wh* condition (dotted line). Note the shift in the locus of the negative effect to left central regions.

were due to changes over the right hemisphere, separate ANOVAs were performed on the data from the two hemispheres. These results confirmed that negative differences seen between 300 and 500 msec in comparisons of the *wh–wh* (object) condition (38) to the other two conditions (40 and 41) were in fact left hemisphere effects [main effect of complement type: $F(2,56) = 3.99, p < 0.024$; *wh–wh* vs. *wh–that*/*if*, $F(1,28) = 4.43, p < 0.044$; *wh–if* vs. *wh–that*, $F(1,28) = 3.31, p < 0.079$; complement type × anterior/posterior: $F(8,224) = 2.93, p < 0.039$; *wh–wh* vs. *wh–that*/*if*, $F(4,112) = 3.95, p < 0.054$; *wh–if* vs. *wh–that*, $F(4,112) = 1.51$, n.s.]. There were no significant differences over the right hemisphere between the *wh–wh* (object) condition (38) on the one hand and the *wh–that* (40) and *wh–if* (41) conditions on the other [main effect of complement type: $F(2,56) = 2.09$, n.s.; *wh–wh* vs. *wh–that*/*if*, $F(1,28) = 0.40$, n.s.; *wh–if* vs. *wh–that*, $F(1,28) = 4.22, p < 0.049$; complement type × anterior/posterior: $F(8,224) = 0.73$, n.s.; *wh–wh* vs. *wh–that*/*if*, $F(4,112) = 0.71$, n.s.; *wh–if* vs. *wh–that*, $F(4,112) = 0.73$, n.s.].

While *wh–wh* questions with embedded object fillers (38) are clearly ungrammatical at this point in the sentence, so are *wh–wh* questions with embedded subject fillers (39). It is therefore all the more striking that these ungrammatical question types are indexed by different ERP effects at this position in the sentence: a LAN effect following direct object gaps, and an N400-like effect between 300 and 700 msec following lexical NPs in direct object position of embedded *wh*-clauses [complement type × anterior/posterior: $F(8,224) = 3.22, p < 0.026$; *wh–wh* (39) vs. *wh–that/if*, $F(4,112) = 5.69, p < 0.006$; *wh–if* vs. *wh–that*, $F(4,112) = 0.37$, n.s.]. This provides further evidence consistent with the hypothesis that the LAN effect indexes retrieval of the embedded direct object filler from working memory. However, at this point it is unclear if the more temporoparietal distribution of the left hemisphere negativity seen in this comparison is the same as the LAN effect seen in all the other comparisons (see *How Many LAN Effects Are There?* for further discussion).

Summary of Results

We conclude this section with a brief summary of results.

1. An effect of enhanced left anterior negativity (LAN) between 300 and 500 msec poststimulus was seen when *wh*-questions were compared to yes/no-questions early in the matrix clause, when all strings were still grammatical.
2. A similar LAN effect was seen immediately following embedded object fillers but *not* following embedded subject fillers relative to positions following embedded *that* and *if* complementizers in grammatical yes/no-questions.
3. A LAN effect was also seen immediately following embedded *object* fillers in ungrammatical *wh*-questions relative to *wh*-questions containing *that* or *if* complementizers. Even though the eliciting condition was ungrammatical in this case, this was determined not to be the crucial variable since no LAN effect was seen immediately following embedded *subject* fillers in ungrammatical *wh*-questions.
4. A LAN effect was seen in the embedded clause each time a *wh*-question containing a particular embedded clause type was compared to the corresponding yes/no-question with the same embedded clause type. This effect was independent of the grammaticality of the *wh*-question involved and also of the nature of the filler in the embedded *wh*-clause, suggesting that it was due solely to the presence of a long-distance dependency from the matrix clause into the embedded clause of the *wh*-question.
5. A LAN effect was again seen immediately following direct object gaps relative to positions immediately following lexical NP direct objects in grammatical yes/no-questions.
6. A left hemisphere negativity with a more temporoparietal distribution was seen immediately following direct object gaps in ungrammatical *wh*-questions with embedded *wh*-clauses. Ungrammatical *wh*-questions with embedded subject fillers and lexical NPs in direct object position elicited an N400-like response instead.

DISCUSSION

The results presented led us to conclude the following: (a) the LAN effect was correlated with the storage of fillers in working memory and their subsequent retrieval upon gap detection for purposes of gap assignment, and (b) the effect was independent of and orthogonal to the grammaticality of the eliciting condition. There are certain other conclusions that one might be tempted to make on the basis of these same results. We will address each of these in turn, indicating why we feel that such conclusions cannot be drawn from this set of data, pending further research. Following that will be a discussion of the role of working memory in sentence processing.

Interpretation of the LAN Effect

What Exactly Does the LAN Effect Index?

Although we have hypothesized that the LAN effect indexes the storage of a filler in working memory and its subsequent retrieval, we are not claiming that it is *exclusively* associated with filler–gap dependencies, or for that matter with the actual process of filling gaps. There are two reasons for this. First, there are other reports in the electrophysiological literature in which left anterior negativity has been reported, namely in a paired associate learning task (Lang, Lang, Uhl, Kornhuber, Deecke, & Kornhuber, 1988) and in a modified Sternberg task (Ruchkin, Johnson, Canoune, & Ritter, 1992). Consistent with our general view, Ruchkin, Johnson, Canoune, and Ritter (1990, 1992) found that this LAN was sensitive to working memory load. Although the tasks involved in these studies were also linguistic ones (Lang, Lang, Uhl, Kornhuber, Deecke, & Kornhuber, 1987, 1988; Ruchkin et al., 1990, 1992), it is not yet clear whether left anterior negativity is peculiar to the role of working memory in language processing or more generally reflective of working memory use. It is interesting in this regard that manipulations of working memory load in non-linguistic tasks such as mental rotation, mental arithmetic (Ruchkin, Johnson, Canoune, & Ritter, 1991), and visuospatial processing (Ruchkin et al., 1992) are associated with slow potential shifts of different topographical profiles than those found in linguistic tasks.[13]

Beyond this, if left anterior negativity were exclusively associated with the process of filling gaps, then it should no longer be present after a gap has already been filled. To test this, we compared the function word (capitalized) immediately following the lexical NP in embedded prepositional object position across our yes/no-question conditions.

yes/no–*wh* (object):	Can't you tell [*what* she intends to drum ____ into you BY the end of the quarter]?	(42)
yes/no–*wh* (subject):	Can't you remember [*who* ____ tried to scare him into selling his property BY means of threats]?	(43)
yes/no–*that*:	Can you believe [that he was able to lure them into this shady deal WITH all their experience]?	(44)
yes/no–*if*:	Can't you tell [if she intends to drum this stuff into you BY the end of the quarter]?	(45)

Note that there are gaps separated from their fillers only in yes/no–*wh* questions with embedded direct object fillers (42). At the point of comparison, however, these direct object gaps have already been filled. Nonetheless, a LAN effect was seen at this point in sentences that contained direct object gaps (see Fig. 7) [complement type × anterior/posterior × hemisphere: $F(8,224) = 3.49, p < 0.005$; yes/no–*wh* vs. yes/no–*that*/*if*, $F(4,112) = 5.37$, $p < 0.002$; yes/no–*if* vs. yes/no–*that*, $F(4,112) = 0.98$, n.s.].

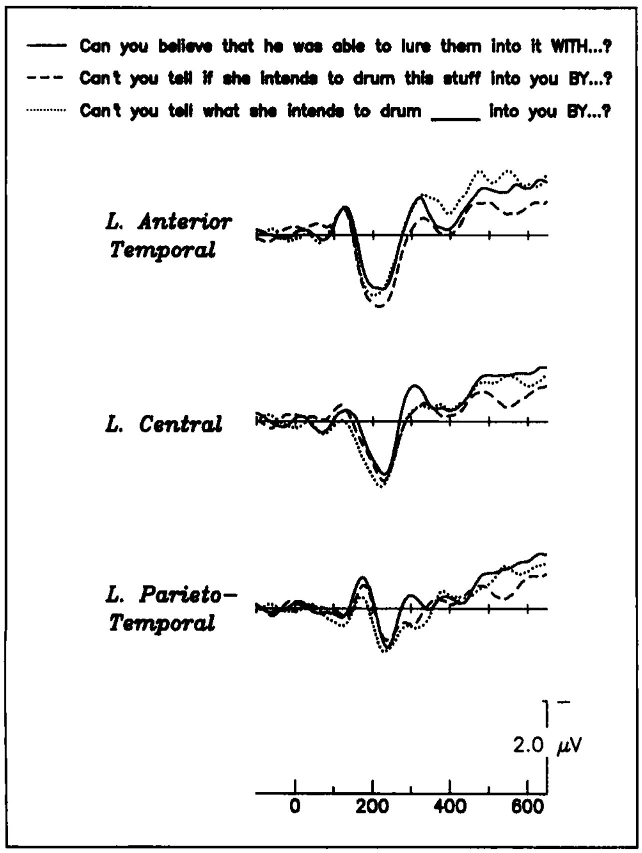

Figure 7. Grand average ERPs (n=30) from three left hemisphere sites elicited by the initial function word of a sentence-ending adjunct phrase immediately following the embedded prepositional object phrase in the yes/no–*that*, yes/no–*if*, and yes/no–*wh* (object) conditions.

Crucially, however, no such effect was seen in yes/no–*wh* questions with purported subject gaps (43) [complement type × anterior/posterior × hemisphere: $F(8,224) = 0.74$, n.s.]. This means that the left anterior negativity in this comparison was still consistently associated with sentences in which fillers had to be held in working memory pending assignment to a gap. Yet the LAN effect apparently did not subside immediately after the filler had been retrieved from working memory and assigned to its gap. Whether the effect continued throughout the entire sentence is something that we cannot say on the basis of our current data, but we can say that no such effect showed up in comparisons of sentence-final words. This suggests that those regions of neural tissue that subserve working memory, at least for purposes of sentence processing, continue to be active for some time after the primary memory task has been completed. This could possibly be due to the overall difficulty of processing sentences containing unbounded dependencies (see Kluender & Kutas, 1992). One way to test this hypothesis would be to design experiments in which averages of entire sentences containing unbounded dependencies can be made. This in turn would require that the experimental sentences consist of the same number of words, however, which is not the case in our materials.

In addition to these considerations, there is partially conflicting evidence regarding the LAN effect from previous research: a very similar enhanced negativity between 300 and 500 msec poststimulus over left anterior regions was reported by Neville et al. (1991) in comparisons of the sentence types shown in (46). Analogous comparisons from the present study are given in (47).

(a) The scientist criticized [a PROOF of the theorem].
(b) The scientist criticized [*Max's* PROOF of the theorem].
(c) *What* did the scientist criticize [a PROOF of ____]?
(d) **What* did the scientist criticize [*Max*'s PROOF of ____]? (46)

(a) Can't you remember [if HE advised them against it on previous occasions]?
(b) Can't you remember [*who* HE advised ____ against it on previous occasions]?
(c) ?*What* can't you remember [if HE advised them against ____ on previous occasions]?
(d) **What*$_a$ can't you remember [*who*$_b$ HE advised ____$_b$ against ____$_a$ on previous occasions]? (47)

Neville et al. reported enhanced left anterior negativity between 300 and 500 msec after presentation of the word *proof* in (46d) relative to the same word in (46b) and (46c). This finding is particularly relevant to the results reported in this study insofar as the eliciting conditions in the two studies are structurally analogous, as can be seen by comparing (46) and (47). In both studies the point of comparison is the second word of an embedded context. In the Neville et al. study this embedded context is a complex noun phrase with a prepositional complement (*proof of the theorem*) introduced by either an indefinite article (*a*) or a possessive specifier (*Max's*), while in the present study it is a complement clause (*he advised them against it on previous occasions*) introduced by either a complementizer (*that* or *if*) or an interrogative pronoun clausal specifier (*what* or *who*). The two studies differ in that the comparison is to content words (*proof*) across conditions in the Neville et al. study and to function words (*he*) in the present study. Any discernible difference in amplitude across studies can plausibly be attributed to this fact. Otherwise, latency, distribution, and morphology of the component seem much the same.

Neville et al. interpret their LAN effect as an index of the ungrammaticality of (46d), in particular as the index of a violation of Fiengo and Higginbotham's (1981) specificity condition. This conflicts with (a) our interpretation of the LAN effect as indexing the storage of a filler in working memory and its subsequent retrieval, (b) the lack of any consistent correlation between grammaticality and the LAN effect in our data, and (c) the fact that the syntactic configuration in our data that elicited the effect is not one ordinarily subsumed by the specificity condition. We therefore suggest that the LAN difference seen in comparisons of (46d) to (46b) can be given the same interpretation as that given the LAN effects in the present study: namely, (46d) differs from (46b) in the existence of a *wh*-dependency from the matrix clause into the prepositional object gap position, i.e., in the requirement for a filler to be held in working memory pending assignment to a gap.

On the other hand, Neville et al. report that they obtain a LAN effect in comparisons of (46c) with (46d). Clearly this difference cannot be interpreted as indexing the existence of a filler–gap dependency in (46d) not present in (46c), as both conditions contain dependencies from the matrix clause into the prepositional object gap position and therefore do not differ on this parameter. However, (46d) does differ from (46c) in the need to access a new discourse referent (*Max*) at the boundary of the embedding, and we have elsewhere (Kluender, 1991, 1992; Kluender & Kutas, 1992; Kutas & Kluender, 1992) argued that the access of discourse referents in such configurations places additional demands on working memory over and above the storage of fillers. This suggests that left anterior negativity may simply be an index of working memory load in sentence processing, or more generally in language processing. These are possibilities that need to be addressed in future research.

However, we would nevertheless like to forestall an interpretation of our data that we believe untenable. Recall that a LAN effect was also seen when (47b) was compared to (47a) in the present study. This was interpreted as an index of the filler–gap dependency in the embedded clause. However, given current conceptions of phrase structure (Chomsky, 1986), which allow specifiers not only in noun phrases (e.g., *Max's*) but in phrases of all grammatical categories, including clauses, one might be tempted to argue that the LAN effect in our data consistently indexes the presence of a *wh*-specifier (i.e., an interrogative pronoun filler such as *who* or *what*) in either the matrix or the embedded clause. But this clearly will not do, for the LAN effect seems to rely on a *wh*-filler that must be held in working memory, e.g., an embedded object filler, and not just on the presence of any *wh*-filler. The presence of a *wh*-specifier alone is neither a necessary nor a sufficient condition for eliciting a LAN effect.

Are There Subject Gaps?

We would like to emphasize that although our data are consistent with theoretical accounts that dispute the presence of subject gaps in configurations like those found in our materials, i.e., where they are not separated from their fillers (Gazdar et al., 1985; Chung & McCloskey, 1983; Chomsky, 1986), and with processing accounts that find no effect of subject gap detection in such configurations (Stowe, 1986), the existence of such subject gaps cannot be ruled out on the basis of our findings. The most coherent interpretation of our results seems to be one based on the role of working memory in the processing of filler–gap dependencies. However, this hypothesis is neutral on the issue of subject gaps that are adjacent to their fillers; subject gaps could very well exist in our stimuli and yet not require the storage of a subject filler in working memory. This is because in our materials purported subject gaps would immediately follow the subject filler, but neither the subject filler nor a subject gap can be identified as such until the subsequent word is encountered. This word, the point of comparison in our study, disambiguates between embedded subject and object fillers: subject fillers in our materials are followed by verbal elements while object fillers are followed by nominal elements in subject position. This means that identification of a subject filler would be simultaneous with detection of a subject gap, allowing instantaneous gap-filling and abrogating the need for anything to enter into working memory.[14]

However, we predict that when subject fillers must be stored in working memory, they should elicit left anterior negativity relative to sentences containing complementizers in analogous positions. This would be the case when subject fillers are separated from their gaps, as in the following example.

(a) Can't you remember [if SHE said [HER sister would take care of her son FOR her during her absence?
(b) Can't you remember [*who* SHE said [____ WOULD take care of her son FOR her during her absence?
(c) Can't you remember [*who* SHE said [HER sister would take care of ____ FOR her during her absence? (48)

Both the subject filler in (48b) and the object filler in (48c) occur in a clause superordinate to the one in which their gaps are located. The crucial comparison would be at the superordinate subject *she*: based on our hypothesis, we would predict a LAN effect in both (48b) and (48c) relative to (48a), since in both cases the filler *who* must be temporarily stored in working memory. In addition, we would predict enhanced LAN following detection of the subject gap in (48b) at the embedded auxiliary *would* relative to the embedded subject *her (sister)* in (48a). We further expect enhanced LAN at the embedded preposition *for* in (48c) relative to the same position in (48a), where no gap-filling takes place. This would be a replication of findings in the present study. Beyond this, it would be possible to study the duration of the LAN effect in (48b) with (48a) as a control.

How Many LAN Effects Are There?

Given the discrepancy between our study and that of Neville et al. (1991), one might reasonably wonder if the LAN effects reported in the two studies are really one and the same. We are not able to decide this issue on the basis of the available data, but the two effects clearly share a number of properties, as pointed out previously. However, independent of this question, we noted that the left hemisphere negativity following direct object gaps in *wh*-questions had a more temporoparietal distribution than other instances of left hemisphere negativity in our data, all of which were largest over anterior regions.

Neville et al. (1991) report a similar pattern, namely a large negativity between 300 and 500 msec poststimulus over left temporal and parietal regions, in response to their "phrase structure violations."[15] These involved the transposition of a noun (*proof*) and a preposition (*of*), and the comparison was made at the preposition (*proof* OF vs. OF *proof*).

(a) The scientist criticized a proof OF the theorem.
(b) *The scientist criticized Max's OF proof the theorem. (49)

Neville et al. interpret this effect as indexing a particular type of violation, namely a phrase structure violation induced by aberrant word order. While we are unable to evaluate this claim, we would like to point out that the eliciting conditions show a striking resemblance across the two studies: in both cases, the eliciting word is a preposition following a missing direct object. In the present study, the direct object was missing because a gap occurred in that position. In the Neville et al. study, the direct object was missing because it had been transposed to the following position. However, upon presentation of the preposition *of* in (49b), it is immediately apparent that a noun phrase constituent is missing. While it is possible that this missing constituent temporarily induces the processor to posit an illicit gap in this position, the relation between gap-filling, phrase structure positions, and missing constituents will have to await further research. The same is true of the relation between LAN and left hemisphere negativity over more posterior regions.

Where Is the LAN Effect Being Generated?

It is well known that ERPs, while providing good temporal resolution of cognitive processes, do not in the absence of additional constraints provide equally reliable information on the source generators of the electrical activity seen at the scalp. It is not unlikely that the LAN effect is being generated in the left hemisphere, in which language functions are lateralized in a large majority of the right-handed population (see Caplan, 1987 for a review). However, this cannot be inferred from the fact that it is largest over left anterior regions. In fact, existing evidence suggests that the N400, which is typically largest over the right hemisphere and over posterior regions, and therefore has almost the inverse distribution of the LAN effect, also appears to have a left-hemisphere source (Arthur, Schmidt, Kutas, George, & Flynn, 1990). In recent years, a number of different methodologies have become available for deducing the source generators of ERP components (see Dale & Sereno, 1992), including current source density analysis (Nunez & Pilgreen, 1991; Perrin, Bertrand, & Pernier, 1987; Perrin, Pernier, Bertrand, & Echallier, 1989), brain electric source analysis (Scherg & Picton, 1991), depth recordings (e.g., McCarthy, Wood, Williamson, & Spencer, 1989), and magnetic recording (Hari & Lounasmaa, 1989; Sutherling, Crandall, Darcey, Becker, Levesque, & Barth, 1988), but we have not subjected any of our data to analyses of this sort, or used these same stimuli to record magnetic or in-depth responses. Nonetheless, the clearly different distributions of LAN and N400 components appear to implicate different brain circuits. Moreover, it is not implausible that gap-filling procedures would be subserved by areas of the frontal cortex, which is responsible for the timing and sequencing of complex events (Goldman-Rakic, 1990; Olton, 1989).

The Role of Working Memory in Sentence Processing

Consider example (10) in the introduction, repeated here as (50) for convenience.

What did she think [he swore [that Mary said [you remembered [you had put the book on ____]]]]? (50)

On the basis of this example, we noted that the only upper limit on the number of clause boundaries spanned by an unbounded dependency would seem at first blush to be dictated solely by constraints of working memory capacity. And indeed, unbounded dependencies have always figured prominently in discussions of processing limitations. Reduced relative clauses such as

The horse [raced past the barn] fell. (51)

and other center-embedded sentences such as

She looked for the cheese [that the rat [that the cat caught ____] ate ____]. (52)

are notoriously more difficult to process than ordinary right-branching structures like

She looked for the cat [that caught the rat [that ate the cheese]]. (53)

These facts have often been attributed to the limiting role of working memory in a perceptual device that is orthogonal to human grammatical competence (Freedle & Craun, 1970; Kimball, 1973; Blaubergs & Braine, 1974; Larkin & Burns, 1977; Wanner & Maratsos, 1978). However, Just and Carpenter (1992) have argued that the presumably modularized encapsulation of syntactic processing is actually a consequence of constraints on working memory capacity. They present evidence that while subjects with small working memory capacities may be unable to take advantage of nonsyntactic (i.e., semantic or pragmatic) information during syntactic processing, this is due to their limited resources. Subjects with large working memories take advantage of such information as an aid to syntactic processing and show reduced reading times when it is available.

Relevant to our immediate concerns, King and Just (1991) compared sentences of the following types.

(a) The reporter [that ____ attacked the senator] ADMITTED the error.
(b) The reporter [that the senator attacked ____] ADMITTED the error. (54)

In (54a), called a "subject relative clause," the matrix subject *the reporter* functions simultaneously as the subject of the relative clause verb *attacked*, as indicated by the gap in the embedded clause; in (54b), called an "object relative clause," the matrix subject *the reporter* is instead the direct object of the relative clause verb *attacked*, again indicated by the gap in the embedded clause. King and Just found that reading times for the final word in the relative clause [*senator* in (54a) and *attacked* in (54b)] as well as for the matrix verb (*admitted* in both sentences) were consistently faster in subject relatives like (54a) than in object relatives like (54b). Comprehension scores also were generally better for subject relatives than for object relatives. However, there was an additional interaction of this effect with working memory capacity. Although subjects with larger working memory capacity showed faster reading times for both subject and object relatives than subjects with smaller working memory capacity, the advantage was more pronounced for object relatives.

On the basis of these data and our own findings, we would predict that in an ERP study, left anterior negativity should be seen following the matrix verb *admitted* in (54b) relative to (54a), since *admitted* is preceded by an object gap in (54b) but not in (54a). We would similarly predict that the purported gap preceding the embedded verb *attacked* in (54a) should not elicit a LAN effect when compared to a relevant control such as[16]

The reporter attacked the senator and admitted the error. (55)

This is because there is no need for storage of a filler in (54a).

Beyond this, we predict that the LAN effect should be seen in any linguistic context that involves working memory. There is already some corroborative evidence for this in studies by Ruchkin and his colleagues. Although working memory tasks involving nonlinguistic stimuli have thus far elicited slow potential shifts that do not exhibit left anterior maxima (Ruchkin et al., 1991; Ruchkin et al., 1992), the question of whether a left anterior negativity can also be elicited in nonlinguistic memory tasks remains an open one. We feel that this is an important area of inquiry, with implications for the proposed encapsulation of syntactic processing from other cognitive mechanisms.

METHODS

Subjects

Thirty right-handed subjects between the ages of 18 and 31 were paid $5.00 an hour for their participation. All were native English speakers with normal or corrected-to-normal vision. Sixteen were men and 14 women; all were right-handed, but 15 (8 men) had left-handed family members, while the other 15 (8 men) did not.

Materials

A total of 295 sets of five parallel questions (matrix yes/no-questions with *if*- or *wh*-complements, and matrix *wh*-

questions with *that-*, *if-*, or *wh-*complements) were constructed from 11 verbs that can take interrogative sentential complements (*ask, be sure, decide, figure out, find out, forget, know, remember, see, tell*, and *wonder*). Points of comparison are indicated in capital letters.

Sets including subject gaps:

1a. yes/no–*if*: Couldn't YOU decide [if YOU should sing something FOR Grandma AT the family reunion]?

2a. yes/no–*wh*: Couldn't YOU decide [*who* ___ SHOULD sing something FOR Grandma AT the family reunion]?

3a. *wh–that*: *Who* did YOU decide [that YOU should sing something FOR ___ AT the family reunion]?

4a. *wh–if*: *Who* couldn't YOU decide [if YOU should sing something FOR ___ AT the family reunion]?

5a. *wh–wh*: *Who*$_a$ couldn't YOU decide [*who*$_b$ ___$_b$ SHOULD sing something FOR ___$_a$ AT the family reunion]?

Sets including object gaps:

1b. yes/no–*if*: Did HE wonder [if HE could coerce her INTO signing THIS time]?

2b. yes/no–*wh*: Did HE wonder [*who* HE could coerce ___ INTO signing THIS time]?

3b. *wh–that*: *What* did HE suppose [that HE could coerce her INTO ___ THIS time]?

4b. *wh–if*: *What* did HE wonder [if HE could coerce her INTO ___ THIS time]?

5b. *wh–wh*: *What*$_a$ did HE wonder [*who*$_b$ HE could coerce ___$_b$ INTO ___$_a$ THIS time]?

As the verbs used in the embedded clause could take more than one complement, namely both a direct object and a prepositional complement, there were two potential gap sites available in each embedded clause. Roughly half of the sentences in conditions 2 and 5 contained embedded *wh*-clauses with subject gaps (2a and 5a), and the other half contained embedded *wh*-clauses with object gaps (2b and 5b). The five conditions were matched as closely as possible in lexical content subject to subcategorization constraints and pragmatic plausibility.[17]

The experimental sentences were supplemented by six sets of 60 filler sentences: grammatical yes/no-questions with *that*-complements, *wh*-questions containing embedded *if*-conditional clauses and monoclausal dependencies in the matrix clause, multi-*wh* questions with monoclausal dependencies in both clauses, complex noun phrase constraint violations (dependencies into both *that-* and *wh*-relative clauses), *that*-trace violations with dependencies from the matrix clause into the embedded subject position, and yes/no-questions with either *that-*, *if-*, or *wh*-complements that had missing noun phrase constituents. Though not matched in lexical content with the experimental sentences, the filler sentences contained embedded verbs that similarly take both direct and prepositional objects, and the set of prepositions used was the same. Thus the filler sentences represented variations on the basic syntactic framework of the experimental conditions.[18]

The 295 sets of experimental sentences were placed in a Latin square design to create five parallel lists of 295 experimental sentences such that no one subject saw more than one sentence from each set. The 360 filler questions were added to each list, and the lists were then randomized and divided into 20 sets of about 33 questions each.

Procedure

Subjects were run in two sessions lasting about 3½ hours each. Assignment of subjects to lists was counterbalanced for family history of left-handedness and gender. At each session subjects saw 10 sets of approximately 33 questions from the list they had been assigned to. Which ten sets of stimulus sentences subjects saw in the first session was also counterbalanced.

During a session, subjects were seated in a comfortable chair in a sound-attenuated chamber at a distance of 110 cm from a monitor under the control of an AT computer. An illuminated rectangular border appeared uninterruptedly in the middle of the monitor during presentation of the questions, for purposes of fixation. One second before onset of the first word of a question, a warning sign of three asterisks appeared on the screen for 500 msec in the same location as the ensuing words. Questions were presented one word at a time for 200 msec each, with an interval of 400 msec between words. A target probe word followed 1.5 sec after the onset of each sentence-final word.

The end-of-sentence probe task required subjects to indicate whether the target word presented had occurred in the immediately preceding question by pressing a button in either their right hand or their left hand as quickly and yet as accurately as possible. The task was thus orthogonal to the question of experimental interest, but obliged subjects to pay close attention to each word of the sentence.[19] Five seconds after onset of the target word to the previous question, the warning sign for the next question appeared on the screen. Before beginning with the first question set, subjects were given a practice set of 33 questions. Subjects were given rest breaks between question sets whenever they wished.

Electrophysiological Recording

The electroencephalogram (EEG) was recorded with tin electrodes mounted in a commercially available elastic cap. Midline frontal (Fz), central (Cz), and parietal (Pz) recording sites were used, along with lateral pairs of electrodes over the posterior temporal (T5, T6) and occipital (O1, O2) scalp as defined by the 10–20 system (Jasper, 1958). Three additional lateral pairs were used: (1) a frontal pair placed midway between F7/8 and T3/4 (approximately over Broca's area and its right hemisphere homologue, Bl and Br), (2) a temporoparietal pair placed 30% of the interaural distance lateral and 12.5% of the inion–nasion distance posterior to Cz (approximately over Wernicke's area and its right hemisphere homologue, Wl and Wr), and (3) a central pair 33% lateral to Cz (approximately over Brodmann's area 41, L41 and R41). Each scalp site was referred to an off-line average of the left and right mastoids (Van Petten & Kutas, 1988). Vertical eye movements and blinks were monitored via an electrode placed below the right eye and referred to the left mastoid. Horizontal eye movements were monitored via a right-to-left bipolar montage at the external canthi.

The EEG was amplified by a Grass Model 12 polygraph with half-amplitude cutoffs of 0.01 and 100 Hz, digitized on-line at a sampling rate of 250 Hz, and stored on magnetic tape along with stimulus codes for subsequent averaging. Trials with eye movement, muscle, or amplifier blocking artifacts were rejected prior to averaging; approximately 5% of the trials were lost for these reasons.

Data Analysis

Mean voltage was measured by computer algorithm relative to a 100 msec prestimulus baseline in a latency range of 300 to 500 msec poststimulus for left anterior negative (LAN) effects, and in a window of 300 to 700 msec poststimulus for N400 effects, where applicable. The statistical analyses consisted of four-way ANOVAs with one between-group factor of family history of handedness (subjects with and without left-handed family members) and three within-group factors, including two or three levels of question type, depending on comparison, five levels of lateral anterior/posterior sites (Bl/r, L/R41, Wl/r, T5/6, and O1/2), and two levels of hemisphere (left or right). The ANOVAs often showed interactions between sentence type and anterior/posterior site, sentence type and hemisphere, or sentence type, anterior/posterior site, and hemisphere, rather than a main effect of condition. Where such interactions are of interest, the Huynh–Feldt correction for sphericity (Huynh & Feldt, 1976) has been applied, and the original degrees of freedom are reported with the corrected probability level. Whenever interactions of sentence type and anterior/posterior site, but no significant interactions of sentence type and hemisphere were found for effects that appeared lateralized as well, partial ANOVAs restricted to the individual hemispheres were also done.

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Notes

1. This displacement can be obviated when *what* is stressed, as in

(i) You put *what* on the table?

In this case, referred to linguistically as an "echo" question, *what* can (though it need not) remain in place (*in situ*) due to the special intonational focus it is given.

2. Following linguistic convention, a sentence-initial asterisk indicates that a sentence is ill-formed ("ungrammatical"), while a sentence-initial question mark indicates that a sentence is less than well-formed but not impossible ("marginal"). Note that the terms "grammatical" and "ungrammatical" as understood by linguists and as used here refer to perceptions of well-formedness and ill-formedness, respectively, and not to prescriptive stylistic values. Thus example (3) is considered by linguists to be fully grammatical, even though one may have been taught in school never to end a sentence with a preposition. In any case this version of the question seems more natural (and more likely to occur in common usage) than the somewhat stilted, supposedly "correct" version:

(i) On *what* did you put the book?

3. Working memory is used here in the sense of Just and Carpenter (1992), referring to any element whose "activation level is beyond some minimum threshold value and is consequently available to be operated on by various processes."

4. However see Kluender (1991) and Kluender and Kutas (1992) for evidence that this traditional view may not be wholly accurate.

5. The generative syntactic account of the facts presented in (12) has evolved over the years, but in general it has been cast in terms of the principle of "subjacency" (Chomsky, 1973, 1977, 1981, 1986). *Wh*-phrases like *what* or *who* are assumed to originate in the gapped positions of (12) at an underlying level of representation, and surface structure is derived by the leftward movement of *wh*-phrases to clause-initial positions. Subjacency is so formulated as to constrain the number of crucially defined nodes in hierarchical constituent structure that a *wh*-phrase may cross in any given leftward movement.

6. Our account, supported by both linguistic and electrophysiological data, offers an explanation in terms of an interaction between the processing load of lexical access and that of holding a *wh*-filler in working memory at the same time.

7. Previous research (Garnsey, Tanenhaus, & Chapman, 1989) has shown that the electrophysiological consequences of gap-filling can actually set in as soon as the embedded verb in an embedded *wh*-clause is encountered. We were not able to look

for effects of gap-filling at this position in our stimulus sentences due to the way in which they were coded.

8. While there are differing opinions within the theoretical literature as to whether or not contexts like (15) contain subject gaps (Clements, Maling, McCloskey, & Zaenen, 1983; Chung & McCloskey, 1983; Gazdar, Klein, Pullum, & Sag, 1985; Chomsky, 1986), processing evidence (Stowe, 1986) seems to indicate that they do not. We will remain agnostic on this issue, however.

9. Since the N400 is a negative ERP component with a latency of 300 to 500 msec poststimulus that is regularly obtained in ERP experiments involving linguistic stimuli, the question may arise how it is to be differentiated from the effect of left anterior negativity described here. The answer lies in the respective distributions of the two effects. The N400 is generally larger over the right hemisphere and over posterior regions (Kutas & Hillyard, 1982), and is minimal to nonexistent over left anterior regions. See Neville, Nicol, Barss, Forster, and Garrett (1991) for a comparison of the two effects. Although the N400 itself has been intensively studied over the past decade, the question of exactly what cognitive process(es) it indexes is still an open one (for reviews see Halgren, 1989; Pritchard, Shappell, and Brandt, 1991; Van Petten & Kutas, 1991b).

10. In this particular case, the ERPs to second words of yes/no-questions [i.e., function words like *you* in (17)] could have been made to appear frontally more positive than the ERPs to third words of *wh*-questions [i.e., function words like *you* in (16)] due to the continuing frontal negativity to the first words of yes/no-questions between 500 and 600 msec of the previous epoch. However, the anterior negativity seen in response to the first words of yes/no-questions was bilateral in distribution. If this alone were causing the second words of yes/no-questions to appear more positive than corresponding third words of *wh*-questions, then the enhanced negativity to *wh*-questions should also have been bilateral. In fact, however, the anterior negativity seen in response to the matrix subjects of *wh*-questions was clearly a left-hemisphere phenomenon; over the right hemisphere homologue of Broca's, where the baseline problem from the previous epoch was exactly the same as over Broca's area itself, no such negative difference was seen.

11. We chose to contrast grammatical *wh–that*, marginal *wh–if*, and ungrammatical *wh–wh* questions for both experimental and theoretical reasons. As to the former, the ungrammatical *wh–wh* questions were constructed by forming a long-distance dependency from the matrix clause into the embedded prepositional object position of the yes/no–*wh* condition, which then served as a control for the *wh–wh* condition. We were interested in seeing what effect this additional dependency would have on the ERP record. As for the latter, we were interested in determining to what extent the ungrammaticality of the *wh–wh* condition was related to its multiple gap configuration. Configurations such as those in the *wh–wh* condition, referred to in the linguistic literature as "*wh*-islands" (Ross, 1968), have been the focus of theoretical interest in recent years (see, for example, Chomsky, 1986 and Frampton, 1990). Our concern was to see whether the ill-formedness of these configurations could be attributed to processing difficulty; this is a line of inquiry that we have discussed in detail elsewhere (Kluender & Kutas, 1992).

More immediate to our present concerns, however, previous reports of left anterior negativity (Neville et al., 1991) have interpreted this ERP effect as an index of ungrammaticality, or, more precisely, as an index of the violation of a particular syntactic constraint. The constraint in question is similar in character to that which under traditional linguistic accounts rules out the occurrence of so-called *wh*-islands (our *wh–wh* condition) as well. Thus, by including ungrammatical sentences that violate syntactic constraints as well as parallel grammatical sentences that do not, it was possible for us to assess the hypothesis that the LAN effect is associated with working memory load.

12. Both *wh–wh* questions with embedded object fillers (26) as well as those with embedded subject fillers (28) differed from corresponding yes/no–*wh* questions (27 and 29) on this parameter: they contained an additional dependency from the matrix clause into the embedded prepositional object position. Of course, this is the same parameter on which *wh*-questions with embedded *that*-clauses (30) and *if*-clauses (32) differed from their corresponding yes/no-questions (31 and 33). Thus the most parsimonious account of the LAN effect seen in these comparisons is one that takes into consideration the extra working memory load of the matrix clause filler in *wh*-questions, independent of whether or not the embedded clause contained a second filler separated from its gap.

13. In nonlinguistic tasks, the slow potentials differ sometimes in being positive rather than negative, and in other cases in being more posterior than anterior.

14. The embedded filler itself elicits an N400, which we have elsewhere interpreted as indexing the search for and establishment of a referent in mental representation. See Kluender and Kutas (1992) for details.

15. In the Neville et al. data, this negativity between 300 and 500 msec was followed by a rather sizable late positive shift of the P600 variety; see Osterhout (1990) and Osterhout and Holcomb (1992). We saw no such effect following direct object gaps in our ungrammatical *wh–wh* questions.

16. Comparisons with (54b) would be problematic in this case due to differences in lexical content: the embedded complementizer *that* is followed by the open-class verb *attacked*, while in (54b) the complementizer is followed by the closed-class article *the*.

17. Certain lexical changes had to be made in the *wh–that* condition (3a and 3b) for these reasons. The verbs *ask* and *wonder* could not be used in this condition as they do not subcategorize for declarative clauses, and were therefore replaced by either *imagine* or *suppose*. In certain instances, *see* was also replaced by *realize* in the *wh–that* condition for reasons of naturalness. For pragmatic reasons, a greater number of matrix auxiliary verbs in the *wh–that* condition were made affirmative rather than negative (85% vs. roughly 50% in the other conditions). This is due to the fact that it makes little sense to ask questions like "What can't you figure out that you should ask the boss about before the meeting tomorrow?"

18. Ideally the grammatical yes/no-questions with *that*-complements would instead have formed part of the experimental set, but this was impossible for purely practical reasons of running time limitations. Comparisons were therefore made between filler yes/no–*that* questions and experimental yes/no-questions where relevant, to complete the experimental paradigm.

19. ERP subjects were not asked to provide acceptability ratings of the questions that they read in order to avoid any judgmental bias in the electrophysiological record of sentence processing. The intention was specifically to avoid categorization of the stimuli into "grammatical" and "ungrammatical" sets by the subjects. There are two problems with such a task. First, subjects can stop paying attention to a sentence without penalty as soon as it can be identified as ungrammatical, i.e., before it has reached completion. As we were particularly interested in the electrophysiological responses to words occurring in the latter half of the sentences, for example at gap location and in sentence-final position, this would have been an undesirable result. Second, the very act of making such a binary decision mid-sentence is likely to elicit a "P300" component; a larger P300 is typically elicited in discrimination tasks by the more infrequent of two stimulus types. Thus the occurrence of a P300 mid-sentence would have overlapped with and possibly washed out the ERPs associated with sentence processing alone.

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References

Arthur, D., Schmidt, A., Kutas, M., George, J., & Flynn, E. (1990). Event-related magnetic fields of the human brain during semantic information processing. In C. H. M. Brunia, A. W. K. Gaillard, & A. Kok (Eds.), *Psychophysiological brain research* Vol. 1. Tilberg: Tilberg University Press.

Blaubergs, M. S., & Braine, M. D. S. (1974). Short-term memory limitations on decoding self-embedded sentences. *Journal of Experimental Psychology, 102*, 745–748.

Caplan, D. (1987). *Neurolinguistics and linguistic aphasiology: An introduction*. Cambridge, England: Cambridge University Press.

Chomsky, N. (1973). Conditions on transformations. In S. Anderson & P. Kiparsky (Eds.), *A Festschrift for Morris Halle*. New York: Holt, Rinehart & Winston.

Chomsky, N. (1977). On wh-movement. In P. Culicover, T. Wasow, & A. Akmajian (Eds.), *Formal syntax*. Orlando, FL: Academic Press.

Chomsky, N. (1981). *Lectures on government and binding*. Dordrecht, Netherlands: Foris.

Chomsky, N. (1986). *Barriers*. Cambridge, MA: MIT Press.

Chung, S., & McCloskey, J. (1983). On the interpretation of certain island facts in GPSG. *Linguistic Inquiry, 14*, 704–713.

Clements, G. N., Maling, J., McCloskey, J., & Zaenen, A. (1983). String-vacuous rule application. *Linguistic Inquiry, 14*, 1–17.

Dale, A., & Sereno, M. (1992). Improved localization of cortical activity by combining EEG and MEG with MRI cortical surface reconstruction: A linear approach. This volume.

Fiengo, R., & Higginbotham, J. (1981). Opacity in NP. *Linguistic Analysis, 7*, 395–421.

Fodor, J. D. (1978). Parsing strategies and constraints on transformations. *Linguistic Inquiry, 9*, 427–473.

Frampton, J. (1990). Parasitic gaps and the theory of wh-chains. *Linguistic Inquiry, 21*, 49–77.

Freedle, R., & Craun, M. (1970). Observations with self-embedded sentences using memory aids. *Perception and Psychophysics, 7*, 247–249.

Garnsey, S. M., Tanenhaus, M. K., & Chapman, R. M. (1989). Evoked potentials and the study of sentence comprehension. *Journal of Psycholinguistic Research, 18*, 51–60.

Gazdar, G., Klein, E., Pullum, G., & Sag, I. (1985). *Generalized phrase structure grammar*. Cambridge, MA: Harvard University Press.

Goldman-Rakic, P. S. (1990). Cellular and circuit basis of working memory in prefrontal cortex of nonhuman primates. *Progress in Brain Research, 85*, 325–335.

Halgren, E. (1989). Insights from evoked potentials into the neurophysiological mechanisms of reading. In A. Scherbel & A. Wechsler (Eds.), *Neurobiological substrates of higher cognitive function*. New York: Guilford.

Hari, R., & Lounasmaa, O. V. (1989). Recording and interpretation of cerebral magnetic fields. *Science, 244*(4903), 432–436.

Huynh, H., & Feldt, L. S. (1976). Estimation of the Box correction for degrees of freedom from sample data in randomized block and split-plot designs. *Journal of Educational Statistics, 1*, 69–82.

Jasper, H. H. (1958). The ten-twenty electrode system of the International Federation. *Electroencephalography and Clinical Neurophysiology, 10*, 371–375.

Just, M., & Carpenter, P. (1992). A capacity theory of comprehension: Individual differences in working memory. *Psychological Review, 99*(1), 122–149.

Kimball, J. P. (1973). Seven principles of surface structure parsing in natural language. *Cognition, 2*, 15–47.

King, J., & Just, M. (1991). Individual differences in syntactic processing: The role of working memory. *Journal of Memory and Language, 30*, 580–602.

Kluender, R. (1991). *Cognitive constraints on variables in syntax*. Unpublished doctoral dissertation. La Jolla, CA: University of California, San Diego.

Kluender, R. (1992). Deriving island constraints from principles of predication. In H. Goodluck & M. Rochemont (Eds.), *Island constraints: Theory, acquisition, and processing*. Dordrecht, Netherlands: Kluwer Academic Press.

Kluender, R., & Kutas, M. (1992). The interaction of lexical and syntactic effects in the processing of unbounded dependencies. Submitted manuscript.

Kutas, M. (1992). In the company of other words: Comparison of single versus sentence contexts. Submitted manuscript.

Kutas, M., & Hillyard, S. (1982). The lateral distribution of event-related potentials during sentence processing. *Neuropsychologia, 20(5)*, 579–590.

Kutas, M., & Kluender, R. (1992). What is who violating? A reconsideration of linguistic violations in light of event-related potentials. In H. J. Heinze, G. R. Mangun, & T. Münte (Eds.), *New developments in event-related potentials*. Boston, MA: Birkhäuser Boston, in press.

Lang, M., Lang, W., Uhl, F., Kornhuber, A., Deecke, L., & Kornhuber, H. H. (1987). Slow negative potential shifts indicating verbal cognitive learning in a concept formation task. *Human Neurobiology, 6*, 183–190.

Lang, M., Lang, W., Uhl, F., Kornhuber, A., Deecke, L., & Kornhuber, H. H. (1988). Left frontal lobe in verbal associative learning: A slow potential study. *Experimental Brain Research, 70*, 99–108.

Larkin, W., & Burns, D. (1977). Sentence comprehension and memory for embedded structure. *Memory and Cognition, 5*, 17–22.

McCarthy, G., Wood, C. C., Williamson, P. D., & Spencer, D. D. (1989). Task dependent field potentails in human hippocampal formation. *Journal of Neuroscience, 9*(12), 4253–4268.

McElree, B., & Bever, T. G. (1989). The psychological reality of linguistically defined gaps. *Journal of Psycholinguistic Research, 18*, 21–35.

Neville, H. J., Nicol, J. L., Barss, A., Forster, K. I., & Garrett, M. F. (1991). Syntactically based sentence processing classes: Evidence from event-related brain potentials. *Journal of Cognitive Neuroscience, 3*, 151–165.

Nunez, P. L., & Pilgreen, K. (1991). The spline-Laplacian in clinical neurophysiology: A method to improve EEG spatial resolution. *Journal of Clinical Neurophysiology, 8*(4), 397–413.

Olton, P. S. (1989). Frontal cortex timing and memory. *Neuropsychologia, 27*(1), 121–130.

Osterhout, L. (1990). *Event related brain potentials elicited during sentence comprehension*. Unpublished doctoral dissertation. Medford, MA: Tufts University.

Osterhout, L., & Holcomb, P. (1992). Event-related brain potentials elicited by syntactic anomaly. *Journal of Memory and Language*.

Perrin, F., Bertrand, O., & Pernier, J. (1987). Scalp current density mapping: value and estimation from potential data. *IEEE Transactions on Biomedical Engineering, 34*(4), 283–288.

Perrin, F., Pernier, J., Bertrand, O., & Echallier, J. F. (1989).

Spherical splines for scalp potential and current density mapping. *Electroencephalography and Clinical Neurophysiology, 72*(2), 184–187.
Pritchard, W. S., Shappell, S. A., & Brandt, M. E. (1991). Psychophysiology of N200/N400: A review and classification scheme. *Advances in Psychophysiology, 4,* 43–106.
Ross, J. R. (1968). *Constraints on variables in syntax.* Bloomington, IN: Indiana University Linguistics Club.
Ruchkin, D. S., Johnson, R., Jr., Canoune, H., & Ritter, W. (1990). Short-term memory storage and retention: An event-related brain potential study. *Electroencephalography and Clinical Neurophysiology, 76*(5), 419–439.
Ruchkin, D. S., Johnson, R., Jr., Canoune, H., & Ritter, W. (1991). Event-related potentials during arithmetic and mental rotation. *Electroencephalography and Clinical Neurophysiology, 79*(6), 473–487.
Ruchkin, D. S., Johnson, R., Jr., Grafman, J., Canoune, H., & Ritter, W. (1992). Distinctions and similarities among working memory processes: An event-related potential study. *Cognitive Brain Research, 1*(1), 53–66.
Scherg, M., & Picton, T. W. (1991). Separation and identification of event-related potential components by brain electric source analysis. *Electroencephalography and Clinical Neurophysiology. Supplement, 42,* 24–37.
Stowe, L. A. (1986). Parsing WH-constructions: Evidence for on-line gap location. *Language and Cognitive Processes, 1,* 227–245.
Sutherling, W. W., Crandall, P. H., Darcey, T. M., Becker, D. P., Levesque, M. F., & Barth, D. S. (1988). The magnetic and electric fields agree with intracranial localization of somatosensory cortex. *Neurology, 38*(11), 1705–1714.
Van Petten, C., & Kutas, M. (1988). The use of event-related potentials in the study of brain asymmetries. *International Journal of Neuroscience, 39,* 91–99.
Van Petten, C., & Kutas, M. (1991a). Influences of semantic and syntactic context on open and closed class words. *Memory and Cognition, 19,* 95–112.
Van Petten, C., & Kutas, M. (1991b). Electrophysiological evidence for the flexibility of lexical processing. In G. B. Simpson (Ed.), *Understanding word and sentence.* Amsterdam: Elsevier Science Publishers.
Wanner, E., & Maratsos, M. (1978). An ATN approach to comprehension. In M. Halle, J. Bresnan, & G. A. Miller (Eds.), *Linguistic theory and psychological reality.* Cambridge, MA: MIT Press.