Event-Related Potentials and Language Comprehension*

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Introduction

The ability to comprehend language dominates our species-specific activity. Correspondingly, deficits in language function (e.g., the dyslexias and aphasias) are extremely debilitating. Yet, despite its central importance, an adequate understanding of the cognitive and neural processes underlying language comprehension remains elusive. One primary reason for the lack of progress has been a paucity of adequate methodologies. Language comprehension occurs very rapidly (in "real time") and any sufficient model must describe the process as it unfolds over time (cf. Swinney, 1981; 1982). Unfortunately, few methodologies allow for rapid and on-line measurement. Most researchers resort to the use of measurements that are made "after-the-fact" (e.g., measures of sentence reading times) or that reflect the state of affairs at a discrete moment during comprehension (e.g., cross-modal priming studies; cf. Swinney, 1979). Furthermore, these measurements are intrusive; one cannot know for certain the influence the measurement itself has on the phenomenon being investigated.

For these reasons, electrophysiological measurements of event-related brain potentials (ERPs) hold great promise as tools for studying the cognitive processes that underlie language comprehension. ERPs provide a continuous account of the electrical activity in the brain, thereby meeting the need for a continuous on-line measure. Electrophysiological measurement is non-intrusive. And since such measurements provide at least a rough estimate of localization and lateralization of brain activity, ERPs also offer the prospect of tying behavior and behavioral models of language comprehension more closely to brain function.
The optimistic view of ERPs as promising tools for investigating language processes stands in contrast to the pessimistic view projected by previous reviewers of the field (see, e.g., Donchin, Kutas, & McCarthy, 1977; Hillyard & Woods, 1979; Picton & Stuss, 1984). One reason for this pessimism has been the apparent failure to discover reliable signs of hemispheric specialization, e.g., the lack of consistent asymmetries in the distribution of language-related effects. Over the past decade, the focus has shifted away from issues of hemispheric specialization and toward an interest in the cognitive processes underlying language comprehension. This shift can be traced in large part to a single study (Kutas & Hillyard, 1980c). Kutas and Hillyard reported that semantically inappropriate words (e.g., "He spread the warm bread with socks") elicited a large-amplitude negative ERP component with a peak latency of 400 msec (the N400 component), relative to the ERPs elicited by semantically appropriate words (e.g., "It was his first day at work"). In contrast, semantically appropriate but physically abberant words (words printed in larger type) elicited a positive-going potential (P560) in the same temporal window as the N400. Kutas and Hillyard speculated that the N400 may be an "electrophysiological sign of the 'reprocessing' of semantically anomalous information" (p. 203). Although more recent data have suggested alternative interpretations of the N400, Kutas and Hillyard demonstrated that electrophysiological recordings of brain activity covary with meaning-related manipulations to language stimuli. This landmark discovery provided the impetus for an intriguing and rapidly growing literature.

The purpose of the current chapter is to review this literature, pointing out findings of particular import for psycholinguistic models of comprehension. Our review is divided into two primary sections. The first section reviews ERP studies aimed at investigating word-level processes (recognizing isolated words and words in single-word contexts). The second section concerns sentence-level processes (recognizing words in sentence contexts and computing syntactic structure). Throughout the review, we focus on findings that are directly relevant to theoretical issues currently being debated by psycholinguists. The goal is to demonstrate, through example, the utility of ERPs as tools for investigating these issues, particularly in cases where traditional measures have produced conflicting sets of data.

Even though the application of ERPs to the study of language comprehension is in its infancy, we are unable to review all of the relevant literature. Specifically, we will not review studies of phonological processes (e.g., Rugg, 1984a, b; Rugg, 1985; Kramer & Donchin, 1987; Polich et al, 1983), repetition priming (e.g., Rugg, 1985, 1987; this volume) and certain single-word tasks (e.g., Rugg, 1983; Neville, Kutas, & Schmidt, 1982). The interested reader should consult the original sources or see one of several recent reviews which have covered these topics (Kutas & Van Petten, 1988; Fischler, 1990; Fischler & Raney, 1991).
Methodological Issues

Two Strategies for Examining Comprehension with ERPs.

ERP researchers typically adopt one of two approaches in examining the relationship between ERPs and language (see Osterhout, 1994; for a somewhat different view, see Kutas & Van Petten, 1988). The first approach focuses on the ERP component itself -- the researcher tries to identify the cognitive events underlying the component. This can be accomplished, in principle, by investigating the necessary and sufficient conditions for altering the component's waveform characteristics (amplitude and latency). The benefits of this approach are clear. With an electrophysiological marker of a specific cognitive process in hand, changes in the underlying cognitive process can be directly inferred from changes in the ERP component. For example, Van Petten and Kutas (1987) concluded, on the basis of previously collected data, that the amplitude of the N400 component reflects a word's "activation level" in memory. More specifically, they concluded that highly activated words elicit a small N400, while less-activated words elicit a larger N400. These assumptions allowed them to investigate the effects of context on the processing of polysemous words, by measuring the N400s elicited by target words related to the contextually appropriate and inappropriate meanings of a polysemous word (e.g., "The gambler pulled an ace from the bottom of the DECK", followed by the target word cards or ship). The results revealed a larger N400 to contextually inappropriate targets (e.g., ship) than to contextually appropriate targets (e.g., cards), suggesting that the contextually appropriate meanings of the polysemous words were selectively activated in memory. The strategy of precisely identifying the cognitive events that elicit an ERP component has considerable appeal. However, the mapping between changes in an ERP component and putative cognitive processes is often far from transparent. This point is illustrated by the current controversy over whether changes in N400 amplitude reflect the
same set of cognitive processes as do changes in the amplitude of the N2 component, which is elicited by stimuli that do not match preceding stimuli on some attribute (Naatanen & Gaillard, 1983). Importantly, experimental designs that assume knowledge of underlying language-related processes carry with them the significant risk associated with a misidentification of these processes. For example, if N400 amplitude reflects processes other than word activation, then the set of interpretations one might entertain in explaining the Van Petten and Kutas data might expand significantly.

A second approach to ERP investigations of language comprehension has been to use a known ERP component to study some aspect of comprehension, even if the cognitive and neural events underlying the component have not been identified. This approach becomes feasible once the component is shown to systematically covary with manipulations of stimuli, task, or instructions that influence the cognitive process of interest. Having found such a covariation, one can make certain inferences about relevant psychological processes based on between-condition differences in the ERPs. For example, several researchers have observed a slow positive-going wave (labeled the "P600 effect" by Osterhout & Holcomb, 1992) in the ERP response to syntactically anomalous words (Neville et al., 1991; Osterhout, 1990; Osterhout & Holcomb, 1992, in press; see below). The specific cognitive events underlying the P600 are not known, and there is no evidence that the P600 is a direct manifestation of sentence comprehension. One possibility is that the P600 is a member of the P300 family of waves often observed following unexpected stimuli (cf. Donchin, 1981). The point here is that in order for the P600 to act as a reliable marker of syntactic anomaly (and hence as a useful tool for testing certain theories of comprehension), all that is needed is evidence that it reliably co-occurs with syntactic anomaly, regardless of whether or not it directly reflects the processes that parse sentences during comprehension. Using this logic, Osterhout and Holcomb (1992, in press; see also Osterhout & Swinney, 1989; Osterhout, Holcomb, & Swinney, in press; Hagoort, Brown, & Groothusen, 1993) have successfully contrasted predictions made by certain parsing models concerning when and where syntactic anomaly will be encountered, employing the P600 as an electrophysiological marker of syntactic anomaly.

ERPs and the Timing of Linguistic Processes

ERPs promise to reveal a great deal about the timing and ordering of language-related processes. In temporal evaluations of ERPs, the critical issue often concerns the moment in time at which the ERPs from two conditions begin to diverge significantly, rather than the peak latency of a particular ERP component (see Coles & Rugg, this volume). For example, the peak of the N400 component reliably occurs at about 400 msec after presentation of the word. However, divergences in the waveforms elicited by contextually appropriate and contextually inappropriate words can begin to emerge as early as 50 msec (Holcomb & Neville, 1991) and typically emerge around 200-250 msec following word onset (Kutas & Hillyard, 1980). The importance of this distinction becomes clear when considering whether the N400 is sensitive to the process of lexical
access. The available evidence indicates that lexical access occurs in the range of about 200 msec (Sabol & DeRosa, 1976). If the peak latency of the N400 is taken as the temporal marker of its occurrence, then many would argue that the component occurs too late to reflect lexical access. However, if the onset of divergences in waveforms is taken as the temporal marker, then the N400 is much closer to the time window suggested for lexical access. (See Fischler, 1990, for more discussion of this issue.)

A related issue concerns the sorts of inferences about the timing of cognitive processes that are licensed by ERP data. Unless one knows with certainty the cognitive events underlying a given ERP effect, such inferences can be risky. This is particularly true of ERP effects with relatively late-occurring onsets. For example, the P600 effect elicited by syntactically anomalous words (Osterhout & Holcomb, 1992) typically has an onset around 500 msec. This finding does not necessarily license the inference that the assignment of syntactic roles to words occurs around 500 msec after word onset. The P600 might only indirectly reflect the assignment of syntactic structure; the cognitive events that do in fact underlie the P600 might be temporally removed from the syntactic processes themselves.

Conversely, very early onsets of ERP effects can sometimes license strong inferences about the timing of language processes. For example, the ERPs to contextually inappropriate words in spoken sentences begin to diverge from those to contextually appropriate controls long before the entirety of the word has been encountered by the listener (Holcomb & Neville, 1991). These data clearly indicate that an interaction between word recognition and context occurs long before the word can be recognized solely on the basis of the acoustic stimulus.

ERPs and Word Recognition

Some of the most heavily researched questions in cognitive psychology concern the mental operations and processes underlying word recognition. What are the information processing steps that lead to recognition? Are these steps arranged in a discrete series, with a strictly bottom-up progression? Or are they highly parallel and interactive? What is the nature and organization of the stored mental representations to which incoming sensory information is compared? What aspects of stored information become available to subsequent linguistic processes? What is the time course of word recognition?

A number of researchers have examined word recognition by recording ERPs to words presented in lists (i.e., without a sentence context). In almost all cases this has involved presenting subjects with between 20 and 60 visually displayed items in each of several conditions. Typically, subjects have been asked to perform a task concurrent with reading the words. The most frequently used task has been the lexical decision task (LDT), in which the subject must rapidly decide if a letter string is a legal English word or a nonword (e.g., FLARK). Unfortunately, the other task frequently used to study word recognition, the naming task, is not suitable for use while collecting ERPs. Muscle
"artifact" is produced when the mouth and tongue are moved during speaking; this artifact interferes with reliable recording of ERPs.

Semantic Priming.

Several ERP researchers have investigated semantic priming (cf. Meyer & Schvaneveldt, 1971). In a typical semantic priming experiment, pairs of letter strings are presented. The first letter string (the prime word) is followed by a semantic associate of the prime word (the related target), a word unrelated to the prime (the unrelated target), or a nonword. Numerous behavioral studies have shown that a subject's processing of related targets (e.g., DOCTOR - NURSE) is enhanced or facilitated, in comparison to the processing of the unrelated targets (e.g., WINDOW - NURSE). This facilitation has typically taken the form of faster reaction times (RTs) to related targets that to unrelated targets during a lexical decision task. Several mechanisms have been proposed to account for such semantic priming. One of the earliest and most enduring accounts, automatic spreading activation (Collins & Loftus, 1975), proposes that representations of words in the mental lexicon are organized semantically and that related words are either located closer together in the lexicon or have stronger links relative to unrelated words. When a prime word's representation is accessed due to "bottom-up" processing of the sensory information, activity passively spreads to semantically related items, boosting their activation beyond normal resting levels. When a target word is presented a short time later, it will be processed more quickly or efficiently if its representation is one of those passively activated by the prime. In contrast, processing of the target will not benefit if the target is unrelated to the prime. We should note that the locus of this type of automatic priming has generally been assumed to occur prior to the actual recognition of the target word -- hence the term pre- or inter-lexical priming.

As the literature on semantic priming has grown, the pattern of observed effects has become more difficult to account for via a purely passive spreading activation process. For example, in experiments in which the proportion of related items was high and/or the interval between target and prime was relatively long (> 500 ms), RTs were reported to be longer than expected when the target and prime were unrelated (e.g., den Heyer et al., 1983; Neely, 1976, 1977; Tweedy et al., 1976). This suggested that in addition to the facilitatory spreading activation process, an inhibitory mechanism was operating under certain circumstances. Because automatic spreading activation was supposed to function without costs or inhibition, Neely (1977), among others, proposed a second, limited capacity priming mechanism to account for inhibition effects. According to this view so-called attentional or strategic priming occurs when the subject actively anticipates the occurrence of the target item based upon the meaning of the prime word (cf. Becker, 1980). This further facilitates RT beyond automatic levels when the prime and target are related, but slows RT when they are unrelated, because attention, which is relatively slow, must be shifted from the anticipated related representation to the appropriate unrelated one (Posner & Snyder, 1975).
The locus of such attentional priming effects is not clear. For example, Neely (1991) has suggested that they are pre-lexical, implying that attentional processes can direct the lexical access process. Others (e.g., Seidenberg et al., 1984) have argued that attentional priming is post-lexical because larger effects are found in the LDT than in the naming task (as used here, post-lexical implies that the process operates after an item's representation has been activated in the lexicon). Seidenberg et al. assume that naming is primarily sensitive to pre- or inter-lexical influences (but see Balota & Chumbley, 1985).

For a number of years much of the literature on semantic priming seemed consistent with one or both of the above processes. However, recent data from both the naming task and the LDT have cast doubt on the ability of these two mechanisms to fully explain semantic priming. Neely and Keefe (1989) have suggested that a third process may be important under certain circumstances when the lexical decision task is involved. Their argument is based on the assumption that LDT reaction times are influenced by post-lexical "decision" factors as well as by pre-lexical factors. (Note that according to Neely this is not the same as the attentional mechanism, which he argues is a pre-lexical effect). In other words, the decision process occurs after an item has activated its representation in the lexicon. But how do subjects actually decide to respond "nonword?" An exhaustive search of the lexicon would appear to be inefficient and too time consuming. This issue has never been convincingly resolved, but it increasing looks as though nonword responses might be made in different ways under different conditions (e.g., Balota & Chumbley, 1984). Neely and Keefe (1989) have suggested that in semantic priming experiments subjects can sometimes use a relatedness strategy to help make the lexical decision. In effect, subjects might ask themselves, "Are the prime and target related?" If yes, respond "word," if not then consider responding "nonword." Note that this strategy works best if the ratio of nonword to unrelated word trials is relatively high, and if nonword targets are not paired with semantically related primes (e.g., DOCTOR-NARSE).

In an extensive review of the priming literature, Neely (1991) concluded that a combination of three of the above reviewed factors contributes to the pattern of priming in the LDT: automatic spreading activation, attentional expectancy, and the nonword ratio. However, it should be pointed out that this conclusion is partly based on the assumption that automatic spreading activation and attentional priming are separate pre-lexical mechanisms and that the nonword ratio mechanism is post-lexical. An alternative possibility is a modified two-process account that assumes that attentional expectancy and cognizance of the non-word ratio are two of a host of possible post-lexical strategies that subjects might use in making a lexical decision. In other words, in addition to automatic spreading activation it might be most parsimonious to assume a single flexible process (we will call it "strategic attention") that can deal with information from a variety of sources depending on the demands of the task at hand. In procedures such as the LDT, the ways in which subjects strategically employ and combine these various pieces of information might account for the somewhat different patterns of priming effects seen across studies.
A potential promise of ERPs is that some aspect (component) of these measures might prove uniquely sensitive to one or more of the processes involved in word recognition (e.g., automatic spreading activation), whereas others might reflect post-lexical processes (e.g., strategic attentional factors). The advantages of such a find are clear. Since RT results are frequently ambiguous with respect to the locus of the information process(es) responsible for an effect, the existence of a measure that is sensitive to a specifiable, restricted set of these processes would provide valuable data for modelers of word recognition.

Bentin, McCarthy, and Wood (1985) were one of the first groups to record ERPs to visually presented word pairs in a semantic priming/lexical decision experiment. They found that all three of their target types (related to the prime, unrelated to the prime, and nonword) elicited a large ERP positivity (550 to 650 ms). However, two types of targets (targets unrelated to the prime and nonword targets) produced a large negative-going wave which peaked at approximately 400 ms. Bentin et al. suggested that the negative-going activity might be related to the N400 component previously observed following contextually inappropriate words (Kutas and Hillyard, 1980; see above). Similar findings have been reported by Rugg (1985) and Holcomb (1986, 1988). In another study (Bentin, 1987), subjects made either antonym judgments or lexical decisions about targets preceded by a prime word or nonword. Targets that were antonyms of the prime produced almost no negativity in the N400 region. In contrast, targets that were unrelated to the prime produced a clear N400. Pronounceable nonwords generated the largest N400 response.

Subsequent work has been aimed at determining whether these modulations to N400 amplitude reflect a pre- or post-lexical process. For example, Holcomb (1988) manipulated both the instructions given to subjects and the proportion of related prime-target pairs (17% vs. 67%) within the list. In one block, the instructions and the relatively small proportion of related prime-target pairs were ideally suited for producing only automatic priming. In a second block, the instructions and the larger proportion of related prime-target pairs encouraged subjects to attend to the semantic relationship between prime and target words; that is, the second condition presumably induced subjects to employ strategic processes in responding to the targets. In both blocks, target words that followed an unrelated word or a neutral prime (a row of x's) elicited larger N400s than targets that were related to the prime. However, this N400 effect was larger in the "attentional" block than in the "automatic" block. If the N400 is sensitive to the "inhibition" or "interference" associated with processing a target word that is unrelated to the prime, one might predict that targets following an unrelated prime should elicit larger N400s than targets following a neutral prime. No such difference in N400 amplitude was observed. One interpretation of this finding is that N400 amplitude is sensitive to processes that facilitate target processing (e.g., spreading activation) but not to processes that inhibit or interfere with target processing (e.g., conscious expectations generated only by attending to the prime-target relationships). Interestingly, a later "slow wave" differentiated the neutral and unrelated targets, but only in the attentional condition. Holcomb concluded that these results are in agreement with the substantial literature that supports the two process account of semantic priming. Specifically, the N400 may be
sensitive to priming due to automatic spreading activation and to the additional priming that results from the allocation of attentional resources, but not to the inhibitory or interference effects of unrelated targets. Conversely, differences in the late slow wave might reflect the interference effects engendered by target words that were unrelated to the preceding prime word.

Figure 2: Panel A shows ERPs to related, unrelated, and neutral target words in a semantic priming lexical decision task. The ERPs in the upper half of this figure are from the "automatic" block of trials and the lower half are from the "attentional" block. Stimulus onset in this and all subsequent figures is the vertical calibration bar. Each tic mark is 100 ms. LP and RP are left and right parietal sites, LTP and RTP are left
and right temporal-parietal sites, Fz is frontal midline and Oz is occipital midline. Panel B shows difference waves calculated by subtracting related or unrelated targets from neutral targets. The large negative deflection in the neutral-related waves is the "N400 effect." (From Holcomb 1988.)

Other studies have attempted to determine whether N400 amplitude reflects one specific pre-lexical process, namely, automatic spreading activation. Evidence that N400 amplitude is sensitive to automatic spreading activation would be consistent with the claim that this component is sensitive to activation of word representations (lexical access or some other word-level recognition process). One possibility is that N400 amplitude is sensitive to the amount (or number) of resources utilized in pushing a word's detector past its recognition threshold (as in Morton's, 1969, logogen model). According to this account, N400 is small to primed target words because the lexical detector for the target benefits from the "spread of activation" associated with the processing of the prior prime word. However, when the target word is preceded by an unrelated prime there is no such benefit and more resources are required to drive the target word's detector past its recognition threshold. The utilization of these extra resources might be what is reflected by the larger N400 to these words. This view of the N400 (or one very close to it) is favored by a number of ERP researchers (e.g., Van Petten and Kutas, 1991; Fischler & Raney, 1989).

The possibility that the N400 is sensitive to an automatic lexical process is bolstered by two recent studies. Kutas and Hillyard (1989) instructed subjects to determine if a target letter was present in either the first or second member of a word pair (delayed letter search task). The ERPs to second words produced the following pattern: N400 was largest when the preceding prime word was semantically unrelated, intermediate when the semantic relationship was relatively weak, and smallest when pairs were highly related (see Figure 3). Because this task does not appear to require the subject to process either word for meaning, it is possible to argue that the obtained priming effects were due to automatic spreading activation.
Figure 3: ERPs to prime words (the first 700 ms) and target words (700 to 1800 ms) in a delayed letter search task. Note particularly the large N400 to the unrelated targets and the somewhat smaller N400 to moderately related targets. (From Kutas & Hillyard 1989; reprinted with permission of the authors and the publishers.)

More recently, Besson et al. (1992) demonstrated that the N400 is larger to unrelated than to related targets when the subject's task involved a graphemic judgement (do the prime and target words have a similar or dissimilar initial and final consonant-vowel characteristics), even at relatively short prime/target intervals (300 ms SOA). Neely (1977) has argued that at short SOAs only the automatic spreading activation process, which is relatively fast, has time to become active. So, the finding of N400 priming effects at short intervals suggests that this component is sensitive to automatic spreading activation. This conclusion is bolstered by a study by Boddy (1986) who also found similarly large N400 effects for long (1000 ms) and shorter (200 ms) stimulus-onset-asynchronies in a LDT.

However, the fact that in all of the above studies both the prime and target were part of the active task structure prevents us from concluding that the N400 effects were not mediated by a strategic post-lexical process. Even in the case of the 300 ms SOA of Besson et al. it is still possible that subjects might have used attentional resources to aid in the processing of the prime/target relationship -- particularly since the target N400 peaks at such a relatively late point (700 ms post-prime onset in the Besson et al study). To more conclusively determine if the N400 is sensitive to strictly automatic processes would require a procedure which prevents attentive processing of the prime. Masking of the prime at the level of identification, which presumably prevents the subject from attending to the meaning of the prime word, has been shown to produce purely automatic behavioral priming in lexical decision (e.g., Fowler et al., 1981; Marcel, 1983). Two such studies have been conducted with ERPs. Brown and Hagoort (1993) failed to obtain an
N400 effect between related and unrelated words in a masked prime LDT even though they did find evidence of RT priming (they found typical N400 effects when the prime was not masked). In a second study Neville et al. (1989) found robust N400 semantic priming effects in the LDT at both long (533 ms) and relatively short (100 ms) prime/target intervals when the prime and target were identifiable. However, they failed to find an N400 semantic priming effect when the prime was obscured by a prior pattern mask, although there was an earlier left hemisphere negativity (200 to 300 ms) that distinguished unrelated from related targets. The results of these two masking studies cast doubt on the hypothesis that the N400 reflects activity in an automatic spreading activation, pre-lexical process.

Another candidate for the cognitive process underlying the N400 is some type of post-recognition process. At least two possibilities exist. First, N400 may reflect activity in a post-lexical conceptual memory system. In some comprehension models conceptual/semantic knowledge is separated from lexical knowledge, primarily for reasons of cognitive economy. For example, Ellis and Young (1988) have proposed that each modality (spoken words, written words and possibly pictures) has its own input lexicon that feeds into an amodal semantic system. In this type of model semantic priming might occur at the lexical level (e.g., due to lexical items being organized semantically) and/or at the conceptual/semantic level (e.g., due to related concepts sharing features). N400 could be sensitive to processes at either or both of these levels (although the masked priming studies suggest that lexical priming is unlikely; see above). The rapid onset of N400 semantic priming effects between spoken and written words (Holcomb & Anderson, 1993), and between words and pictures (e.g., Nigam et al., 1992; see below), can be construed as evidence favoring the claim that modulations in N400 amplitude reflect an amodal conceptual/semantic level process. According to this account, such cross-modal effects result because both input modalities tap a common set of conceptual knowledge representations.

A second possibility is that N400 reflects an even higher-level "integrative" process (Rugg, 1990; Rugg, Furda & Lorist, 1988; Holcomb, in press). In some psycholinguistic models, integrative processes are used by the language comprehension system to help coalesce information provided by a variety of "lower" processes (e.g., lexical/semantic, syntactic, pragmatic, etc.) into an ongoing discourse representation (e.g., Kintsch, 1988; Marslen- Wilson, 1987). There are at least two possibilities for how N400 could reflect priming-like operations at this level. First, integration may be directly affected by up-stream word recognition operations, such as the amount of resources required to activate a lexical or conceptual representation. For example, the processes that integrate the language input may receive semantic and syntactic output from the lexicon, as well as information on how easily this information could be activated. Integration (and N400) might then be sensitive to this latter information. However, at a functional level, this characterization does not differ significantly from the above proposal for a word-level locus of N400 priming. A more reasonable possibility, vis-a-vis the integration hypothesis, is that N400 amplitude reflects the ease with which various knowledge sources (e.g., lexical, syntactic and semantic) are used to form an integrated discourse
representation; the more difficult it is to integrate a given piece of information into the ongoing representation, the larger the N400 effect elicited by that information.

A host of behavioral studies have shown that degraded linguistic stimuli slow down the speed of word processing. Meyer et al. (1975) were the first to show that stimulus degradation interacts with semantic priming. In their experiment the difference in RT between target words preceded by semantically related primes and targets preceded by unrelated primes was greater when the targets were degraded by an overlaid matrix of dots. This pattern of results was true for both lexical decision and naming latency. Based on additive factors logic, Meyer et al concluded that priming and degradation affect a common process, which they argued was an initial encoding stage (i.e., lexical access). If this conclusion is correct and if N400 is closely tied to this level, then N400 amplitude, like RT, should produce a larger difference between primed and unprimed words when the words are degraded than when they are intact. On the other hand, if N400 is more closely associated with a mechanism that is not directly affected by degradation, such as a later post-lexical process, then the difference between primed and unprimed words should not necessarily increase in amplitude when these items are degraded.

Figure 4: Difference waves, computed by subtracting ERPs to targets preceded by a related prime from those preceded by an unrelated prime, showing N400 amplitude in a task in which subjects performed a lexical decision task. Targets were either "undegraded" or "degraded." ATL and ATR are left and right anterior temporal sites, PTL and PTR are left and right posterior temporal sites, and Fz and Cz are frontal and central midline sites. Note that the N400 effect is not larger in the degraded condition, but that N400 onset is shifted later in time. (From Holcomb 1993.)

Recently, Holcomb (1993) conducted such an ERP study using intact and degraded targets in a semantic priming LDT. The behavioral results replicated the basic degradation/priming interaction seen in the Meyer et al study (i.e., priming was greater under degraded conditions). Analyses of the ERP data indicated that degrading the target had a small but non-significant affect on the overall time-course of the N400. However,
and more importantly, there was no difference in the size of the ERP priming effects (amplitude or latency) for intact and degraded targets. In other words, the larger priming effect seen in RT for degraded targets was not present in the N400. Moreover, this lack of a priming-by-degradation interaction was accompanied by a large main effect of priming on N400 (amplitude and latency -- see Figure 4). Holcomb argued that these data are most consistent with the view that the mechanism underlying the N400 is a relatively late (post-lexical) process. However, the data from this study cannot distinguish between the two above-mentioned post-lexical accounts (conceptual vs. integration) of the N400.

Figure 5: ERPs elicited in a lexical decision task under conditions of semantic priming. Panel A plots ERPs recorded to visually presented target words. Panel B plots ERPs elicited under identical conditions with
auditory stimuli. RW and UW refer to related and unrelated targets, respectively. F7 and F8 are left and right frontal sites, LT and RT are left and right temporal sites, LTP and RTP are left and right temporal parietal sites (approximately over Wernicke’s area and its right hemisphere analogue), P3 and P4 are left and right parietal sites, and O1 and O2 are left and right occipital sites. (From Holcomb & Neville 1990.)

Recognizing Spoken Words

Most researchers investigating word recognition have presented visual stimuli. This preference for visual presentation of language stimuli is understandable, given the relative difficulty of presenting language auditorily in a controlled experimental situation. However, several recent experiments have recorded ERPs to auditorily presented words. For example, Holcomb and Neville (1990) directly compared and contrasted semantic priming in the visual and auditory modalities. Subjects participated in two versions (one visual, one auditory) of a lexical decision task, in which stimuli were word pairs consisting of a prime word followed by a semantically related word, an unrelated word, or one of two kinds of nonwords: pseudowords, and "backwords" words either spelled (visual) or played (auditory) backwards. N400s were larger to unrelated words than to related words in both modalities (see Figure 5). However, this ERP "priming effect" began earlier and lasted longer in the auditory modality than in the visual modality. Holcomb and Neville concluded that there may be overlap in the set of processes that underlie priming in each modality but that these processes are not identical. In particular they noted that the earlier onset of the N400 in the auditory modality was consistent with the model of speech comprehension proposed by Marslen-Wilson (1978, 1987) -- that auditory word processing can begin prior to the arrival of all of the acoustic information in a spoken word and that the time-course of this processing can be influenced by semantic properties of a prior word.
Is the N400 Specific to Linguistic Stimuli?

In the experiment discussed above, Holcomb and Neville (1990) reported that in both modalities pseudowords produced large N400s, but that "backwards" words (words spelled or played backwards) showed no evidence of an N400 response in either modality; the related words actually had a larger N400 response than the backwards words. They argued that these data were consistent with the hypothesis that the N400 is
elicited only by linguistic stimuli; that is, they claimed that the component is language-specific. The reasoning behind this argument is that if the N400 is a generic mismatch response (i.e., an N2) that responds to any kind of discrepancy between prime and target stimuli (e.g., Polich, 1985), then both kinds of nonwords should have produced equivalent negativities. Since un-word-like nonwords (backwards words) failed to show any hint of N400 activity, they concluded that the N400 is selectively sensitive to language-like stimuli (see Figure 6).

The language-specificity hypothesis is supported by the results of other studies as well. Besson and Macar (1987) had subjects listen to well-known melodies that ended either with the expected note or with an unexpected note (i.e., the musical version of a priming task), and to sentences that ended in the expected final word or an incongruous word (the Kutas and Hillyard paradigm). In comparison to the expected final note, the unexpected notes did not produce an N400-like response, but rather produced an enhanced positivity (P3). A similar pattern was obtained with geometric shapes and musical scales. Comparison of the expected and incongruous sentence final words revealed a large N400 response for the incongruous words, replicating the original Kutas and Hillyard (1980c) result.

Recently, several priming studies have shown N400-like effects to pairs of related and unrelated pictures (Barrett & Rugg, 1990) or a combination of words and semantically appropriate and inappropriate pictures (Nigam et al, 1992). These findings would appear to cast some doubt on the language specificity of the N400. However, if pictures and words are represented in a common representational system (e.g., in conceptual memory), or if picture and word representations are separate but highly interconnected, then priming between input domains might be viewed as contradictory only to a strong specificity hypothesis.

Summary

Although specific ERP components (e.g., the N400) are clearly sensitive to important aspects of word recognition, the precise cognitive processes underlying such ERP effects remain undetermined. In particular, the evidence available to date does not allow one to bifurcate these effects into "pre-lexical" and "post-lexical" categories. One might tentatively conclude from the data reviewed here that the N400 component is not solely a direct reflection of the cognitive processes underlying lexical access. Rather, N400 amplitude appears to be quite sensitive to relatively late-occurring processes. (For a dissenting view, see Fischler & Raney, 1991). Identification of the specific nature of the processes underlying the N400 component will require additional research.

ERPs and Sentence Comprehension
Words only occasionally appear in isolation. Usually, words are embedded within sentences, and the meaning of a sentence is determined in part by the specific combination of words within the sentence. A number of questions immediately arise when one attempts to describe how readers and listeners successfully comprehend a sentence. Some of these questions concern the relationship between word processing and sentence context. For example, does sentence context influence the earliest stages of word recognition, or are these processes isolated from the effects of context? Other questions concern the determination of relations between words in the sentence, that is, the computation of syntactic structure. (The processes underlying syntactic analysis are often referred to as parsing). Do readers and listeners compute syntactic representations that are distinct from semantic representations? Assuming that syntactic representations are indeed computed, then precisely how are such representations arrived at? In particular, how does the sentence parser deal with the ubiquitous syntactic indeterminism present in natural languages?

An important methodological concern in any study of sentence processing is the mode of stimulus presentation. Since measurement of ERPs does not require an intrusive "secondary" task (e.g., pressing a button after each word or sentence), this method allows researchers to more closely approximate a normal comprehension environment. A number of recent studies have presented connected natural speech (Holcomb & Neville, 1990, 1991; Osterhout & Holcomb, 1993; McCallum, Farmer, & Pocock, 1984). Others have linked ERP measurements with eye saccades during "normal" reading (Marton & Szirtes, 1988). However, the standard method in most of the work to date (and of most of the work reviewed below) has involved the visual presentation of sentences in a sequential, word-by-word manner. Intervals between the onset of words have ranged from about 100 msec to over one second, with typical word onset asynchronies of 300 to 1000 msec.

**ERPs to Sentences**

Before reviewing the ERP literature relevant to psycholinguistic models of sentence comprehension, we will briefly consider the typical ERP response to sentences. Sentences elicit a sustained and increasing negativity; this negativity has been associated with the Contingent Negative Variation (CNV; Rohrbaugh & Gaillard, 1983; see Coles & Rugg, this volume). ERPs to individual words within the sentence are superimposed on the negative-going activity (Fischler et al., 1983; Kutas & Hillyard, 1980c; Kutas, Van Petten, & Besson, 1988; Neville et al., 1982). When the temporal separation between words is sufficiently large, the early "exogenous" components (e.g., the P1-N1-P2 complex) are clearly observable in grand averages. Later-occurring "endogenous" components are also visible; for example, most words within the sentence elicit the N400 component (Kutas, et al., 1988; Van Petten & Kutas, 1990; Van Petten & Kutas, 1991). Hemispheric asymmetries have been observed, both for exogenous and for endogenous components elicited by words. Specifically, the P1, P2, and N400 components all appear to be slightly larger over the right hemisphere (Kutas et al., 1988). Finally, sentence-
ending words in grammatical, coherent sentences are often followed by a slow positive wave (Friedman et al., 1975). This wave is greatly reduced when the sentence is ungrammatical or incoherent (Herning, Jones, & Hunt, 1987; Osterhout & Holcomb, 1992; Van Petten & Kutas, 1991).

**Word Recognition in Sentence Contexts**

When subjects are asked to name or make lexical decisions about words in sentences, they respond more quickly to words preceded by related context than to words preceded by unrelated context (Fischler & Bloom, 1979; Shuberth & Eimas, 1977; Shuberth, Spoehr, & Lane, 1981; Stanovitch & West, 1983). This and other evidence indicates that word processing is influenced by the sentence context in which it occurs. Various mechanisms have been proposed to account for such influences. One hypothesis is that these effects reflect the automatic spread of activation from "active" concepts to related concepts within the lexicon or conceptual knowledge store (see ERPs and Word Recognition section). A second hypothesis is that context engenders expectations concerning the identity of subsequent words (cf. Becker, 1980). More recently, this issue has been couched in terms of a dichotomy between interactive models, in which context influences early (pre-lexical) stages of word processing (cf. Marslen-Wilson, 1987), and modular models, in which the early-occurring word recognition processes are isolated from the influences of context (Swinney, 1979). According to the modular model, sentence context has its effects on late-occurring, post-lexical processes. Efforts to uncover the locus of sentence context effects with behavioral measures have produced a substantial literature but no consensus. The continuous, on-line nature of ERPs would appear to make them ideal tools for investigating the time course of sentence context effects on word recognition.

**Priming Within Sentences.** The pioneering work of Kutas and her associates (Kutas & Hillyard, 1980a, 1980b, 1980c) clearly demonstrated that the N400 component of the ERP is sensitive to the semantic relationship between a word and preceding sentence context. In their study described above, Kutas and Hillyard (1980) observed that contextually inappropriate words elicit a larger N400 component than do contextually appropriate words (see Figure 1). Subsequent studies have indicated that N400 amplitude is responsive to word expectancy. For example, Kutas and Hillyard (1984) manipulated the expectedness of sentence-final words by varying the cloze probability of these words. (Cloze probability is determined by requiring a large group of subjects to fill in the missing final word in a set of sentences.) Although all of the sentence-final words were semantically acceptable, less-expected final words (e.g., "The bill was due at the end of the hour") elicited a larger N400 than more likely or predictable completions (e.g., "The bill was due at the end of the month"). In addition to demonstrating that N400 amplitude can be influenced by word expectancy, these results indicate that semantic anomaly, although perhaps a sufficient condition, is not a necessary condition for eliciting the N400 effect.
Other data appear to indicate that both word expectancy and automatic activation within the lexicon play a role in determining N400 amplitude. Kutas, Lindamood, and Hillyard (1985) compared the N400 elicited by three types of sentence-ending words (e.g., "The pizza was too hot to eat/drink/cry"). The first type (eat) was the high-cloze (i.e., most expected) completion to the sentence. The second type (drink) was related to the high-cloze completion, but was itself an anomalous ending. The third type (cry) was both unrelated to the high-cloze completion and semantically anomalous with respect to context. Unrelated anomalous endings elicited a large N400 and expected words elicited a small N400. Of more interest was the response to the anomalous endings which were related to the most likely completions. The N400 to these words was larger than the N400 to the most likely completions, but smaller than the N400 to anomalous words unrelated to the high-cloze word. These results were taken to indicate that N400 amplitude is responsive to both (a) word expectancies engendered by context, and (b) associations between individual words (e.g., the association between eat and drink), not all of which need to be physically present in the sentence (cf. Kutas & Van Petten, 1988).

Another question receiving quite a bit of attention in the psycholinguistic literature is whether the effects of single-word contexts on word processing are distinct from the effects of sentence or discourse context. Put differently, the question is whether "lexical" and "sentential" priming result from a single mechanism or from distinct mechanisms. The prevailing view has been that lexical and sentential priming reflect qualitatively distinct processes. For example, one common claim is that lexical priming results from the spread of activation among related items in the lexicon, whereas sentential priming reflects processes that integrate individual words into a conceptual representation of the discourse (for a review, see Van Petten, 1993). This standard view was examined by Kutas (1993), who reasoned that if lexical and sentential priming do indeed occur via qualitatively distinct mechanisms, then the effects of such priming might take the form of qualitatively distinct changes in the ERP waveform. However, Kutas (1993) found no such evidence when she directly compared the ERP manifestation of lexical and sentential priming. Both types of priming had remarkably similar effects. Specifically, both types of context reduced the amplitude of the N400 component, and neither the latency nor the scalp distribution of these effects differed as a function of context. Kutas interpreted these findings as indicating that there is a qualitative similarity between the processes underlying lexical and sentential priming.

This conclusion, however, is at least partially at odds with the results of another recent study. Van Petten (1993) also directly compared lexical and semantic priming, but did so by recording ERPs to associated and unassociated word pairs that were embedded in semantically anomalous or coherent sentences. Van Petten found what could be construed as evidence that qualitatively distinct processes underlie in the two effects. For example, the sentential context effect had a longer duration but smaller amplitude than the lexical context effect. Furthermore, these effects appeared to be additive, perhaps indicating some degree of independence. Finally, the sentential context effect was predictive of subsequent recognition accuracy, whereas the lexical effect was not.
Interaction Between Sentence Context and Word Frequency. As noted above, subjects respond more quickly to words preceded by related context than to words preceded by unrelated context. Similarly, subjects respond more quickly to frequent words than to less frequent words. The interaction between context and word frequency has implications for models of lexical access. Given the simplifying assumptions of additive-factors logic, interactive models predict an interaction between the effects of word frequency and context on responses to targets, because both factors are presumed to influence a common processing stage (e.g., the processes associated with lexical access). In contrast, modular models predict that these effects should be additive, since word frequency is presumed to influence lexical access, whereas context is presumed to influence post-access processes.

Behavioral tests of these predictions have produced conflicting results, with some studies reporting additive effects (Schuberth & Eimas, 1977; Schuberth, Eimas, & Lane, 1981; Stanovitch & West, 1981) and others reporting interactive effects (Becker, 1979; Cairns & Foss, 1971; Forster, 1981). Van Petten and Kutas (1990) examined this issue with ERPs by measuring N400 amplitude to words in grammatical, semantically coherent sentences. The ERP responses to open-class words (e.g., nouns and verbs) were sorted and averaged according to word frequency and ordinal position within the sentence. Words occurring in early positions within their sentences were associated with larger N400s than words occurring later in the sentences. The authors interpreted this as indicating that as contextual constraints became stronger (simply by the addition of more sentence material), N400s to words in the sentence decreased in amplitude. Furthermore, less-frequent words elicited larger N400s (relative to more frequent words) when they occurred in early positions in their respective sentences, but this frequency effect disappeared for words occurring in later positions. Van Petten and Kutas argue that this interaction between sentence position and word frequency is most compatible with an interactive model of lexical access in which the effects of contextual constraints can supersede the effects of word frequency during early stages of word recognition.

A subsequent study (Van Petten and Kutas, 1991) isolated the effects of semantic and syntactic constraints on the N400 effect. The word position and frequency effects observed by Van Petten and Kutas (1990) were replicated in semantically coherent, grammatical sentences. But in sentences that were grammatical but semantically incoherent, (e.g., "They married their uranium in store and cigarettes"), word position had no effect on N400 amplitude. One reasonable interpretation of this finding is that although semantic constraints interact with lexical access, the constraints imposed by sentence structure do not.

Sentence Context and Lexical Ambiguity. Another means for contrasting interactive and modular models of lexical access focuses on lexical ambiguities, that is, words associated with two or more meanings. According to interactive models (Marslen-Wilson & Tyler, 1980), contextual information can be used to selectively retrieve information from the lexicon. Given adequately biasing context, interactive models predict that only the contextually relevant meaning of a lexical ambiguity will be retrieved. In contrast,
modular models (Swinney, 1979) propose that lexical access operates independently of context; hence, such models predict that multiple meanings of a lexical ambiguity will be retrieved, regardless of the semantic content of context.

Attempts to resolve this issue with behavioral measures have provided compelling evidence that multiple meanings of lexical ambiguities are accessed, even in the presence of strongly biasing context (Onifer & Swinney, 1981; Seidenberg, Tanenhaus, Lieman, & Bienkowski, 1982; Swinney, 1979). Swinney and his associates employed a cross-modal priming technique, in which sentences containing biasing context and a subsequent ambiguous word were presented auditorily, while a visual target word (related to one meaning of the ambiguous word) was presented concurrent with the offset of the ambiguous word. Lexical decisions were facilitated to targets related to either the contextually relevant or the contextually inappropriate meaning of the ambiguous word, suggesting that context did not prevent both meanings from being accessed.

Such interpretations have been criticized for failing to take into account the possibility of backward priming -- the effects of the target word on the processing of the preceding ambiguous word (Kiger & Glass, 1983). Specifically, the close temporal proximity of the target to the ambiguous word might allow the target to act as a context for the ambiguous word, encouraging the activation of the meaning related to the target word (see Glucksberg et al., 1986). Conceivably, this backward priming process could occur rapidly enough to affect subjects' responses to the targets.

Given the continuous, millisecond-by-millisecond nature of ERP recordings, ERPs might provide a better test of the backward-priming hypothesis than discrete measures such as reaction time. For example, one might predict that the response facilitation due to backward priming would have a later onset than that due to the effects of context preceding the ambiguous word. Van Petten and Kutas (1987; see above) adopted an all-visual variation of Swinney's method. The ambiguous word appeared as the final word in the sentence, and was followed (after a 200 ms delay) by the target word. Van Petten and Kutas made the crucial assumption that N400 amplitude is a metric of the activation level of a word's meaning. The contextually inappropriate targets elicited a larger-amplitude N400 than did the contextually appropriate words, and (within the window normally associated with the N400) ERPs to inappropriate targets did not differ from those to unrelated control words. However, later in the epoch the ERPs to the inappropriate words did become more negative-going than ERPs to controls. These results were taken to indicate that only the contextually relevant meaning was active prior to presentation of the target words (accounting for the absence of a difference in N400 amplitude to inappropriate targets and controls early in the epoch). Furthermore, the relatively late-occurring differences in the ERPs to inappropriate and control targets could be accounted for by a backward-priming mechanism.

Syntax and Sentence Comprehension
Sentence comprehension involves more than simply retrieving word meanings. It is generally (although not universally) agreed that sentence comprehension also requires an analysis of constituent structure, that is, an analysis of the relative ordering of words in the sentence and of the grammatical roles played by these words. Over the past decade, one of the primary goals of psycholinguistic research has been to specify the psychological processes underlying syntactic analysis. Do readers and listeners compute separable syntactic and semantic representations of a sentence during comprehension, or can the meaning of a sentence be derived directly, without an intervening syntactic representation? Assuming that syntactic representations do play a role, then exactly how are such representations constructed by the reader or listener? And how do the syntactic and semantic representations of a sentence interact during comprehension?

The Syntax/Semantics Distinction. From a linguist's point of view, sentences that violate syntactic constraints (e.g., "John hoped the man to leave") are quite distinct from sentences that violate semantic or pragmatic constraints (e.g., "John buttered his bread with socks"). Whether or not these anomaly types are distinct with respect to the psychological and neurological processes engaged during comprehension remains a point of dispute. A common assumption in much recent psycholinguistic work is that separable cognitive processes derive syntactic and semantic interpretations of a sentence (cf. Berwick & Weinberg, 1983; Fodor, Bever, & Garrett, 1974). However, other theorists claim that purely syntactic processes play no role in comprehension (cf. Ades & Steedman, 1982; Riesbeck & Schank, 1978). This fundamental question has been difficult to address with standard measures, largely because these measures tend to respond similarly to anomalies at different levels. The multidimensional nature of ERPs might make them a more efficacious tool for addressing this question, given two reasonable assumptions. One assumption is that the processes associated with a given level of analysis are distinct from those associated with other levels. The second assumption is that cognitively distinct processes are mediated by neurally distinct systems. Given these assumptions, evidence that syntactic and semantic anomalies elicit dissimilar patterns of brain response could be construed as evidence that separable syntactic and semantic processes exist (cf. Hagoort et al., 1993; Neville et al., 1991; Osterhout, 1994; Osterhout & Holcomb, 1992).

Previous work, discussed above, has been taken to indicate that one type of semantic anomaly (contextually inappropriate words) elicits a large N400 component. Several recent studies have examined the ERP response to syntactic anomalies. Kutas and Hillyard (1983) presented sentences containing errors in bound morphemes that designated word number or verb tense (e.g., "As a turtle grows its shell grow too"). Few reliable differences were found between the ERPs to agreement-violating and control words, although the errors were associated with an increased negativity between 200 and 500 ms post-stimulus at some sites.

However, errors of number and tense agreement are quite distinct from anomalies associated with the determination of sentence structure. Osterhout and Holcomb (1992)
examined the ERP response to violations of constraints on permissible verb arguments, as in sentence (2):

(1) The broker hoped to sell the stock.

(intransitive-verb sentence)

(2) * The broker persuaded to sell the stock.

(transitive-verb sentence)

The clausal complement to sell the stock can be easily attached to the sentence fragment The broker hoped in (1). However, when used in its active form the transitive verb persuade does not allow an argument beginning with the word to (i.e., a prepositional phrase or an infinitival clause) to occur immediately adjacent to the verb. Such restrictions on verb arguments are known as subcategorization restrictions. Hence, the word to in (2) is likely to be perceived as syntactically anomalous, i.e., a violation of verb subcategorization. Figure 7 plots the ERPs elicited by the critical word to in each sentence type. This word in sentences like (2) elicited a widely distributed positive-going wave with an onset around 500 ms. Since the midpoint of the positivity was near 600 ms, Osterhout and Holcomb labeled this effect "P600." Importantly, the P600 is quite distinct from the N400 elicited by semantically anomalous words.

![Figure 7: ERPs from the Cz (midline central) electrode site to apparent violations of verb subcategorization (dashed line) and grammatical control words (solid line). (Adapted from Osterhout & Holcomb 1992.)](image)

In a second experiment, Osterhout and Holcomb presented lengthened versions of sentences like (1) and (2). An extra phrase (was sent to jail) was added onto the end of each sentence, as indicated below:

(3) * The broker hoped to sell the stock was sent to jail.
(intransitive-verb sentence)

(4) The broker persuaded to sell the stock was sent to jail.

(transitive-verb sentence)

In (3) the added phrase cannot be attached to the initial part of the sentence. (The phrase cannot be attached to the preceding sentence fragment without violating English phrase structure rules.) Thus, sentence (3) is ungrammatical, and it becomes ungrammatical at the auxiliary verb was. Conversely, the added phrase can be attached to the initial part of sentence (4); the verb persuade can be passivized, and this allows a reduced relative clause interpretation of the sentence (i.e., "The broker (who was) persuaded to sell the stock was sent to jail"). Under such an analysis, the auxiliary verb was can be attached as part of the main clause (i.e., "The broker was sent to jail"). Therefore, if the P600 is associated with syntactic anomaly, then the word was in (3) should elicit a P600 relative to ERPs to the same word in (4). The ERP response to auxiliary verbs in the two sentence types is shown in Figure 8. As predicted, the auxiliary verbs in sentences like (3) elicited a large positive-going wave with an onset around 500 ms (the P600) relative to the response to the same words in sentences like (4). These words also elicited a left-hemisphere negativity between 200-500 ms, largest over frontal and parietal regions.

![Figure 8: ERPs from the Cz electrode site to phrase structure violations (dashed line) and grammatical controls (solid line). (Adapted from Osterhout & Holcomb, 1992.)](image)

Although these findings appear to indicate that syntactically anomalous words elicit a brain response that is quite distinct from the response to semantically inappropriate words, it is unclear whether or not the P600 is in any sense "language-specific." One possibility is that the P600 is a member of the family of late positive components (P300 and related components) often observed following unexpected, task-relevant events (Donchin, 1981; see Coles and Rugg, this volume). One might assume that readers anticipate grammaticality, and that syntactically anomalous words are an "unexpected event." Furthermore, subjects in the Osterhout and Holcomb study were asked to make "acceptability" judgments after each sentence; hence, the syntactically anomalous words...
were clearly task-relevant. However, the possibility that the P600 is "just another" P300 is made less likely given the recent findings of Hagoort et al. (1993). Hagoort et al. visually presented Dutch sentences containing several types of syntactic anomalies. Subjects were asked to silently read each sentence and were not required to make explicit grammaticality or acceptability judgments. Under these conditions, the syntactically anomalous words were no longer as clearly task-relevant. Even so, two types of anomaly (phrase structure and agreement violations) elicited a positive-going wave very similar to the P600 observed by Osterhout and Holcomb.

Based on these and similar findings, several researchers have speculated that the N400 and P600 are general responses to semantic and syntactic anomalies, respectively (Hagoort et al., 1993; Osterhout, 1994; Osterhout & Holcomb, 1992). However, this generalization is seemingly inconsistent with some recently reported findings in which syntactic anomalies have been associated with a negative-going wave, rather than the P600. For example, Munte, Heinze, and Mangun (1993) recorded ERPs to word pairs. In the semantic condition, these pairs were either semantically related (gangster-robber) or unrelated (parliament-cube). In the syntactic condition, the pairs were either "grammatical" (you-spend) or "ungrammatical" (your-write). Target words (the second word in each pair) in the semantically unrelated condition elicited a negative-going wave with a centroparietal distribution (an enhanced N400), whereas targets in the ungrammatical condition elicited a negative-going wave that was largest over frontal and left-hemisphere sites, relative to controls. In a separate study, Rosler, Friederici, Putz, and Hahne (1993) presented sentences that ended either in a semantically or a syntactically anomalous word. Subjects made lexical decisions to the final words. Both anomalies elicited a negative-going wave. As in the Munte et al. paper, the response to semantic anomalies was posteriorly distributed whereas the response to ungrammaticality was frontal and largest over the left hemisphere.

Given the distinct scalp distributions of the responses to syntactic and semantic anomalies, the authors concluded that separable processes underlie each type of processing. However, these data are seemingly at odds with the claim that the P600 is a general marker of syntactic processing difficulty. We believe that the proper interpretations of these findings, and the caveats they might necessitate with respect to the claim that syntactic anomalies elicit the P600, are not yet clear. For example, word pairs might not fully engage the syntactic processing system. Nor do we know how the lexical decision task might interact with the detection of and response to the syntactic anomaly. But perhaps most importantly, the critical word in both studies was the last stimulus presented prior to the subject’s response, and in the Rosler et al. study the critical word appeared in sentence-final position. There are a number of reasons for suspecting that such a placement introduces the possibility of confounding the response to the anomaly with sentence wrap-up, decision, and response factors. For example, recent work (Hagoort et al., 1993; Osterhout & Holcomb, 1992, 1993) has indicated that the final words in sentences that are typically judged to be unacceptable, regardless of the cause of the unacceptability, elicit an enhanced N400-like component. Thus, a sentence containing a syntactic anomaly embedded within the sentence typically elicits two responses, relative to well-formed controls: a P600-like response to the anomalous word,
and an N400-like response to the sentence-final word. One speculation is that these two effects co-occur in the same epoch when the anomalous word is in sentence-final position. Given the effects of temporally overlapping components, the resulting waveform might look like neither the P600 nor N400 when these effects occur in isolation.

Taken together, then, recent ERP data appear to indicate that the brain response to certain types of syntactic anomaly is quite distinct from the brain response to semantically inappropriate words. This, in turn, supports the claim that separable cognitive/neural processes are involved in syntactic and semantic processing during comprehension. Neville and her associates have reached a similar conclusion based on quite different evidence. Neville, Mills, and Lawson (1992) contrasted the ERP response to "open class" words (e.g., nouns, verbs, and adjectives) and "closed class" words (e.g., prepositions, articles, and conjunctives). Open class words carry semantic information by referring to specific objects and events, while closed class words serve primarily as indicators of sentence structure. Several lines of evidence suggest that these two word classes are treated differently during comprehension. One frequent claim has been that open and closed class words are associated with different modes of lexical access (Bradley, Garrett, & Zurif, 1980). Clinical evidence has been interpreted to suggest that different neural systems are associated with the comprehension of open and closed class words. Specifically, lesions to anterior regions in the left hemisphere appear to disrupt the use and comprehension of closed class vocabulary, while lesions of posterior regions in the left hemisphere disrupt the use and comprehension of open class vocabulary (Friederici, 1985; Swinney, Zurif, & Cutler, 1980).

By examining the ERP response to visually presented words in sentences, Neville et al. (1992) have shown that open and closed class words are associated with dissimilar ERP responses. Open class words elicited a bilateral, posterior negativity in the 400 ms range (the "classic" N400 component). In contrast, closed class words elicited a negative peak around 280 ms (N280) that was most evident over anterior regions in the left hemisphere. One might speculate that the N280 component reflects the special grammatical function of closed class words (and perhaps the activation of neural systems associated with the construction of syntactic representations). If so, then one reasonable prediction is that the N280 should be reduced or absent in comprehenders who do not have full grammatical competence. Neville et al. (1992) tested this prediction by presenting sentences to deaf subjects who had not fully acquired the grammar of English. Although the open classed items elicited a posterior, bilateral N400 component, ERPs to closed class words did not display the N280 component. In contrast, ERPs from deaf readers who had acquired a full competence in English grammar showed both the N280 over left anterior regions to closed class words and the N400 over posterior regions to open class words. These results are consistent with the claim that non-identical semantic and syntactic processes operate during sentence comprehension.

The basic distinction between syntax and semantics is not the only relevant distinction made by current theories of grammar. For example, Government and Binding (GB) theory (Chomsky, 1981, 1986) posits the existence of multiple modules of grammatical
knowledge. GB includes one module specifying constraints on the phrase structure of sentences, and other modules constraining the "movement" of sentence elements for question and relative clause formation. It is conceivable that a direct mapping exists between the grammar and the comprehension system, such that there is one "processing module" for each module in the grammar. This possibility was examined by Neville et al. (1991), who contrasted the ERP response to several types of syntactic anomaly, as exemplified by sentences (5) - (7):

(5) * The man admired Don's of sketch the landscape.

(phrase structure violation)

(6) * Whati was a sketch of ___i admired by the man?

(subjacency violation)

(7) * Whati did the man admire Don's sketch of ___i?

(specificity violation)

The underlined word in each sentence represents the point at which a specific grammatical constraint is violated. The blank spaces in sentences (6) and (7) represent "gaps" formed by the movement of a sentence constituent from its canonical position to another position within the sentence during question formation. The subscripts index the gap to the moved constituent. In both (6) and (7) the gap is co-indexed with the moved constituent what. The violations in the above sentences are as follows: In (5), the string The man admired Don's of cannot be assigned a well-formed phrase structure. The question in (6) has been formed by movement out of the subject noun phrase, which is not allowed in English. In GB, the ungrammaticality of such movement has been subsumed under the subjacency condition, which is the central constraint on constituent movement. The ill-formedness of (7) reflects the fact that questions cannot be formed by moving a specified or definite noun phrase from its canonical position, a principle known as the specificity constraint. Within the GB framework, phrase structure rules, the subjacency condition, and the specificity constraint reflect the operation of three distinct modules of grammatical knowledge.

Neville et al.'s data revealed differences in the brain response to each type of anomaly. ERPs elicited by the underlined words in sentences similar to (5) - (7) were compared to ERPs elicited by non-violating control words. Phrase structure violations elicited both an enhanced negativity between 300-500 ms over regions of the left hemisphere, and a subsequent positive-going wave (largest over posterior sites) beginning at about 500 ms. This pattern of brain activity was strikingly similar to that observed by Osterhout and Holcomb (1992, discussed above) following phrase structure anomalies. Violations of the subjacency constraint elicited a broad-based positivity with an onset at about 200 ms that lasted for the duration of the epoch. Violations of the specificity constraint produced a
slow negative potential, largest at anterior sites in the left hemisphere, with an onset as early as 125 ms. Hence, each violation type was associated with a distinct brain response.

**Sentence Parsing.** Given evidence that ERPs are sensitive to syntactic aspects of sentence comprehension, it becomes feasible to use ERPs as on-line tools for investigating the processes engaged in deriving syntactic representations during comprehension. One topic attracting considerable experimental interest in recent years is the processing response to syntactic ambiguity, i.e., situations in which more than one well-formed syntactic analysis is available for one string of words. How does the processing system deal with the indeterminism introduced by such ambiguity? Competing theories of sentence parsing provide different answers to this question. Proponents of serial parsing models (e.g., Frazier & Rayner, 1982) claim that a single "preferred" structure is initially constructed, with subsequent re-analysis when the preferred structure turns out to be the incorrect one. Others have claimed that no grammatical roles are assigned until the correct ones are known with certainty (Marcus, 1980), or that all possible structures are built in parallel (Gorrell, 1989).

Data from the few ERP studies that have examined this issue are, by and large, consistent with the serial parsing model. Osterhout, Holcomb, and Swinney (in press) presented sentences containing a syntactically ambiguous noun phrase, as in (8):

(8) The lawyer charged the defendant was lying.

(9) The lawyer charged that the defendant was lying.

In sentence (8) the proper grammatical role of the noun phrase the defendant is temporarily uncertain; it can serve either as object of the verb, or as the subject of an upcoming clause. The fact that the noun phrase is playing the subject role in (8) becomes clear only after the syntactically disambiguating auxiliary verb was is encountered. In contrast, the overt complementizer in sentence (9) unambiguously indicates that the noun phrase is the subject of an upcoming clause. Considerable psycholinguistic evidence (cf. Frazier, 1987b; see below) has indicated that readers experience processing difficulty upon encountering the auxiliary verb in sentences like (8), relative to sentences like (9). For example, Frazier and Rayner (1982) observed longer eye fixations and more eye regressions in the disambiguating region of sentences like (8) than in the corresponding region of sentences like (9) (the so-called garden-path effect). These results have been interpreted as indicating that readers initially assign the object role to the ambiguous noun phrase in sentences like (8).

If readers erroneously assign the object role to the underlined noun phrase in (8), then the disambiguating auxiliary verb will be perceived to be syntactically anomalous; under a direct object analysis the auxiliary verb cannot be attached to the preceding material. Osterhout et al. observed the ERP response to the auxiliary verb in sentences like (8) and (9). The auxiliary verbs in sentences like (8) elicited the P600 effect, relative to ERPs to
the same words in unambiguous sentences like (9). Assuming that the P600 is a metric of syntactic anomaly, this finding is fully consistent with the serial parsing model proposed by Frazier and her associates. At the same time, these data suggest that the P600 can be elicited by syntactic anomaly resulting from strategies employed by the comprehender, as well as by anomaly resulting from outright violations of grammatical constraints.

If readers initially pursue a single analysis for syntactically ambiguous sentences, as claimed by the serial parsing model, then what factors determine which path is attempted first? Frazier and her colleagues (Frazier, 1987b; Frazier & Rayner, 1982) have persuasively argued for a "minimal attachment" model in which the simplest analysis (as defined by the number of nodes in the phrase structure) is always attempted first, with backtracking and reanalysis when the simplest structure turns out to be inappropriate. Others have argued for a "lexical preference" model in which information about the main verb in the sentence dictates the initial parse (Holmes et al., 1989). Implications of these two approaches are illustrated by sentences (10)-(13):

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

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

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

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

These sentences can be distinguished in terms of the subcategorization information associated with the main verb in each sentence. The subcategorization properties of the verbs in (10) and (11) unambiguously indicate the proper role of the noun phrase the patient. Specifically, the intransitive verb hope in (10) does not allow a direct object noun phrase, unambiguously indicating that the noun phrase is the subject of an upcoming clause. The transitive verb force in (11) requires a direct object, so the noun phrase must be assigned the direct object role. Sentence (11) becomes ungrammatical at the auxiliary verb, since the sentence-final phrase was lying cannot be attached to the sentence unless the noun phrase is assigned the subject role.

The verbs in (12) and (13) can be used with or without a direct object. This introduces temporary syntactic ambiguity when the noun phrase the patient is encountered; the noun phrase might be acting as the direct object of the verb, or as the subject of an upcoming clause. Because the direct object analysis is syntactically simpler than the subject-of-a-
clause analysis, a minimal attachment parser would initially assign the object role to the noun phrase in both sentence types. This will lead to parsing difficulty and re-analysis when the parser encounters the auxiliary verb in both sentence types. In contrast, the lexical preference model predicts that the initial analysis attempted by the parser will be determined by the subcategorization "preferences" of the main verb. The verb in (12) is biased toward intransitive use (use without an object noun phrase) while the verb in (13) is biased toward transitive use (use with a direct object noun phrase) (Connine et al., 1984). Hence, according to the lexical preference model, the subject role will be correctly assigned to the noun phrase in (12), since the verb believe "prefers" to be used without a direct object. But the direct object role will be erroneously assigned in (13), since the verb charge "prefers" to be used with a direct object. This will lead to parsing difficulty at the auxiliary verb in sentences like (13). To summarize: the minimal attachment model predicts that the parser will encounter syntactic anomaly at the auxiliary verb in sentences like (11), (12), and (13), while the lexical preference model predicts anomaly only in sentences like (11) and (13).

Osterhout et al. (in press) presented sentences similar to (10)-(13). Sentences were presented visually in a word-by-word manner, with word onset asynchronies of 650 ms. ERPs to the auxiliary verb (e.g., was) in each sentence type are shown in Figure 9. As expected, when these words followed "pure" transitive verbs, such as in sentence (11), they elicited a large positive-going wave that was largest over parietal sites (the P600). More importantly, auxiliary verbs that followed transitively biased verbs, as in sentence (13), also elicited a P600, although the amplitude of this effect was much smaller than that elicited in sentences with pure transitive verbs. Auxiliary verbs that followed either an intransitive verb (sentence 10) or an intransitively biased verb (sentence 12) did not differ from each other and did not elicit this positive-going activity. Again assuming that the P600 is a metric of parsing difficulty, then these findings are consistent with the claim that the structural analysis readers initially pursue is determined by lexical preferences, rather than by syntactic complexity.

Figure 9: ERPs from Pz (parietal midline) to the final three words in each of four sentence types: intransitive (solid line), transitive (small dashes), intransitively biased (large dashes), and transitively
Another type of syntactic ambiguity involves the processing of "filler-gap" relationships within sentences. As noted above, certain structures contain constituents which have been "moved" from one location to another within the sentence. The moved constituent is called the "filler", and its original location is called the "gap" (Fodor, 1978). Presumably, the comprehension system must match up each filler with the appropriate gap before the sentence can be fully understood. However, this process is far from trivial, largely due to uncertainty over the proper location of the gap. For example, the fragment "The mother found out which book the child read . . ." can be continued in several ways, each with a different gap location (e.g., "The mother found out which book the child read ___ in school"; "The mother found out which book the child read about ___ in school"). How does the processing system deal with such uncertainty? Two models have been contrasted in the recent literature. A first-resort parser assigns a filler to the first possible gap, while a last-resort parser waits until there is unambiguous information about the location of the true gap location.

Garnsey, Tanenhaus, and Chapman (1989) conducted a clever experiment to contrast these parsing models. They presented sentences similar to (13) and (14):

(13) The businessman knew which customer the secretary called ___ at home.

(plausible filler)

(14) The businessman knew which article the secretary called ___ at home.

(implausible filler)

The first possible gap location in these sentences is after the verb, in direct object position. However, the sentences could have continued in such a way that a later gap location existed ("The businessman knew which article the secretary called about ___ "). A first-resort parser would attempt to assign the filler to the direct object position in (13) and (14) as soon as the verb called is encountered, while a last-resort parser would wait until the location of the gap could be assigned with certainty (i.e., no filler-gap assignments would be made until words subsequent to the embedded verb had been encountered). The noun customer is a plausible filler for a gap in direct object position, while the noun article is not. The logic of the experiment was as follows: If the parser associates the filler with a gap in direct object position immediately after seeing the verb, and if the filler is implausible for that gap, then there should be an N400 in the response to the verb. If the parser waits until later in the sentence to make a filler-gap assignment, then the N400 should not occur in response to the verb but may appear later in the sentence. The results indicated that the verb in sentences like (14) (called) elicited a larger N400 than the same verbs in sentences like (13), providing support for the first-resort parsing model.
In a more recent ERP study involving sentences containing "filler-gap" relationships, Kluender and Kutas (1993) recorded ERPs to words intervening between the filler and the gap, and compared these to ERPs elicited by the same words in sentences without a filler-gap relationship. For example, they examined the ERPs to the pronoun he in sentences like (15) and (16):

(15) Can't you remember that he advised them against it on previous occasions?

(sentence without filler-gap relationship)

(16) Can't you remember who he advised ____ i against it on previous occasions?

(sentence containing filler-gap relationship)

ERPs to he in sentences like (16) (i.e., sentences containing a filler-gap relationship) were more negative-going over left anterior regions, compared to ERPs elicited by he in sentences like (15) (sentences without a filler-gap relationship). Although the correct interpretation of this effect is uncertain, one possibility is that it reflects the added processing load associated with holding a filler in memory (cf. Wanner & Maratsos, 1978).

Comprehending Spoken Sentences

A skeptical observer might readily object to the mode of stimulus presentation used in the studies described above. Visual word-by-word presentation of sentences, at rates ranging up to one second per word, is far from a "normal" comprehension environment. One way to address this objection is to present sentences in the form of natural, continuous speech. Such experiments not only provide a replication of the visual studies; they allow investigations of processes that are by their nature restricted to auditory input (e.g., speech segmentation). They also provide an opportunity for directly contrasting visual and auditory sentence comprehension. Although auditory studies are at present few in number, the preliminary data are largely consistent with their visual analogues.

Speech Segmentation. A considerable amount of theorizing has been directed at the problem of speech segmentation (e.g., Cole & Jakimik, 1980; Cutler, 1987; Frazier, 1987a; Pisoni & Luce, 1987). It has been known for many years that the speech signal is not composed of a series of discrete words, but rather is a continuous flow of sound with few breaks or pauses (e.g., Pisoni & Luce, 1987). Two important questions that arise from this observation are: how do listeners segment the complex spoken signal into individual units? and what are the basic units of speech perception? The ERP technique permits the recording of brain wave activity time-locked to the onset of each word in a sentence. Numerous studies have shown a consistent pattern of early "sensory"
components in ERPs recorded to isolated nonlinguistic (e.g., Picton, Hillyard, Krausz & Galambos, 1974) and linguistic (e.g., Holcomb & Neville, 1990) sounds. A reasonable preliminary question then is: Do words in connected speech generate a consistent pattern of sensory ERP components? Evidence from Holcomb and Neville (1991) suggests that they do. In their study all open class words in the middle of naturally spoken sentences were averaged together to form a single ERP. The resulting waveforms, although small in overall amplitude, revealed a clear set of early ERP components. That these waves represent the P1, N1, and P2 components frequently seen to other auditory stimuli was supported by their scalp distributions, latencies and relative positions in the ERPs. The existence of a relatively normal set of early ERP components time locked to the onset of words in natural continuous speech is consistent with the hypothesis that speech segmentation occurs on-line and at a relatively early point in the processing of speech stimuli. However, whether these ERP findings directly reflect the segmentation process at work or whether they indicate that segmentation is complete prior to the occurrence of these early waves is unclear.

Comprehending Words in Spoken Sentences. McCallum, Farmer and Pocock (1984) performed an auditory replication of the original Kutas and Hillyard (1980c) visual sentence study. They included sentences spoken by a male with best completion endings (e.g., “The pen was full of blue ink”), semantically anomalous endings (e.g., “At school he was taught to snow”) and best completion endings that had a physical deviation (the final word spoken by a female). As in previous visual studies, ERPs to the anomalous endings produced a negative component (peak latency 456 ms), while ERPs to appropriate endings produced a relatively flat response between 200 and 600 ms and ERPs to physically deviant endings produced a large positivity in this latency band. McCallum et al noted that while their auditory N400s had a similar scalp distribution to those recorded by Kutas and Hillyard (1980c) in the visual modality, they were also somewhat less peaked.

Holcomb and Neville (1991) also replicated an earlier Kutas et al (1984) study with auditory stimuli. However, unlike McCallum et al their sentences were spoken as natural "connected" speech. McCallum used natural speech for all but their final words, which were spliced in from other sentences. This removes the effects of between word speech cues such as co-articulation and prosody that can be used by the listener to help decode the speakers message. Even though the average duration of final words was 561 ms in the Holcomb an Neville study, the ERPs at posterior electrode sites reliably registered a difference between sentence final words that were contextually appropriate and those that were contextually anomalous as early as 50 ms post-word-onset (see Figure 10). As with their earlier word-pair study (Holcomb & Neville, 1990) this result is consistent with Marslen-Wilson's (1987) claim that contextual factors can have an effect on auditory word processing prior to the point at which all the acoustic information about a given word is available. This finding is particularly striking when compared to similar data from procedurally equivalent visual studies (see above), where all of the information about a given final word is available at stimulus onset. In these studies the difference
between best completion and anomalous final words typically does not start prior to 200 ms. It is also noteworthy that the latency of Holcomb and Neville's (1991) effects were 100 to 150 ms earlier than the onset of the first effects visible in the McCallum et al (1984) study. A likely possibility for this finding is the presence of non-semantic contextual cues (i.e., prosody and across-word co-articulation) in the natural speech stimuli from the Holcomb and Neville study. To check this possibility Holcomb and Neville ran a second experiment in which the impact of prosodic and co-articulatory factors were minimized (an artificial 750 ms ISI was introduced between the words of the spoken sentences). Although there were still N400 like effects in this experiment, the onset of these effects was 100 to 150 ms later.

Figure 10: ERPs from six pairs of lateral electrodes. Best completions were final words that fit with the context of the sentence (e.g., He spread the warm bread with butter), unrelated anomalies were final words that did not fit with the sentence context and were semantically unrelated to the best completion (He spread the warm bread with socks), and related anomalies were final words that although anomalous were semantically related to the best completion (He spread the warm bread with milk). (From Holcomb & Neville 1991.)

Syntax and Spoken Sentence Comprehension. Only one study has explicitly examined syntactic analysis during the comprehension of connected, natural speech. Osterhout and Holcomb (1993) replicated their earlier visual study (Osterhout & Holcomb, 1992), in which sentences like (1) - (4) above were presented. Apparent violations of subcategorization and phrase structure constraints elicited a positive-going wave (P600) similar to that observed during visual presentation (Figure 11). However, this effect tended to have an earlier onset (between 50 and 300 msec poststimulus) during spoken language comprehension, relative to the effects observed during reading (around 500 msec). Furthermore, the P600 appeared to have a more posterior distribution in the auditory experiment than in the visual experiment. Since the effects observed during the
reading experiment were closely replicated in its auditory analogue, it is tempting to conclude that (at least under certain conditions) the parsing strategies employed during spoken language comprehension closely mirror those employed during reading. In both modalities, comprehenders show signs of using a serial parser with a proclivity for building simple structures. The sensitivity of ERPs to aspects of syntactic analysis during auditory comprehension also opens the door to investigation of phenomena difficult to study with more traditional measures. For example, it should be possible to carefully examine the influence of prosodic and other phonological information on the on-line syntactic analysis of sentences.

![Figure 11: ERPs from site Pz to phrase structure violations and grammatical controls. Stimuli were presented as continuous natural speech. (Adapted from Osterhout & Holcomb 1993.)](image)

**Summary**

ERP studies of word processing in sentence contexts were initially motivated by the seminal findings of Kutas and Hillyard (1980a, 1980b, 1980c), who found that contextually inappropriate words elicit the N400 effect. Subsequent studies have examined the sentence-level factors that influence the size of the N400 effect. It is now generally agreed that (a) most words within a sentence elicit an N400 component (cf. Kutas, Van Petten, & Besson, 1988; Van Petten & Kutas, 1991); (b) the amplitude of the N400 is sensitive to semantic aspects of sentence context (although exactly which aspects remains a point of contention; see Fischler, 1990; Kutas & Van Petten, 1988); and (c) N400 amplitude appears to be influenced by a complex interaction between lexical and contextual factors (Van Petten & Kutas, 1991).

Changes in N400 amplitude resulting from principled manipulations to linguistic stimuli have been used to arbitrate between modular and interactive models of word recognition. For example, an apparent interaction between word frequency and sentence context on N400 amplitude has been taken to indicate support for interactive models of word recognition (Van Petten & Kutas, 1990).
ERPs have also been used to examine syntactic processes. Perhaps the most intriguing outcome of these studies is the dramatic difference in the ERP response to deviations from semantic and syntactic well-formedness. Deviations from semantic well-formedness (e.g., contextually inappropriate words) generally elicit a large N400 component. Several types of syntactic deviations are associated with an ERP response, but none of these elicits a "classical" N400-like effect. Furthermore, although the syntactic anomalies examined to date have elicited a variety of ERP responses, three types of anomaly (phrase structure violations, apparent subcategorization violations, and violations of Subjacency) have been associated with a long-lasting, widely distributed positive-going wave. Although the precise cognitive processes reflected in these components are unknown, these observations allow one to speculate that, at least under certain experimental conditions, the N400 and the slow positive-going wave (the "P600") are elicited as a function of the representational level of the anomaly (semantic and syntactic, respectively). In general, the ERP studies reviewed above provide rather striking evidence of a correspondence between the neural and cognitive processes involved in comprehension, and distinctions made within formal theories of language.

These studies also demonstrate that ERP measures are sensitive to at least an interesting subset of the neural and cognitive processes engaged during sentence comprehension. The available ERP evidence is largely consistent with a parsing model in which a single structural analysis is pursued initially, even when the parser is confronted with uncertainty about the correct analysis. Preliminary data suggest that the parser's early decisions can be influenced by word-specific information (e.g., verb subcategorization knowledge), rather than solely by biases in the application of phrase structure knowledge. This parsing model appears to hold regardless of the modality of input (visual or auditory).

**Conclusions**

We began our review by noting that previous reviewers have projected a noticeably pessimistic view concerning the use of ERPs as tools for comprehending language comprehension. This view has been shared by many psycholinguists, who have (seemingly) looked upon ERPs as something akin to an intriguing but largely unfulfilled promissory note. We believe that the literature reviewed here justifies a decidedly more optimistic view. It is now clear that ERPs are sensitive to relevant aspects of the processes underlying comprehension, and that this sensitivity can be exploited to reveal a great deal about these processes. Indeed, given their unique combination of properties (on-line, non-intrusive, multidimensional measurement), ERPs are ideally suited to address certain questions that would be difficult or impossible to address with more conventional measures. For example, given their multidimensional nature, ERPs have a better chance (in principle and, it appears, in practice) of distinguishing between distinct cognitive states. This allows the researcher to determine (to a first approximation) not only when an anomaly has been detected, but also what kind of anomaly has been perceived. Similarly, it appears that meaningful language-sensitive changes in the ERP
can be obtained under extremely natural comprehension conditions; for example, under conditions in which subjects are asked to simply process the language without a secondary task (Hagoort et al., 1993), or when the stimulus is presented as continuous natural speech (Osterhout & Holcomb, 1993). To all appearances, the foreseeable future will offer a productive marriage between the tools of cognitive psychophysiology and the theoretical richness of modern psycholinguistics.

Of course, ERPs are not a panacea for the difficulties afflicting psycholinguistic research, and in all likelihood certain questions will remain largely unilluminated by ERP measurement. The observant reader might have noted that much of the work reviewed here has examined aspects of comprehension that occur early in the information-processing flow (e.g., word recognition, integrating a word into context, and syntactic analysis). These "early-occurring" processes can be contrasted with "later-occurring" processes (e.g., making inferences, integrating propositional content into the discourse representation, and interpretating non-literal speech acts). As noted by Fischler (1990) and others, this is an appropriate and perhaps inevitable focus for ERP studies of language comprehension. Event-related potentials represent brain activity averaged over both items and subjects, typically time-locked to the presentation of a stimulus. The most observable and reliable ERP effects are those that have an invariant temporal relation to the onset of the stimulus. A priori, it seems likely that early-occurring processes, such as those involved in word recognition, maintain a more consistent temporal relation to stimulus onset (across both items and subjects) than do later-occurring processes. The interesting question of how far down the "path of comprehension" ERPs will take us remains to be answered.

In sum, ERPs have been shown to be sensitive measures of a number of language-related processes. The literature reviewed here allows us to hope that the success or failure of the ongoing effort to comprehend comprehension by recording event-related potentials will be determined largely by the imagination and skill of the researchers, rather than by limitations inherent in the measures themselves.

REFERENCES


Cairns, H.S. & Foss, D.J. (1971). Falsification of the hypothesis that word frequency is a unified variable in sentence processing. *Journal of Verbal Learning and Verbal Behavior, 10*, 41-43.


