CHAPTER TWENTY-ONE

LANGUAGE

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The Brain - is wider than the sky -
For - put them side by side -
The one the other will contain -
With ease and you beside

The Brain is deeper than the sea -
For - hold them - Blue to Blue -
The one the other will absorb -
As Sponges - Buckets - do

The Brain is just the weight of God -
For - Heft them - Pound for Pound -
And they will differ - if they do -
As Syllable from Sound.

Emily Dickinson (1896/1970)

Historical Context

As Dickinson notes, brains have a remarkable capacity that differentiates them from other sorts of material substances: the ability to represent things intentionally. Although we often take this capacity for granted, it is no small feat that we are able to entertain the thoughts of a woman who has long since died. Many consider Dickinson to be a gifted poet, yet her ability to exploit the representational capacity afforded by language is shared by all humans. This capacity allows us to communicate with one another across distances of time and space and to affect one another's behavior.

Natural language is a species-specific system that enables speakers to evoke cognitive models in listeners via the systematic combination of vocal sounds or visual signs. A schematic characterization of the speech event begins with the speaker's desire to communicate a message and ends with the listener's apprehension of that message. In this simplified model of the communicative act, language mediates between thoughts and motor commands on the speaker's end, and between acoustic signals and thoughts on the listener's end. However, the real magic in the system lies in the brains of the speech participants, and it is to the brain that psychophysiologists turn for answers to fundamental questions about the nature of language representations and the relationship between language and other cognitive processes.

Linguists have posited a number of different kinds of representations to account for language production and comprehension. These constructs have proven quite useful for thinking about language processes, but their psychological reality remains a serious question. Much regularity can be observed in language, but are those regularities due to the fact that the brain implements linguistic rules? Work on the psychophysiology of language processing - using techniques such as ERPs, PET, and fMRI - has attempted to monitor how the brain changes with manipulations of particular linguistic representations. The assumption is that language subprocesses are subserved by different anatomical and physiological substrates that will generate distinct patterns of biological activity. These patterns can then be picked up by methods sensitive to fluctuations in electromagnetic and hemodynamic activity.

Related to these representational questions has been a set of issues about the architecture of the language processing system as a whole. Fodor (1983) characterized cognition as "modular"; that is, as the result of a large number of autonomous, highly specialized input modules feeding into a more general-purpose central processor. Input modules transform particular inputs into representations that can be handled by the central processor. These input systems are regarded as "informationally encapsulated" (protected from influence by other types of information). Additionally, it is argued that the central processor has access only to the outputs of the input modules and not to any

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intervening representations in the modules themselves. A modular approach to language processing assigns low-level aspects of processing (such as parsing and word recognition) to the input modules while leaving higher-level aspects such as semantics and pragmatics to the central processor. The difference between a modular account of language processing and a nonmodular, or "interactionist," account chiefly concerns the time course of processing. In the modular account, lower levels of processing occur autonomously and are integrated only later by the central processor. By the interactionist account, the lower levels of processing are not independent of higher levels but rather interact continuously with them during the processing of a sentence.

It now seems fairly clear that language processing is neither completely modular nor completely interactionist. However, psycholinguists continue to argue about whether certain language abilities result from dedicated brain regions specialized for specific kinds of linguistic representations, or whether these abilities are more accurately described as resulting from general mechanisms, such as constraint satisfaction as implemented in neural network models. Such models portray language abilities as the outcome of the simultaneous application of general-purpose constraints at many different linguistic levels (MacDonald, Pearlmutter, & Seidenberg 1994).

Psychophysiological studies of language processing are well suited to examine issues of both representation and processing. Techniques with high spatial resolution, such as PET and fMRI, can help pinpoint brain areas important for language processing. Techniques with high temporal resolution, such as ERPs and eye tracking, can help reveal how language processing unfolds over time; they can be used to track the availability of different sorts of linguistic information and the temporal course of their interactions. Additionally, studies of brain-damaged patients, in conjunction with the use of psychophysiological measures, can provide important insights about which brain areas are necessary and/or sufficient for certain types of linguistic processes and about the relationship between language processing and other cognitive abilities. In this chapter, we consider the role of the brain in understanding and producing natural language utterances. We review how psychophysiologists have addressed this issue in the past and consider how these methods might best be employed in the future.

Physical Context

Language production, or speaking, depends on the brain systems that enervate the muscles and coordinate movements of the lungs, vocal cords, jaw, and lips. Language comprehension depends on brain systems which transform the acoustic information that hits the listener's eardrum (or the visual information that hits her eyes, in the case of sign language) into her understanding of what has been said. Language processing thus involves perceptual transformations in auditory and/or visual cortices; motor control processes mediated by the motor cortical areas, basal ganglia, and cerebellum; memory processes - both long-term and working - in hippocampal, medial temporal, and frontal lobe structures; attentional shifts as mediated by the parietal lobe; and so forth. When considering the neural basis of language processing, it is therefore important to appreciate the extent to which the brain as a whole is involved.

Despite the fact that language processing recruits large portions of the brain, some parts of the brain are considered by most to be particularly concerned with the processing of language. An area of the frontal cortex (Brodmann's areas 44 and 45) known as Broca's area is one example. Damage to Broca's area (which usually also includes underlying subcortical tissue and white matter) causes an aphasia characterized by halting, "telegraphic" speech (lacking in function words) but with reasonably good comprehension. In contrast, damage to Wernicke's area (Brodmann area 22) in the parietal cortex produces a "fluent" aphasia (speech has normal rate and rhythm) with impaired comprehension. While Wernicke's aphasics produce speech easily and use function words appropriately, they produce large numbers of paraphasias (incorrect word substitutions) that render their speech nearly incomprehensible. There remain many debates about what Broca's and Wernicke's areas specifically contribute to language processing (e.g., motor vs. sensory, syntax vs. semantics). However, these are two brain areas that are clearly necessary for normal language functions (see Goodglass 1993 for a discussion of other types of aphasia and their neural correlates).

More recently, an area in the basal temporal fusiform gyrus (the basal temporal language area) has been shown to be important for word processing. Stimulation of this area (in epileptic patients undergoing surgery) results in language deficits ranging from anomia to global expressive and receptive aphasias (Luders et al. 1986). The fact that only transient aphasia results from damage to the basal temporal language area suggests that its functions are or can be duplicated by other brain areas. Although not necessary for language function, this area does seem likely to play an important role under normal conditions. In fact, with the advent of noninvasive brain imaging methods (PET, fMRI), a number of areas that seem important (but not necessary) for language functioning have been described. For example, these studies have implicated a left prefrontal area in tasks requiring language production (Petersen & Fiez 1993) or semantic judgments (Kapur et al. 1994); such activations are not observed during the processing of pseudowords, which clearly have many of the phonological and some of the lexical properties of real words but are devoid of meaning.

Imaging studies point consistently to some brain areas as important for language tasks, yet there is considerable diversity in the other areas activated in particular studies (see Fletcher et al. 1995; Petersen et al. 1991; Wise et al. 1991). The precise areas activated in a study depend heavily on the choice of experimental and control tasks and the methods used to process and analyze the data. When drawing conclusions from neuroimaging data, as from all types of psychophysiological data, it is thus important to recognize the inferential leaps required by and the inferential limitations inherent in mappings from physiology to psychology (see Sarter, Berntson, & Cacioppo 1996 and Chapter 1 of this volume).

Social/Cognitive Context

For at least 100,000 years, our species has used language to describe - and construct - the world around us. First, and perhaps most obviously, language provides a medium for the communication of thoughts via a structured stream of sound. Upon hearing language, listeners are somehow able to formulate a mental representation of the speaker's message, which can alter the listener's mental state and affect her subsequent behavior. Language thus provides the primary means of social interaction and enables the coordination of group action. Second, language enables us to transmit cultural knowledge such as customs and values. An integral part of social interaction, it plays an organizing role in social relationships. Like the clothes we wear, the way we talk can reveal much about our cultural heritage. Our accents suggest the place of our upbringing. Our choice of slang words is highly suggestive of group identification. As James Baldwin (1963) noted, "To open your mouth in England is (if I may use Black English) to 'put your business in the street': you have confessed your parents, your youth, your school, your salary, your self-esteem, and, alas, your future." Besides describing the world, language is used to affect and effect it. Language is used to ask questions, make requests, issue warnings; to make promises, enact business contracts, seal marriage vows; to tell stories and lies, crack jokes, and sometimes just to pass the time of day. In short, language is as much a tool for the social construction of reality as a conduit for thoughts and feelings.

The cognitive basis of this complex human skill involves representations and processes at a number of different levels. The study of linguistics is divided into several subdisciplines based on observations of regularities at multiple levels of analysis. Moving from sound to meaning, these disciplines include phonology, the study of linguistic sound; morphology, the study of word formation; grammar (syntax), the study of hierarchical structure in utterances; semantics, the study of context-invariant aspects of meaning; and pragmatics, the study of meaning in use. Although it is unclear how traditional linguistic categories map onto brain structures and functions, it is important to consider the work of linguists as a relevant starting point for exploration of these issues.

Dickinson notes the distinction between syllable, a construct specific to language, and sound, which is more general. Because of naturally occurring anatomical variation in vocal tracts, everyone's voice is different. Factors such as age, sex, health, and size all influence the physical character of speech sounds. Therefore, if we compare the acoustic signal corresponding to the pronunciation of *chowder* by a little girl and an elderly man, the phonetic (i.e., sound) characteristics would differ dramatically. There can even be considerable variation within a given speaker due to factors such as health and mood. Nonetheless, most people would be able to recognize that it was the word *chowder* and not clams that was uttered regardless of who says it or how excited the speaker is. This suggests a level of representation of speech that abstracts away from the raw sensory aspects of the acoustic stimulus. These representations are not directly available in the sensory input but rather are constructed in the listener's mind.

Although our intuition is that the fundamental unit of language is the word, linguistic research suggests that words are composed of more fundamental units known as phonemes. For example, the monosyllabic word cat is made up of three phonemes /k/, /a/, and /t/, where "phoneme" is defined as the smallest unit of speech input that makes a difference in a word's meaning. So, /k/ and /m/ are both phonemes because we can substitute them for each other in /kat/ and get words with different meanings. Words can also be broken down into "morphemes," which are combinations of phonemes that have their own meaning. As morphemes are the smallest meaning pieces into which a word can be cut, the word cat has only one morpheme. In contrast, the word *unsuccessfully* consists of four morphemes, each of which contributes to the meaning of the word as a whole: un-success-ful-ly. This idea of building up meanings by combining representations at different levels is a recurrent one in linguistics because it helps explain how we can express an infinite number of different meanings with a limited repertoire of speech sounds. Thus, phonemes are combined into morphemes, morphemes into lexemes (another word for words), words into phrases, and phrases into sentences.

Just as words are built up out of sounds, sentences are built out of words. The relationship between words and sentences is complex and involves structure at a number of different levels. "Parsing" is the process of analyzing the input into a series of lexical units and then mapping higher-order structures onto those units in a consistent and eventually meaningful way. In addition to what might be called word-level semantics, these include phrase structure, thematic structure, and referential structure, as depicted in Figure 1.

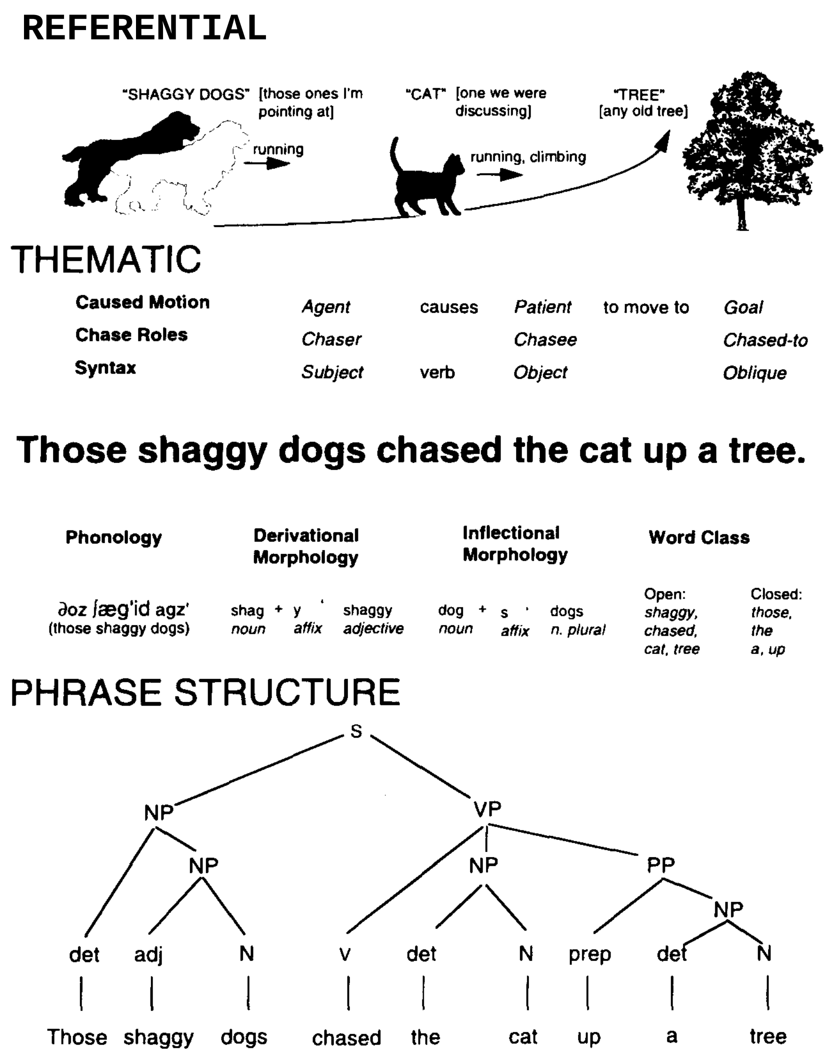


Figure 1. Cartoon view of language processing with illustrations of processes and terms used in this chapter.

Most students of English grammar have learned that parts of speech can be assigned to words and that certain relationships hold among them (in English, for example, adjectives often precede nouns). Linguists also divide words into different, more abstract, classes and study relationships among them. The study of these relationships is "phrase structure" and is probably what most psychologists would think of as "grammar" or "syntax."

Rules (or regularities) of phrase structure capture our intuitions that, in the following example sentences, the syntax of the phrase *those dogs* is basically similar to that of *those shaggy dogs* and also, perhaps, of *dogs*.

(Dogs) like me.
(Those dogs) like me.
(Those shaggy dogs) like me.

The pronoun *they* may also be interchangeable with the nouns in these examples, when it is known that *they* refers to the dogs in question. English thus has a kind of phrase that contains at least one noun or something acting like one (e.g., a pronoun); these are called "noun phrases" or "NPs." Note that a noun phrase can be used not only as the subject of a sentence, but also as an object: "I want (those dogs)."

The noun phrase thus seems to be a useful description of a variety of word combinations that can be found in different locations in sentences. Note that there are constraints on what can and cannot be found in noun phrases that renders *them want,* which contains a verb, ungrammatical. Likewise, in English, only some word orders are allowed: *shaggy those dogs* is not an acceptable NP.

All these example sentences have the structure [NP V NP] (where V stands for verb). Other types of sentences are possible:

The child slept.
The child slept in the hammock
The child slept in the afternoon.

These sentences lack an object, ending either with a verb or an optional phrase that indicates where or when the sleeping event took place. Their structure is [NP V location-phrase] or [NP V time-phrase]. The location and time phrases that begin with a preposition are prepositional phrases, or PPs. The sequences [V NP], [V], and [V PP] are all types of "verb phrases" (VPs).

We thus can find structures that have important, stable properties in different sentences and in different parts of the same sentence. At another level of representation, then, we can characterize sentences (S) as being built up from basic structures like [NP VP]. In turn, NP and VP are built from strings of other categories, which in turn are abstractions for large numbers of individual words. (For more on phrase structure, see e.g. Sells 1985.)

Although the form of the two PP-containing sentences just displayed is the same, there is an obvious difference in meaning between descriptions of location and of time. Locations are interesting linguistically not only because there are so many ways to express the concept but also because there are situations where they must be mentioned in order for a sentence to be grammatical. Consider the following examples.

The shaggy dog put the newspaper into the hammock.
*The shaggy dog put the newspaper.
*The shaggy dog put into the hammock.

Only the first sentence is grammatical. (By convention, ungrammatical sentences are prefixed with an asterisk.) A verb such as *put* requires both an object ("patient") to be placed and a location (or "goal") where it will be placed. In the first sentence, *the newspaper* plays the role of patient while *the hammock* plays the role of goal. *The shaggy dog is* the "agent" who performs the act of putting. Agent, patient, and goal are the three "thematic roles" that are required in a clause where the main verb is *put;* thus, *put* is said to "assign" three thematic roles to the NPs in its clause. In contrast, a verb like *want* assigns only two thematic roles, and *sleep* just one. Information about how many and what thematic roles a verb assigns is referred to as the verb's "argument structure" or "subcategorization requirements" (Sells 1985).

One might assume a hard-wired, one-to-one mapping between a thematic role and particular grammatical category - so that, for example, the agent is mapped to the subject, the patient to the object, and the goal to a prepositional phrase. However, while this might be a canonical mapping, it is not always the case.

John gave the bone to the dog.

subject	object	oblique
agent	patient	goal

John gave the dog the bone.

subject	object	object2
agent	goal	patient

The dog was given the bone by John.

subject	object	oblique
goal	patient	agent

Thus, for example, a verb like *give* requires that a goal be present, but that goal can be expressed as a subject, an object, or the object of a preposition (here, "oblique" - a term we use loosely for an argument, required by a verb, that is neither subject nor object). In fact, rather than being hard-coded, verb argument structure seems to be sensitive to the existence of form-meaning pairings known as "constructions." For instance, the caused-motion construction described by Goldberg (1995) pairs the [NP V NP PP] structure with a meaning in which the subject (referred to by the first NP) causes the object (referred to in the second NP) to move to the place described in the PP.

He sneezed his napkin off the table.

subject	object	oblique
agent	patient	goal

In this example, the man sneezes and causes the napkin to fall off the table. As a so-called intransitive verb, *sneeze* does not normally take a direct object. However, when it participates in the caused-motion construction, it adopts the argument structure of that construction.

The preceding discussion of thematic roles suggested that roles are assigned to the NPs involved. However, they are actually best viewed as mappings from NPs in a sentence to the discourse entities that are the basic units of a "referential" or "message-level" representation. Referential structure is a level of conceptual organization between the situation being described and the linguistic structures that describe it (Langacker 1987). For example, Fauconnier (1994) demonstrated the utility of "mental spaces" as organizational features of referential structure. In Fauconnier's model, a mental space contains a partial representation of the current scenario, including one or more elements and frames that represent relationships among the different discourse entities. Complex scenarios can be represented by positing a number of mental spaces interconnected in various ways.

With all factors taken into consideration, the task of language comprehension involves combining linguistic and nonlinguistic information to construct a message-level representation. Although it is still unclear how much the various aspects of language processing interact, the overall process can be thought of as comprising a number of different subprocesses. The speech stream is decoded into words and other representations (such as morphemes) that can be used in the interpretive process. Parsing involves the assignment of hierarchical structure to the input. Using phonological, morphological, and constructional information, speakers group words into phrases and sentences. Meaning construction is the coordination of linguistic and nonlinguistic information necessary to complete the representation of the discourse event.

Language production involves many of the same computations, albeit in a different order. Here, the speaker's task begins with a message-level representation and ends with the execution of a motor command. Given a message that she would like to evoke, the speaker must choose which words and constructions are most likely to prompt listeners to adopt the desired conceptualization. Moreover, in real time, the speaker must transform these abstract lexical and constructional representations into articulatory commands.

Psychophysiological methods have been used to study language representations and processes at nearly all levels of analysis. Successfully using physiological measures to explore language functions crucially requires that both the right method and the right experimental design be employed to investigate the question of interest. In the remainder of this chapter we describe the types of measures and designs that have been used to study language, as well as the conclusions that have been drawn. We begin with language comprehension, first at the level of the word and then with successively larger units. We then examine language production and studies of brain-damaged individuals. We conclude with a discussion of where psychophysiological approaches to the study of language have brought us - and what remains to be explored.

Inferential Context

FIRST, THERE WAS THE WORD

Until recently, the majority of psychophysiological investigations of language processing have focused on the level of the word. Although there is still considerable debate amongst linguists as to what constitutes a word, we use the term here in its lay sense. Psychophysiological methods have been aimed at better specifying the features of a word, the organization of different kinds of information associated with a word, and the influences on word processing. One proposal is that information about words is represented in a mental dictionary, or "lexicon." This lexicon is thought to contain both low-level phonological and orthographic information and higher-level information such as a word's meaning and its syntactic category. On the standard model, recognizing a word activates the information represented in the lexicon in a process known as "lexical access." This information, in turn, is used to combine the meanings of words into phrases and the meanings of phrases into sentences.

Because information about words is so clearly important for language processing, much psychophysiological research on language has addressed how words are recognized. Event-related potentials provide a continuous, real-time measure of neural processing that is potentially sensitive to qualitatively different kinds of information. Therefore, language researchers have employed this technique to uncover the time at which different types of information about words become available. The first issues we consider are how, where, and when the brain is able to distinguish between sensory input that is treated as language and other sorts of perceptual information. Next, we consider how factors such as global frequency in the language and local frequency in the experimental setting affect the ERPs elicited by words. Finally, we review the literature on the sensitivity of ERPs to linguistic factors such as lexical word class and word meaning.

Lexical versus Perceptual Processing of Word Forms

Does the processing of words differ significantly from the processing of other perceptual forms? If so, when and where in the perceptual stream are recognition processes specific to words first evident? Because, at one level, written words are merely overlearned visual patterns with meaning, we might expect them to be processed similarly to pictures and other kinds of iconic representations. However, at other levels of analysis, words and pictures are quite different and must be differentiated.

Schendan, Ganis, and Kutas (1998) examined the time course of visual classification by comparing the ERPs to objectlike stimuli (real objects, pseudo-objects that were scrambled versions of real objects, and strings of familiar icons) and wordlike stimuli (words, random letter strings, and a pseudo-font). Regardless of task, at about 95 msec an occipital negativity (N100) distinguished responses to single objectlike stimuli (objects and pseudo-objects) from responses to strings (icon, pseudo-font, random-letter strings, and words). This effect was followed in 10 msec by a further distinction between strings composed of real letters (words and random-letter strings) and nonletters (pseudo-font and icon strings). Thus, in the scalp-recorded ERP, the first sign of specialized processing of letter strings appears at around 105 msec. About 100 msec later, words can be discriminated from random-letter strings; by 250 msec, the ERPs to all stimuli are clearly differentiable from each other (see Figure 2). Overall, the latencies of these ERPs from the human scalp reveal a hierarchy in which visual responses become increasingly selective for classes of visual stimuli over time.

Studies using neuroimaging techniques with high spatial resolution have provided some indications of which brain areas are involved in the processing of words and pictures. As would be predicted from the ERP results, visual areas believed to be early in the visual processing stream show very similar blood flow responses for word and picture stimuli. Differential responses are observed, however, in brain areas further downstream. Left medial extrastriate regions, for example, become active for words and pseudowords but not for nonwords or false fonts (Petersen & Fiez 1993). Further, pictures selectively activate the right middle occipital gyrus, whereas words selectively activate left inferior parietal areas (Vandenberghe et al. 1996).

Similar findings have been reported for the auditory modality. For example, ERPs to meaningful and nonsense words are very similar within the first 150 msec (Novick, Lovrich, & Vaughan 1985), but they begin to diverge by 200-250 msec after stimulus presentation. Findings via PET suggest that activity early in the auditory processing stream - primary auditory cortex and posterior temporal areas - are unlikely to be language-specific. In contrast, responses in and around Wernicke's area seem more specific for words and for tasks requiring phonological processing, such as judging whether two words rhyme (Liotti, Gay, & Fox 1994). Hence, across modalities and methods, observations support the idea that processing of words and other perceptual stimuli diverges within about 200 msec and that this differentiation occurs in secondary perceptual processing areas of the brain.

Frequency, Repetition, and Semantic Variables

Once words have been categorized by the perceptual system, other factors known to play a role in language processing begin to affect the brain's response to them. In fact, around the time that the processing of words and other perceptual stimuli diverges, effects of word frequency are observed. These effects relate to the word's overall

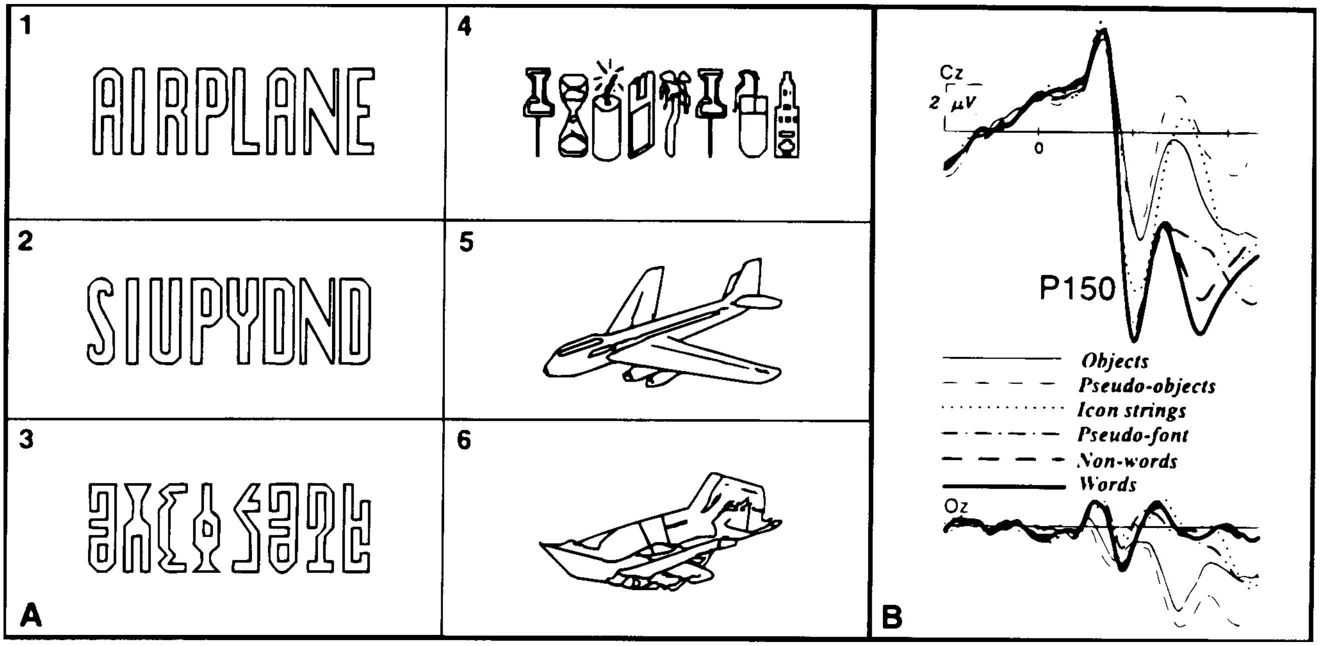


Figure 2. Sample stimuli including words (1), nonwords (2), pseudofont (3), icon strings (4), objects (5), and pseudo-objects (6) and the associated grand average ERPs from a midline central (Cz) and a midline occipital (Oz) electrode site. Note that the P150 is large and equal for words, nonwords and the pseudofont, small and equal for objects and pseudo-objects, and intermediate for icon strings. Negativity is plotted upward on this and all subsequent figures depicting ERPs. Reprinted with permission from Schendan, Ganis, & Kutas, "Neuropsychological evidence for visual perceptual organization of words and faces by 150 ms," *Psychophysiology*, vol. 35, pp. 240-51. Copyright 1998 Cambridge University Press.

frequency in the language as well as the frequency of its occurrence in the experimental situation (i.e. repetition). Between 200 and 400 msec, the ERP to written words shows a sensitivity to the eliciting word's frequency of occurrence in the language (King & Kutas 1998). The highest correlation is shown by the latency of a left anterior negativity, referred to as the lexical processing negativity (LPN); this subsumes the so-called N280 component (Neville, Mills, & Lawson 1992). See Figure 3.

For words occurring in a list rather than in sentences, frequency is also reflected in the amplitude of a negativity with a posterior, slightly right-hemisphere amplitude bias known as N400 (for a review see Kutas & Van Petten 1994). This negativity characterizes the response to any letter string that is orthographically legal and pronounceable. In other words, words and pseudowords elicit an N400 whereas nonwords do not. For real words, the amplitude of the N400 is an inverse function of the word's eliciting frequency, all other factors held constant (Figure 4).

The N400 amplitude is also quite sensitive to repetition (for reviews see Mitchell, Andrews, & Ward 1993; Van Petten et al. 1991). For example, repeating nouns in a list or in text yields a smaller-amplitude N400 on the second as opposed to first presentation - see Figure 4. Such repetition effects occur both within and across the visual and auditory modalities. The N400 repetition effect is also sensitive to the lag between occurrences of the word, the reduction being largest for immediate repetitions.

Another repetition-sensitive component of the ERP is a late positivity (hereafter LPC). In list presentations, the LPC is larger for the second than the first presentation of a word and is specific to low-frequency words (Rugg 1990). There also are some reports of a repetition effect preceding the N400, in the latency range of the P2 (200-250 msec, primarily frontal; Rugg 1987). However, this early effect

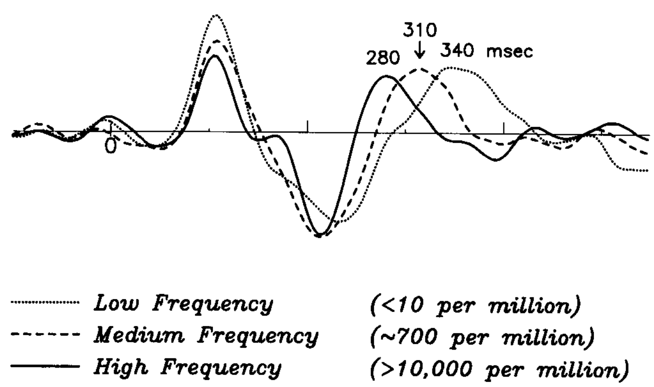


Figure 3. Grand average ERPs from a left anterior site overlying Broca's area in response to words presented one at a time in sentences read for comprehension. Overlapped are three ERPs to words (of both open and closed class) sorted as a function of their frequency of occurrence in the English language and digitally high-pass-filtered at 4 Hz. Note the latency of the negative peak (known as the lexical processing negativity or LPN) is longest for low-frequency words, shortest for high-frequency words, and intermediate in latency for words that are intermediate in frequency.

has been ephemeral - present in some studies but absent in other apparently similar experimental designs, and not always in the same direction (for review, see Van Petten et al. 1991).

During the 200-400-msec time range in which the ERP becomes sensitive to word frequency and repetition, effects of lexical class (open versus closed class) appear. Words with significant semantic content such as nouns and verbs are called "open class" words, while words with more relational content such as determiners and prepositions are called "closed class" or "function" words. Languages tend to have a finite set of closed-class words that remains relatively constant over time; English has had approximately the same 200-300 function words for hundreds of years. In contrast, as knowledge and technology changes, new nouns and verbs are regularly added to the open class (e.g., *motherboard, faxing, camcorder, internet).*

The LPN is sensitive to word frequency, irrespective of word class. Thus, two words with the same frequency in the language elicit LPNs with the same latency even if one is an open-class and the other a closed-class word. In contrast, later components in the ERP are sensitive to lexical class. For example, closed-class words typically elicit much smaller N400s than open-class words, except under particular circumstances where the closed-class word is less expected than usual (King & Kutas 1995; Kluender & Kutas 1993a).

The ERP is also sensitive to further lexical subdivisions within open-class words, such as between nouns and verbs. Koenig and Lehmann (1996) reported ERP laterality differences between nouns and verbs in a list as early as 120 msec, and Brown, Lehmann, and Marsh (1980) likewise noted distributional differences between them beginning about 300 msec after word onset. The latter study used noun-verb homophones (e.g. *fire), so* the processing difference occurred when the same perceptual forms were interpreted either as a noun or as a verb. Differentiations within the category of nouns have also been described. Concrete nouns - those depicting a tangible, often pictureable, entity - elicit larger N400s than do abstract nouns depicting an entity that is not readily pictureable (e.g. *honor)* (Kounios & Holcomb 1994).

The N400 amplitude thus varies with lexical and lexical-semantic factors. As we shall see shortly, N400 amplitude is also sensitive to the semantic relations between words in isolation and within sentences. The results of intracranial recording studies, performed on patients undergoing testing prior to surgery for temporal lobe epilepsy, have suggested that at least some of the activity recorded at the surface in the N400 time window derives from medial temporal lobe structures (Nobre & McCarthy 1995). And PET studies of semantic processing (e.g. Vandenberghe et al. 1996) have described activations in medial temporal lobe areas that are consistent with their proposed involvement in lexical and semantic processing.

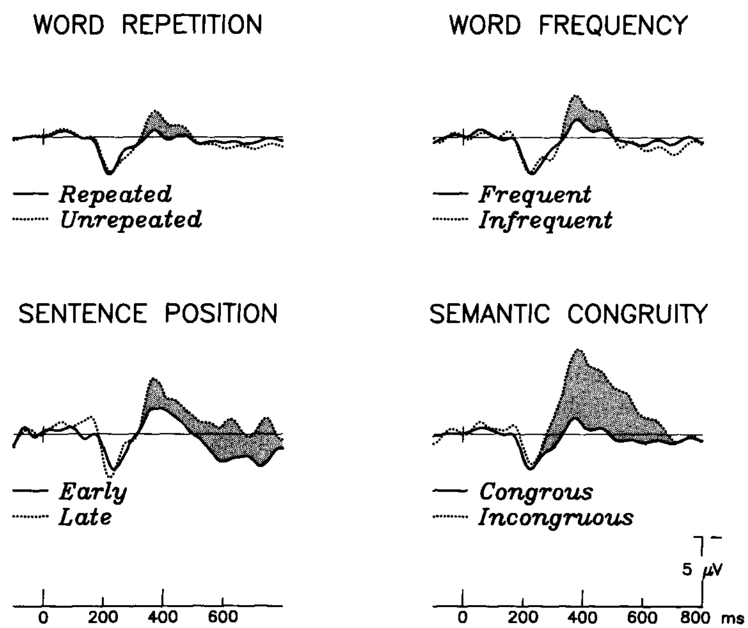


Figure 4. Shown are a sample of N400 effects at a midline parietal recording site averaged across subjects and sentences. *Top left*. Word repetition effect, reflecting the reduction in N400 amplitude with repetition in sentence contexts. *Top right*. Word frequency effect, reflecting the reduction in N400 amplitude with increasing word frequency. *Bottom left*. Sentence position effect, reflecting that - in congruent, declarative sentences - open-class words early in the sentence have larger N400s than those later in the sentence. *Bottom right*. Semantic congruity effect, reflecting the large N400s to semantically incongruous endings.

TWO OF A KIND: PROCESSING OF WORD PAIRS

As previously noted, much language research is predicated on the existence of a mental lexicon and thus is aimed at determining its internal organization. Toward this end, a large number of studies have contrasted the responses to pairs of words that systematically vary along some dimension (orthography, phonology, morphology, semantics) as participants make some decision about them. These studies, only some of which are reviewed here, ask: (1) what features constitute a lexical entry, (2) how words with multiple meanings are represented and accessed (e.g. Van Petten & Kutas 1987); and (3) whether or not it makes sense to talk about an "amodal" representation of the meaning of a concept that can be accessed via written, spoken, and signed words (as well as via pictures).

Phonological and Morphological Relationships in Word Pairs

As interfaces between the perceptual form of a word and its lexical and semantic properties, orthographic and phonological information are important components of most models of the lexicon. Several ERP studies have shown that the influences of these cues can be observed in the N400 time window and beyond. For example, in rhyme judgment tasks, rhyming word pairs elicit a smaller negativity between 250 and 550 msec than do nonrhyming word pairs (Sanquist et al. 1980). When the rhyming pairs are orthographically dissimilar (e.g., *moose juice),* reduced N400s could be attributed to the phonemic similarity. However, when phonemic and orthographic similarity are crossed, Polich and colleagues (1983) found that both influence the amplitude of the N400, consistent with behavioral reports that orthography cannot be ignored during rhyme judgment (Seidenberg & Tanenhaus 1979). Rugg and Barrett (1987) further demonstrated that orthographic, and not just visual, similarity modulates N400 amplitude.

Morphological influences on word processing also have been observed in the ERP by about 250 msec. Morphological processing involves both the derivation of new words ("derivational morphology") and the marking of case, number, tense, and other word features ("inflectional morphology"). As it happens, for many subsystems of inflectional morphology, regular patterns (e.g., in English past tense: *stretch/stretched;* in English plurals: *friend/friends)* can be contrasted with irregular ones (e.g., *catch/caught; woman/women).* A current theoretical debate concerns whether or not the same computational algorithms and/or neural hardware can deal with the analyses of both regular and irregular word forms. Traditionally, our ability to generalize from regularities in the language to novel instances has been taken as evidence that rules of the sort described by linguists are stored in our brains. Proponents of this view contend that there are two distinct mechanisms for dealing with regular and irregular words: (i) a set of rules that are routinely applied to regular forms and to new words, and (ii) a memorized store of a few frequent, irregular forms (e.g. Prince & Pinker 1988). There are those, however, who have argued that a single, domain-general, associative mechanism - as in some connectionist models - can deal with, for instance, past tense formation or plural formation of both regular and irregular words (Plunkett & Marchman 1993). This is a highly controversial area of investigation to which a number of psychophysiological techniques have been summoned.

Because electrophysiological measures reflect subtle processing differences between different classes of stimuli, they are well suited for determining the extent to which regular and irregular word forms are differentially processed. Penke et al. (1997) examined the German past participle system, which is similar to the English past tense in having regular and irregular verbs but different in that all irregular verbs share the same suffix ("-n," with or without a vowel change in the stem). They employed a morphological violation paradigm wherein participants saw both regular and irregular participles with correct and incorrect suffixes. In three experiments, irregular verbs with the (incorrect) regular inflection elicited a left anterior negativity (LAN); violations of regular verbs showed no such activity. This same pattern of effects was observed for similar comparisons in the German plural system (Weyerts et al. 1997).

Weyerts and co-workers (1995) examined this same issue by comparing ERPs to past participles primed either by themselves (identical repetition) or by their respective infinitive (morphological repetition). For regular verbs, both identical and morphological repetitions showed a similarly sized enhanced positivity from about 250 msec. For irregular verbs, however, the morphological repetition effect was small and delayed relative to identity repetition. In short, various ERP analyses do point to processing differences between regular and irregular morphological forms in adults. Yet it remains an open question exactly how distinct the neural representations of the two are.

Semantic Relations

A number of reaction time and psychophysiological measures indicate that the processing of a single word is facilitated by the prior occurrence of a semantically related word. For instance, the word *cat* is easier to process if it is preceded by a word (such as *dog)* that bears a meaningful relationship to it. This facilitation, known as "semantic priming," is generally interpreted as indicative of the way in which lexical (word) representations are organized in our mental lexicon.

Electrophysiological signs of semantic relations between words have been investigated primarily using two tasks. In the lexical decision task (LDT), participants are asked to decide whether or not a letter string constitutes a real word (Bentin, McCarthy, & Wood 1985; Holcomb 1988). In the category membership verification task, participants indicate whether or not a word is a member of a particular category (Boddy & Weinberg 1981; Fischler et al. 1983; Heinze, Munte, & Kutas 1998; Neville et al. 1986).

In both these tasks, ERPs to semantically primed words are more positive between 200 and 500 msec than are those to unprimed words. The ERP difference is presumably the same N400 component discussed previously in the section on frequency and repetition effects (and to be discussed later with respect to semantic violations in sentences). Very similar effects obtain for written and spoken words - including cross-modally, when one of the words is spoken and the other is written - as well as when priming is by a line drawing, picture, or an environmental sound (Ganis, Kutas, & Sereno 1996; Van Petten & Rheinfelder 1995). The N400 effects in different modalities are similar in consisting of a monophasic negative wave between 200 and 600 msec, but they differ in overall amplitude, onset latency, and scalp distribution. For example, Holcomb and Neville (1990) found that - compared with visual priming - the auditory priming effect was larger, began 50-100 msec earlier, and was more pronounced over frontal and left hemisphere sites. Distributional differences notwithstanding, the reliability with which N400 amplitude is modulated by semantic relations has made it a useful metric for testing various hypotheses about language processing.

Among the more controversial issues in semantic priming literature has been the relative contribution of "automatic" and "attentional" processes to the observed response facilitation (e.g. Den Heyer, Briand, & Dannenbring 1983). This controversy grows out of the larger debate over the modularity of language abilities, with the assumption that modular processes are automatic. Thus, of some interest is the question of whether the N400 component of the ERP indexes automatic lexical (modular) processes or rather nonmodular, controlled effects. Studies examining N400 modulation - by factors such as the proportion of related and unrelated words (Chwilla, Brown, & Hagoort 1995; Holcomb 1988), the stimulus onset asynchrony (SOA) between the prime and target (Anderson & Holcomb 1995), the presence of a mask on the prime or target (Brown & Hagoort 1993; Neville, Pratarelli, & Forster 1989), and subjects' attentional stance with respect to various aspects of the experimental design (Bentin, Kutas, & Hillyard 1995; Gunter et al. 1994; McCarthy & Nobre 1993; Otten, Rugg, & Doyle 1993) - suggest that the N400 in fact indexes processing that is neither completely automatic nor completely controlled.

SENTENCE COMPREHENSION

Even though the psychology of words seems a rich enough field to absorb all of our language research effort for years to come, analyses at the word level alone will not suffice to explain how we derive meaning from language. Many aspects of words themselves are very difficult to understand without appealing to the sentence- or text-level phenomena with which they interact.

Semantic Context in Sentences

Much of the research employing sentences focuses on the response to a particular word that either fits or does not fit with the sentence's meaning or structure. For example, studies using eye movement protocols typically embed words of interest into connected prose and measure eye movement variables on the target word. These variables include the duration of fixation (initial, or total) as well as number of fixations (i.e., if and how often a word is fixated or refixated). Many of these studies test hypotheses about the modularity of language processes such as lexical access. Word forms (either phonological or orthographic) are often associated with more than one meaning (e.g., *bank* - a money-lending institution or the land flanking a river). Controversy surrounds proposals as to how the different meanings for these ambiguous forms are accessed and the extent to which this lexical access is open to contextual modification.

To address these issues, researchers have compared eye movements to ambiguous and unambiguous words in sentence contexts designed to bias interpretation of the ambiguous word toward one of its several meanings. Ambiguous homographs may be either "biased," where one of the meanings for the word is much more frequent, or "unbiased," where the frequency of occurrence of the multiple meanings is essentially the same. Pacht and Rayner (1993) found in neutral contexts that readers fixated longer on balanced than on biased homographs, suggesting an increased processing load for determining the meaning of an ambiguous word when neither frequency nor context provided clues. However, in biasing contexts (with the bias always toward the subordinate meaning), readers read balanced homographs as quickly as unambiguous controls but fixated on biased homographs for a longer duration. Pacht and Rayner (1993) and subsequently Sereno (1995) suggested that these results from eye movement studies support a "reordered access model" for the processing of ambiguous words in which all meanings of an ambiguous word are accessed independent of context but in an order that is contextually controlled (see Van Petten and Kutas 1987 for an electrophysiological study of homographs).

The processing of words in sentences and their influence by semantic and syntactic constraints has also been extensively studied with ERPs. For instance, Kutas and Hillyard (1980) reported that a semantically anomalous word at the end of a sentence elicits a large negativity peaking around 400 msec (N400) (Figure 4). A similar N400 effect is observed for semantic anomalies in written, spoken, and signed language. Subsequent research has shown that N400 elicitation is not specific to semantic violations and that its amplitude for words in a sentence reflects finer gradations of the semantic constraints placed on that word (for review see Kutas & Van Petten 1994).

In fact, N400 amplitude and the "cloze" probability of a word (i.e., what proportion of subjects will fill in a particular word as being the most likely completion of a sentence fragment; Taylor 1953) are inversely correlated at a level above 90%. In this context, it is important to note the distinction between the cloze probability of a terminal word and the contextual constraint of a sentence fragment per se. For example, "The paint turned out to be the wrong ... " is of high contextual constraint in that most people will fill in color, whereas "He was soothed by the gentle ... " is of low contextual constraint because there are a number of acceptable endings, none of which is clearly preferred over the others (Bloom & Fischler 1980). But both fragments can be completed by words of equal (low) cloze probability, as in, "The paint turned out to be the wrong shade" and "He was soothed by the gentle wind." Crossing several levels of contextual constraint with several levels of cloze probability revealed that N400 amplitude is specifically correlated with the doze probability of the final word and not with the contextual constraint of the preceding sentence fragment (Kutas & Hillyard 1984; Kutas, Lindamood, & Hillyard 1984). This result was critical in establishing that N400 amplitude does not index the violation of previously established expectancies for a particular word that was not presented; rather, it is sensitive to the degree to which the sentence fragment prepares the way for the word that actually follows.

This effect of contextual constraint on the N400 is also seen in the ERPs to open-class words averaged according to sentence position (Figure 4); the amplitude of the N400 decreases monotonically with a word's ordinal position (Van Petten & Kutas 1991). The observation that this decrement did not occur in random word strings of equal length was taken as evidence that it was due to a sentence-level factor. Semantic context is also capable of eliminating the N400 frequency effect; thus, the effect of larger N400s to low- than high-frequency words observed early in a sentence is absent near the end of a sentence (when N400 amplitudes are equal). This interaction is not apparent in either random word strings or syntactically legal but semantically anomalous sentences, so it seems to be due to semantic factors (Van Petten & Kutas 1990, 1991).

Contrasts of lexical-associative semantic relationships and sentence-level semantic relationships indicate that both independently influence N400 amplitude (Kutas 1993; Van Petten 1995; Van Petten & Kutas 1991; see also Fischler et al. 1985 for a similar conclusion) and interact with comprehension skill (Van Petten et al. 1997). The N400 is thus sensitive to relationships between (i) a word and its immediate sentential context and (ii) a word and other words in the lexicon. Federmeier and Kutas (1999) examined this feature in a study where participants were asked to read pairs of sentences leading to an expectation for a particular item in a particular semantic category.

Ann wanted to treat her foreign guests to an all-American dessert.
So she went out in the back yard and picked some apples.

These sentence pairs were terminated with either the expected item *(apples),* an unexpected item from the expected category (another fruit - e.g. *oranges),* or an unexpected item from a different semantic category (e.g. *carrots).* Both types of unexpected endings elicited an N400 relative to congruent endings. However, even though both kinds of unexpected endings had the same cloze probabilities and were rated as equally implausible, the unexpected item from the expected category had a smaller N400 than did the one from a different category. The extent of this reduction correlated with sentential constraint - that is, how much the expected item was expected. These results suggest that the N400 is sensitive to the organization of background knowledge as well as to the relationship between words and sentence contexts. More generally, the findings suggest that on-line comprehension processes utilize background semantic knowledge to make sense of sentences.

Syntactic Manipulations

The influence of structural aspects of language is studied in a subfield of psycholinguistics called sentence processing. Psychophysiological approaches to these phenomena have only recently become more common. We begin by describing investigations of subsentence units such as phrases and clauses. We then examine work done at the sentence level, including studies of syntactic violations and ambiguities and argument structure violations.

There has been relatively little work done directly on the psychophysiological correlates of the processing of phrases, especially noun phrases. In fairness, this dearth of research parallels that seen in the behavioral psycholinguistics literature (but see Murphy 1990). (Related, but conceptually distinct, is work in so-called modifier attachment ambiguities, discussed shortly.) Typical of the studies that indirectly address these issues is Neville et al. (1991), where one condition contrasted sentences that had normal phrase structure with those that had the following kind of phrase structure violation.

The scientist criticized Max's proof of the theorem.
*The scientist criticized Max's of proof the theorem.

Loosely speaking, a possessive NP like *Max's* acts like a definite article when it occurs in the context of another NP (here, the expected object of *criticized).* In a typical NP, a definite article is followed by either an adjective or a noun; since *of* is a preposition, this can be viewed as a violation of phrase structure. In this case, this violation was indexed by a brief enhancement of the negativity at left anterior electrode sites followed by a large, widespread positivity that is frequently observed in response to syntactic violations of many kinds.

The Neville et al. (1991) paper illustrates a key difficulty of using the violation approach to investigate phrase structure: generating a phrase structure violation at one point often causes phrase structure violations at other points and very possibly violations of other grammatical principles as well. Thus in the second sentence, *of* should begin a prepositional phrase (PP). The structure of a PP dictates that a preposition be followed by an NP, so *proof* should begin an NP. But this is not the case - one cannot say either "*Max corrected proof" or ""Max corrected proof of the theorem." Similarly, *the theorem* in the second sentence violates the entire VP because the verb *criticized* requires one and only one argument NP and *the theorem* is the second. Neville et al. (1991) focused on "Max's of proof" as an ungrammatical NP and did not discuss what effects these subsequent phrase structure errors had on the recorded ERPs.

Clauses are units larger than phrases. For example, in "The sentences that have been discussed previously

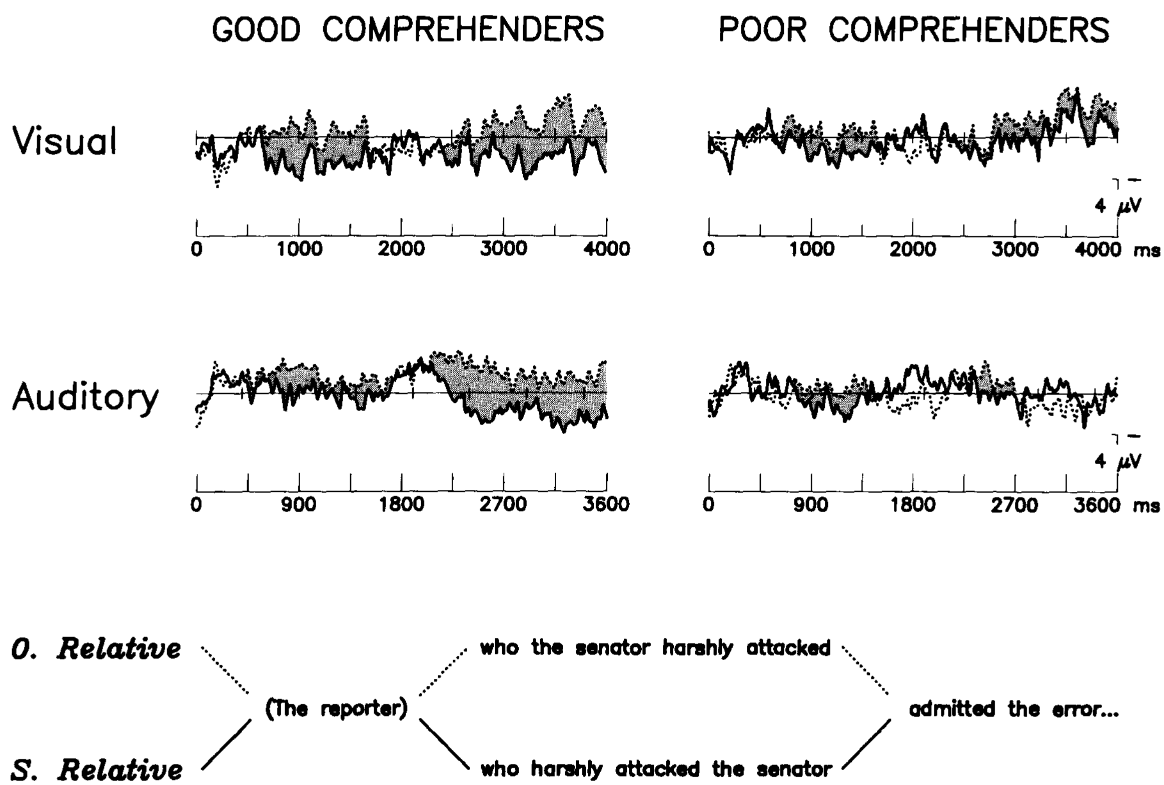


Figure 5. Comparison of grand average ERPs to subject-relative (solid line) and object-relative (dotted line) sentences from a left anterior site in good and poor comprehenders. The visual sentences were presented one word every 500 msec, whereas the auditory sentences were presented as natural speech. Note that the two sentence types are equivalent both prior to and after the relative clause. The shading represents the area where object-relative sentences are reliably more negative than subject-relative sentences. The visual data are taken from King & Kutas (1995), the auditory data from Mueller, King, & Kutas (1997). Reprinted by permission of the authors.

contained no relative clauses," the subject of the sentence has been modified by a relative clause ("that have been discussed previously"). Conventionally, relative clauses are analyzed as sentences missing one of their NPs - in this case, the object of the verb *discussed.* Since this relative clause is missing its object, it is called an "object relative clause." Sentences like these are known to be more difficult to process than many other sentence types, including others containing relative clauses. Object relatives are particularly difficult to comprehend when the NPs in the main and relative clauses both refer to human, animate actors. Consider the following examples.

Object Relative
The reporter who the senator attacked admitted the error.

Subject Relative
The reporter who attacked the senator admitted the error.

Figuring out who did what to whom is more difficult in an object-relative sentence like the first one than in a so-called subject-relative sentence like the second, whether difficulty is measured using gaze duration (Holmes & O'Regan 1981), word-by-word reading times (King & Just 1991), or pupillary diameter (Just & Carpenter 1993). Based on these measures, the point of greatest difficulty is located at the end of the object-relative clause, when it is necessary to assign thematic roles to the actors involved.

Part of the difficulty involved in parsing these kinds of structures may be related to load they place on working memory (WM). Information provided earlier in the sentence must be maintained over time in order to determine the identity of the "missing" NP. In fact, the need to maintain information over multiple words is a general property of sentence processing. The earliest emphasis on WM constraints in sentence processing focused on the possibility that limited capacity could lead to parsing failures for otherwise grammatical constructions (Miller & Chomsky 1963). Even when parsing does not fail altogether, however, "subcritical" loads can affect the time course and nature of parsing and interact with reading ability (Just & Carpenter 1992).

Relative clauses provide a controlled way to study working memory and other factors in sentence processing because they differ in complexity despite a close similarity in structure. Moreover, without being ungrammatical, they offer opportunities for making comparisons at multiple time points during processing. Results for English versions of these sentences in both the visual and auditory modality are summarized in Figure 5. These ERPs are the brain responses at a left frontal electrode site elicited by the words throughout relative clauses when read one word at a time (King & Kutas 1995) or heard as natural speech (Mueller, King, & Kutas 1997). As can be seen, the electrophysiological differences are present for good comprehenders and absent for poor comprehenders in both modalities. Although the largest difference between the two sentence types does occur near the end of the relative clause, there is an earlier negativity (left anterior over all scalp sites) that begins as soon as the second NP is encountered in the object-relative clause. This effect has been hypothesized to index the temporary storage of NP-related material in working memory (King & Kutas 1995) and is similar to effects noted in related sentence types by Kluender and Kutas (1993a,b). The later effect in these data may be of similar origin (WM operations required to perform thematic role assignments) or more directly related to the sentence processing task.

Although these relative clause types are unambiguous in English, in German they can be made to be ambiguous until the final word of the clause (Mecklinger et al. 1995). When this is the case, readers appear to expect the more frequent (subject-relative) structure, and a late positivity similar to that seen in response to patently ungrammatical stimuli is elicited by the less frequent object-relative structure. Moreover, if readers are given contextual cues that can be used to generate specific expectancies for a clause type then they appear to do so, as reflected in modulations of the amplitude of the late positivity (Ferstl & Friederici 1997).

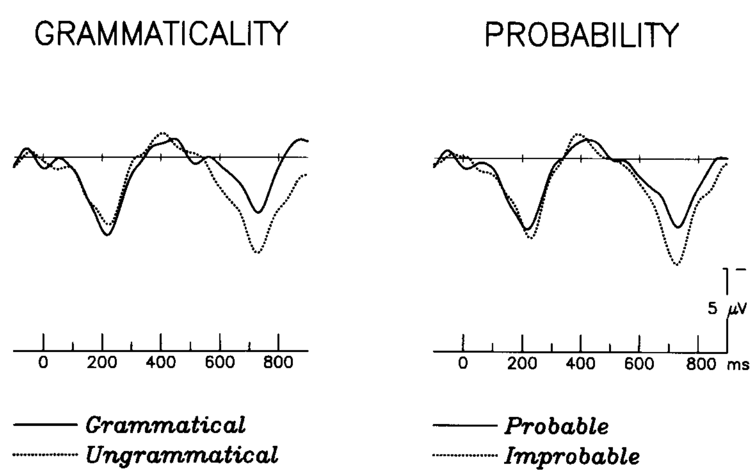
Irrespective of clause type, clause boundaries are critical junctures for the study of sentence processing. Eye movement data have revealed that extra processing occurs at these points (Just & Carpenter 1980), while studies using skin conductance responses have suggested that active syntactic processes may be "wrapped up" or relaxed at clause boundaries (Bever, Kirk, & Lackner 1969). There are also clear clause-ending effects in ERP data in both the visual and auditory modalities; these take the form of fronto-central negativities that are larger and more marked over the left than the right hemisphere (Kutas & King 1996; Mueller et al. 1997). These clause-ending negativities (CENs) are different from most of the ERP effects discussed previously in that they do not appear to be just another component of the response to a single word; rather, they are one of several slow brain potential effects that occur during sentence processing.

One brain potential that has played an important role in the study of syntactic and morphosyntactic processing is the P600, sometimes called the syntactic positive shift (SPS). This slow positive shift has been described in several studies (Coulson, King, & Kutas 1998; Hagoort, Brown, & Groothusen 1993; Neville et al. 1991; Osterhout & Holcomb 1992) examining a range of phenomena - including agreement, phrase structure, subcategorization, and subjacency - in three languages (English, German, and Dutch). Although the nature of the P600 component has not been wholly consistent across studies, it is typically described as beginning around 500 msec and having its midpoint around 600 msec. Its distribution is most often posterior, although anterior effects have also been reported. The P600 component is sometimes preceded by a negativity over left anterior sites.

The P600 has been observed in response to a host of morphosyntactic and syntactic violations, including relatively "local" agreement like subject-verb agreement (Coulson et al. 1998; Hagoort et al. 1993) and pronoun agreement (Coulson et al. 1998). Using Dutch stimuli in which sentential subjects agreed or failed to agree with their verbs, Hagoort and colleagues (1993) observed an SPS (P600), beginning after 500 msec and largest over parietal scalp sites, to the violations. Coulson et al. (1998) likewise observed a P600 to violations of subject-verb agreement ("Every Monday he *mow the lawn) and pronoun agreement ("The plane took `we to paradise and back") in English. However, they found that its amplitude varied with the probability of ungrammatical trials within an experimental block. In fact, the P600 to all improbable trials (collapsed across grammaticality) was indistinguishable from that to all grammatical violations (collapsed across probability) - see Figure 6. These effects of grammaticality and probability were nonadditive, implying overlapping neural generators. Thus, Coulson et al. (1998) argue that the P600 is not a syntactic-specific component but rather a variant of a domain-general component known as P36, which has been hypothesized to reflect "context updating" (Donchin & Coles 1988).

In addition to indexing local relationships, the P600 has also been observed in response to more global syntactic violations. Both Neville et al. (1991) and Osterhout and

Figure 6. Grand average ERPs to midsentence critical items at a right parietal electrode site. The left half shows a larger late positive wave (P600) to ungrammatical than grammatical continuations of a sentence frame. The right half shows a similar larger late positivity when the continuation, regardless of its grammaticality, was improbable (20%) within that experimental block. Data are from Coulson, King, & Kutas (1998).



Holcomb (1992) describe a slow positive shift between 500 and 700 msec to violations of phrase structure in English (e.g., "The broker hoped to sell the stock *was sent to jail"), albeit with different scalp distributions. Hagoort et al. (1993) observed a broadly distributed positivity beginning about 100 msec in response to phrase structure violations in Dutch sentences. Subjacency violations have also been reported to elicit broadly distributed P600 effects beginning after 700 msec (Neville et al. 1991). Finally, Osterhout and Holcomb (1992) reported a posterior P600 effect between 600 and 900 msec to subcategorization violations, an effect that others have failed to observe (Hagoort et al. 1993; Rosler et al. 1993).

In summary, the diversity of the time course and distribution of the ERP potentials labeled P600 or SPS makes it difficult to determine what this component is - if, indeed, it is a single phenomenon. The work by Coulson and colleagues (1998) further suggests that at least the component observed for morphosyntactic violations may not be just a "syntax ERP." However, that a positivity or family of positivities is observed to most syntactic violations at a number of levels provides a convenient tool for testing hypotheses about grammatical processing.

Parsing, as discussed in the introduction, includes the assignment of phrase and argument structure to parts of a sentence. In some cases, however, this assignment can be ambiguous. For example, on hearing "After Joan kicked the ball ... " it is unclear whether *ball is* an argument of *kicked* ("After Joan kicked the ball, her brother became angry") or the subject of a new clause ("After Joan kicked, the ball was passed to the other team"). These ambiguities offer an opportunity for examining how different aspects of sentence processing interact (or fail to interact). Can the initial assignment of structure be influenced by semantic context? Or do the assignment of form and the derivation of meaning take place in different modules?

Eye movement studies of reading have suggested that context does not affect a sentence's initial parse. Rather, it appears that a single interpretation is automatically assigned in cases of structural ambiguity. Note that this contrasts with eye movement results for lexical ambiguity, where all possible interpretations seem to be activated. These initial structural assignments, which some have argued are not influenced by linguistic context or world knowledge, may result in misparsings that can be detected by long fixations and/or regressive eye movements at the point in the sentence where the ambiguity is resolved (for a review see Rayner & Morris 1992).

Debate over the influences of context on syntactic processing, however, still looms large. These eye movement results from reading paradigms conflict with those from other paradigms showing that context and/or world knowledge can influence syntactic assignment. Tanenhaus et al. (1995) measured natural eye movements as individuals scanned objects while listening to simple commands. The assignment of ambiguous prepositions (e.g., whether *on* in "put the red box on the ... " modified *red box* or described the location of action) was significantly influenced by the set of items available for manipulation. Furthermore, ERP data suggest that at least some kinds of context can affect parsing during reading.

For example, Garnsey, Tanenhaus, and Chapman (1989) constructed stimulus sentences so that the presence or absence of an ERP violation response would answer the question of whether or not subjects use verb argument preferences as an on-line aid to sentence parsing. They used sentences with embedded questions to determine when subjects would assign a questioned item (i.e. filler) to a possible gap, as follows.

(a) The babysitter didn't know which door the child PUSHED ____ carelessly at the store.
(b) The babysitter didn't know which name the child PUSHED ____ carelessly at the store.
(c) The tour operator wondered which visitor the guide WALKED ____ briskly down the hall.
(d) The tour operator wondered which topic the guide WALKED ____ briskly down the hall.

Because *push* usually takes a direct object, a flexible parsing strategy based on verb argument preferences and an inflexible "first resort" strategy would both assign *door* and *name* to the first possible gap location after the verb. Either strategy would thus result in a semantic incongruity at *pushed* in (b), as indexed by a large N400 relative to the control sentence (a). However, the two strategies predict different outcomes when the verb does not preferentially take an object, as in (c) and (d). Strict adherence to a first-resort strategy would result in a large N400 following the verb *walked* in (d) but not in (c). On the other hand, if the parser were sensitive to verb argument preference then neither (c) nor (d) would be anomalous at the verb and no N400 effect would be observed; this is, indeed, what the results showed. The ERP findings thus suggest that parsing may be more flexible and context-sensitive than eye movement studies have suggested thus far.

The Syntax-Semantics Boundary: Thematic Role Assignment

Thematic role assignments are an integral part of parsing. However, thematic roles also tend to be correlated with semantic properties of words and constructions. This aspect of language processing is thus a good venue for examining the syntax-semantics interface and interactions between these two proposed levels. To date, few psychophysiological studies of thematic role assignment have been conducted.

Weckerly (1995) showed that ERPs are sensitive to the relationship between expected thematic roles and noun animacy. Sentence-initial NPs are likely to be agents in a variety of phrase structure types, and the agent role is usually associated with animate discourse participants. Hence it might be the case that, when an inanimate noun occurs in this position, it will be less expected owing to its mismatch with thematic expectations (even before the verb is encountered) and thus will generate a larger N400 response. This is what Weckerly (1995) observed, among other effects at different locations in object-relative constructions. The fact that readers are sensitive to possible animacy-role conflicts early in the sentence suggests that they are continually monitoring the word input stream for potentially useful information and attempting to construct higher-level structures as quickly as possible - even when lower-level structures are incomplete.

Referential Level Processing

Psychophysiological measures likewise have only rarely been used to study referential effects in sentence processing. However, since pronouns refer directly to discourse participants, the response to a pronoun in context can be used to index the success or failure of referential processing. There are syntactic constraints on the use of pronouns versus reflexive pronouns, and Osterhout and Mobley (1995) have investigated these in English. In an experiment where participants were explicitly judging sentence acceptability, violations of both the number and gender of a reflexive pronoun elicited a P600-like response.

Number Violation
The hungry guests helped themselves to the food.
The hungry guests helped *himself to the food.

Gender Violation
The successful woman congratulated herself on the promotion.
The successful woman congratulated *himself on the promotion.

In another experiment, Osterhout and Mobley (1995) compared the ERPs to pronouns that either matched or mismatched the subject noun in gender.

Matching
The aunt heard that she had won the lottery.

Nonmatcbing
The aunt heard that "he had won the lottery.

They found that the nonmatching pronouns elicited a larger P600 response, but only for those participants who judged such sentences unacceptable. Of course, these sentences are actually acceptable if no assumption is made that the pronoun refers to the subject NP. For participants who found such sentences acceptable, the ERPs to the nonmatching trials included a larger negativity over Wernicke's area as well as a broadly distributed and bilateral frontal negativity beginning approximately 200 msec after pronoun onset. Note that, in order to make sense of a nonmatching pronoun sentence without any other context, a reader must hypothesize the existence of an unmentioned discourse participant. The frontal negativity may thus index the processes required to add new elements to the existing message-level representation.

Support for this referential explanation of the frontal negativity comes from King and Kutas (1997), who examined the response to pronouns of both genders in sentence frames where the subject noun was an occupational title that was either more or less likely to be filled by a person of male or female gender.

The engineer redesigned the circuit because
he had detected a flaw.
?she

As one might expect, the paucity of female engineers in reality renders the version of this frame with *she* odd at first glance. Readers appear to treat the feminine pronoun here as referring to someone other than the engineer. The ERPs elicited by such "nonstereotypical" pronouns showed a large anterior negativity after about 200 msec (see Figure 7).

Although further work needs to be done using richer contexts, it appears that processes dependent on discourse reference can be systematically studied using on-line ERP data. In the cases just discussed, the recognition that a new discourse participant may have been mentioned forces a reorganization of the referential representation and possibly a shift in the frame or schema guiding comprehension. Coulson (1996) examined the process of frame shifting itself in greater detail using ERPs in a genre where the need for frame shifting is quite pronounced: the one-line joke. For example, in the following joke - "I let my accountant do my taxes because it saves time: Last year it saved me ten years" - the listener begins by setting up a message-level representation structured by a frame in which a busy professional pays an accountant to do his taxes. However, upon encountering *years* this interpretation is no longer tenable, and the reader is forced to map the existing message-level information into a new frame (i.e., to "frame shift"). By reinterpreting the word *time* as jail time, the reader can construct a revised interpretation in which a crooked businessman pays an accountant to conceal illegal financial dealings.

Coulson (1996) recorded ERPs as individuals read sentences that either ended as jokes and required frame shifting or ended with an equally unexpected but nonjoke ending. Although nonjoke endings were low-cloze (equivalent to the joke endings), they were chosen to be consistent with the contextually evoked frame. Jokes elicited greater-amplitude N400 than nonjokes, suggesting that the nonjoke endings were easier to integrate into the established context than were the joke endings. Results thus suggest that frame-based retrieval of background knowledge plays an important role in sentential integration.

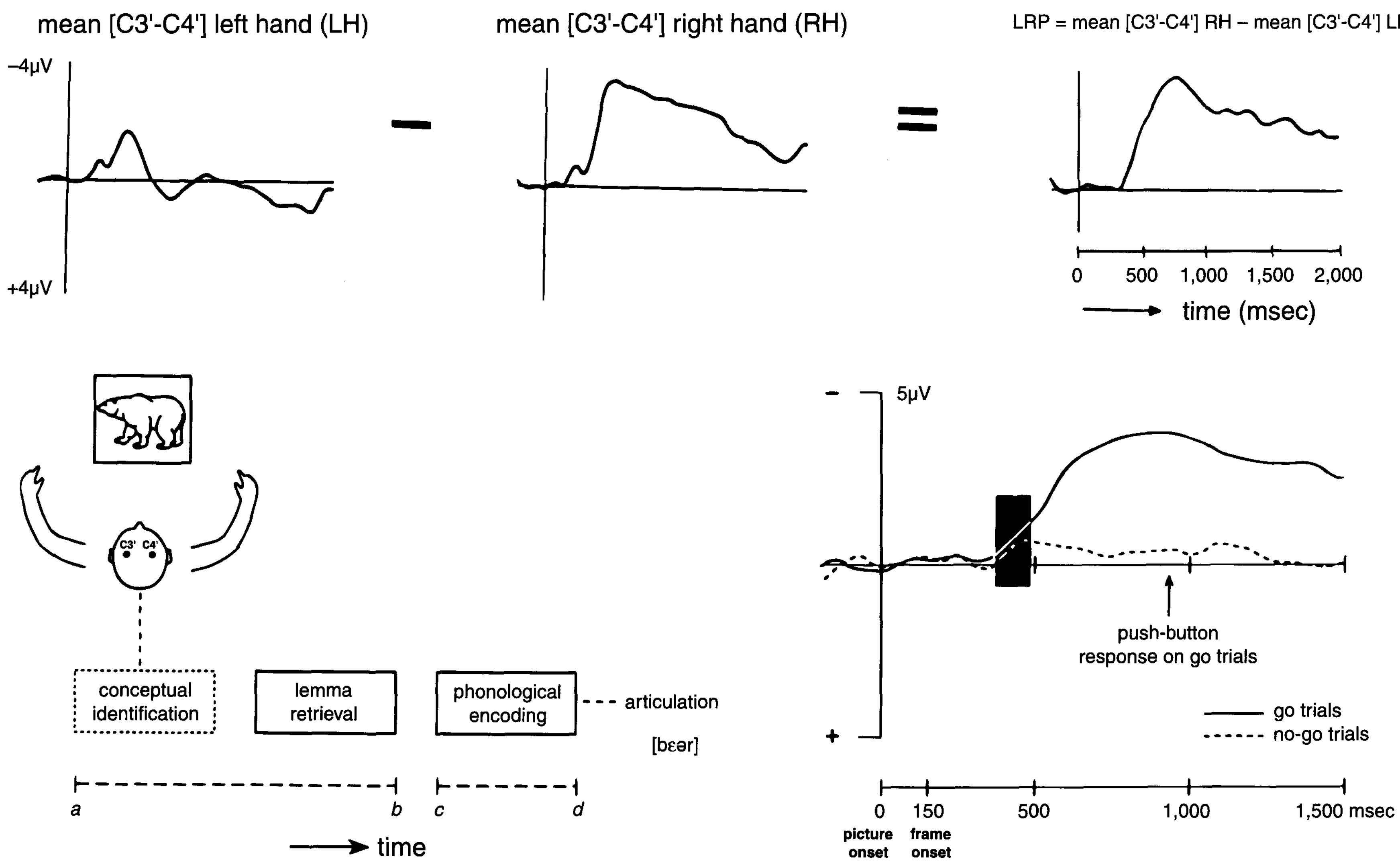


Figure 8. Lateralized readiness potentials (LRPs) during word production. Subjects performed a two-choice reaction time task while viewing pictures of objects and animals in order to name them. The response hand was determined by the living-nonliving distinction; the final phoneme of the word determined whether the response was to be carried out. Preparation of the response hand leads to a lateralized readiness potential that can be differentiated from other lateralized brain activity by a double subtraction (Coles, Gratton, & Donchin 1988; Smid, Mulder, & Mulder 1987), as shown across the top of the figure. As can be seen in the bottom right of the figure, this potential is present even in the No-Go trials, indicating that the semantic (living-nonliving) information was available to the subject before the phonological information. Adapted with permission from van Turennout, Hagoort, & Brown, "Electrophysiological evidence on the time course of semantic and phonological processes in speech production," *Journal of Experimental Psychology: Learning, Memory, and Cognition, vol. 23, pp.* 787-806. Copyright © 1997 by the American Psychological Association.

changes. Among a host of other neuropsychological deficits, patients display language difficulties, primarily naming deficits. Several researchers have found that - like control subjects - patients with probable diagnosis of Alzheimer's disease show reduced N400s to repeated words, despite impairments in their recognition memory (Friedman et al. 1992; Rugg et al. 1994). These results have led to the suggestion that the repetition N400 reflects an intact implicit memory system in Alzheimer's patients.

Smaller and later N400s, however, have been observed in Alzheimer's patients performing more complicated language tasks. Schwartz and co-workers (1996) tested the hypothesis that the hierarchical structure of semantic memory is impaired in Alzheimer's patients so that only broad category memberships are available (Hodges, Salmon, & Butters 1991). They used three levels of categorical abstraction (e.g., living things, plants, flowers) to see if, as predicted from the hierarchical breakdown view, Alzheimer's patients would experience the greatest difficulties with the most specific category members. This was not found to be the case; rather, the congruity effects on reaction times and N400s to the different category levels in patients and controls were similar. However, Alzheimer's patients did have smaller-amplitude N400s at somewhat later latencies than the age-matched controls (see also Iragui, Kutas, & Salmon 1996).

It might prove informative to correlate N400 effects of this type with known neuropathological changes in Alzheimer's disease, including plaques (i.e., aggregates of protein deposited in cortical areas), neurofibrillary tangles, and dramatic decrease in the number of cortical synapses. These changes are most pronounced in the entorhinal cortex and hippocampus, areas that have also been implicated in the generation of the N400 (Nobre & McCarthy 1995). However, the presence of normal N400 word repetition effects in Alzheimer's patients suggests there may be no such significant correlation. Perhaps different neural structures are involved in the generation of the semantic priming (or congruity) N400 effect and the repetition N400 effect.

Basal Ganglia Diseases

Basal ganglia diseases (including Parkinson's disease, Huntington's disease, supranuclear palsy, and others) subsume a set of conditions that - owing to neurodegeneration, predominantly in the basal ganglia - exhibit a complex pattern of hypo- or hyperkinetic movement disorders and associated neurobehavioral symptoms. These symptoms include impairments of executive functions and working memory as well as general slowness of thought processes. These neurobehavioral deficits have been attributed to abnormal functioning of neuronal circuits between the striatum and the cortex, especially frontal regions (Owen et al. 1992).

Disorders of language functioning have also been described in association with basal ganglia diseases. Illes (1989) noted that spontaneous language production in Huntington's patients was characterized by a reduction in syntactic complexity, semantic paraphasias, and a predominance of closed-class phrases, whereas Parkinson's patients used predominantly open-class phrases. Rosser and Hodges (1994) found that both Huntington's and supranuclear palsy patients performed worse than controls on letter (production of words starting with a given letter) and categorical (production of instances of a category) fluency tasks, suggesting problems with initiation and memory retrieval. In two elegant investigations, Natsopoulos and associates (1991, 1993) showed that basal ganglia patients also experience greater than normal difficulty comprehending relative (especially object-relative) clauses and complement clauses. It is known that working memory plays a crucial role in the comprehension of relative clauses (King & Just 1991). These data therefore imply that - although language functions may be compromised in basal ganglia patients - their difficulties in at least some cases may be a by-product of deficits in more domain-general cognitive functions such as working memory, task initiation, and retrieval from memory.

Schizophrenia

The many symptoms of schizophrenia include several disturbances of language: reduced syntactic complexity (Thomas et al. 1996), the use of novel words (neologism) - including blends of existing words (Rochester & Marin 1979) - and the loosening of semantic associations. It is a matter of debate as to whether these deficits reflect difficulties with language processing per se, abnormal organization of semantic knowledge, or a more pervasive problem with information overload and/or attention (Schwartz 1982). Several groups of electrophysiologists have, with variable success, tested these alternatives using the N400. Smaller N400s have been observed in schizophrenic patients, but generally only when an explicit congruency judgment must be made (Grillon, Ameli, & Glazer 1991; Koyama et al. 1991; Mitchell et al. 1991). Thus it appears that at least part of schizophrenics' language dysfunction may reflect a difficulty in directing attention toward the relationship between words.

Schizophrenic individuals exhibit more than normal numbers of intrusions of semantically related words during spontaneous speech and greater than normal semantic priming effects via behavioral measures (Maher et al. 1987). Andrews and colleagues (1993) used ERPs to assess the abnormal organization of semantic memory that may underlie these phenomena. They employed sentences ending with congruous words, wholly incongruous words, and words that were incongruous but semantically related to the expected endings (e.g., "Father carved the turkey with a spoon"). They expected schizophrenics to show a greater N400 attenuation to semantically related incongruous endings, but both groups generated smaller N400s to related than unrelated endings and did not differ from each other. Thus, electrophysiological evidence for a differential organization of semantic memory in schizophrenia is equivocal. By contrast, however, almost all these studies reported a reliable 40-80-msec delay in the N400 latency. Among the potential explanations for this delay are generally slowed information processing (Grillon et al. 1991), overlap with an abnormal late positive component, and antipsychotic drugs.

Schizophrenic patients have also been investigated with PET and fMRI. These studies have employed verbal fluency tasks, known to pose difficulties for schizophrenic individuals and to activate dorsolateral prefrontal cortex. Frith and associates (1995) did not observe the expected reduced PET activation of the dorsolateral prefrontal cortex in schizophrenic patients, but they did note a greater than normal activation of the superior temporal gyrus. The superior temporal gyrus is presumed to be crucial for word representations, so Frith et al. (1995) attributed the symptomatology of the patients to abnormalities in this region. In a very similar design employing fMRI, Yurgelun-Todd and co-workers (1996) observed both the expected decreased activation in the left dorsolateral prefrontal and the greater activation of the left superior temporal gyrus in schizophrenic individuals.

In summary, the currently available data seem most consistent with the hypothesis that language deficits in schizophrenia are secondary to disturbances in other cognitive mechanisms, although the results are far from consistent. The contradictory findings in the literature undoubtedly stem in part from a lack of appreciation for the well-defined subtypes of schizophrenia, which vary significantly in symptomatology. Directing future research efforts toward the study of homogenous groups of patients may permit a more accurate assessment of the extent of strictly language problems in the most advanced stages of this disease.

Developmental Dyslexia

One of the more frequent learning disabilities, developmental dyslexia has been linked to abnormal development of the magnocellular pathway in the visual system (Lovegrove, Garzia, & Nicholson 1990) and/or reduced asymmetry of the planum temporale (Galaburda et al. 1985). At a psychological level, proposed deficits range from the integration of auditory stimuli (Tallal & Curtiss 1988) to syntactic analysis (Byrne 1981).

Several electrophysiological investigations have been aimed at better defining the psychological deficits involved in developmental dyslexia. Neville and colleagues (1993) found that dyslexic children had enhanced N400 amplitudes to sentence final words and interpreted this as a sign of their greater need to use context to compensate for deficits in visual word recognition. Johannes and coworkers (1995) reported similar findings and conclusions for adult dyslexics. However, others have reported that dyslexics have smaller than normal N400s in picture-word-priming (Stelmack & Miles 1990) and rhyme-matching (Ackerman, Dykman, & Oglesby 1994) paradigms.

Paulesu and associates (1996) used PET to examine five adult dyslexics as they performed a phonological matching task and a short-term memory task. Broca's area and the temporoparietal areas were activated in both tasks in the normal controls; by contrast, in the dyslexics, Broca's area was active only during phonological matching and the temporoparietal areas were active only during the short-term memory task. These findings were taken as evidence for a functional disconnection between anterior and posterior language areas in dyslexics.

Aphasia

Despite its clinical importance, aphasia has received relatively little attention in psychophysiological investigations. Psychophysiological techniques might be especially revealing, as the language deficits in aphasia often occur without any apparent associated cognitive deficits. Aphasic patients offer an excellent means of determining if there is a direct link between the presence and absence of certain language symptoms (e.g. agrammatism) and certain purportedly linguistic components of the ERP, such as the P600/SPS.

In an elegant series of experiments, Hagoort, Brown, and Swaab (1996) and Swaab, Brown, and Hagoort (1997) investigated semantic analyses in a group of Dutch aphasics, including Wernicke's and Broca's aphasia. In one study, aphasics, nonaphasic right-hemisphere patients, and normal elderly controls heard pairs of words that were either semantically related *(church-villa)*, associatively related *(bread-butter)*, or unrelated. In normal controls and in those aphasics with mild comprehension deficits, the N400 effects for associative and semantic pairs were of equal size (Hagoort et al. 1996). In contrast, aphasic patients with more pronounced comprehension difficulties showed diminished N400 amplitudes only for the semantically related pairs, fueling speculations about the possible involvement of the right hemisphere in semantic processing (cf. Rodel et al. 1992). Swaab et al. (1997) investigated these same aphasics as they listened to sentences terminated by congruent and incongruent words. The main result was an approximately 100-msec delay of the N400 peak in the aphasic patients with the most profound comprehension deficits. This delay was interpreted as a sign of slower lexical integration, in line with several other reports that aphasics' comprehension difficulties result from a processing rather than a representational deficit (Friederici & Frazier 1992; Haarmann & Kolk 1994). Similar delays in the N400 component have also been observed in closed-head-injury patients who show general cognitive slowing (Munte & Heinze 1994).

Unlike the electrophysiological studies primarily aimed at delineating processing deficits in aphasia, PET studies

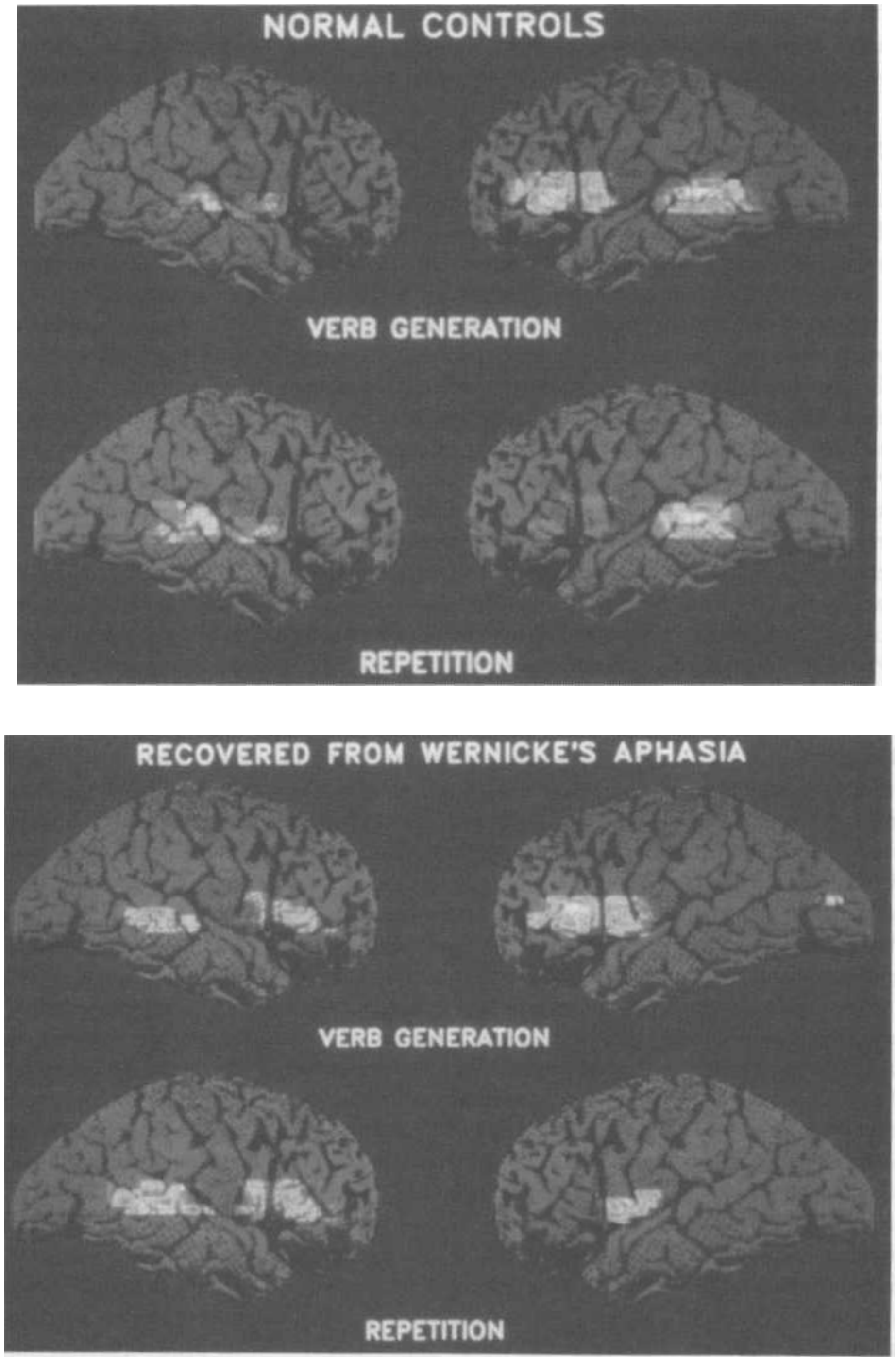


Figure 9. Cerebral regions associated with a verb generation task and a repetition task in six normal volunteers (top) and six patients after recovery from aphasia (bottom), expressed as means for each group based on positron emission tomography (PET). Statistical parametric maps for increases in regional cerebral blood flow during the tasks (compared to rest) rendered onto the lateral surfaces of brains using Talairach and Tournoux coordinates illustrate the distribution of major sites of activation in the right hemisphere. The cutoff for the z-score in the display is 3.09, corresponding to a Bonferroni corrected level of significance of $p < 0.087$. Reprinted with permission from Weiller, Isensee, Rijntjes, Huber, Muller, Bier, Dutschka, Woods, Noth, & Diener, "Recovery from Wernicke's aphasia: A positron emission tomography study," *Annals of Neurology, vol.* 37, pp. 723-32. Copyright © 1995 by the American Neurological Association.

have been focused on the issue of brain plasticity and recovery after language loss. For example, Weiller and colleagues (1995) studied six patients who had recovered from a Wernicke type aphasia. While the expected left hemispheric activations were observed in normal controls, the recovered patients showed activation of the homologous right-hemisphere regions (superior temporal gyrus, inferior premotor cortex, lateral prefrontal cortex) - see Figure 9.

These data were interpreted as reflecting a redistribution of language processing within a parallel pre-existing network (see also Ohyama et al. 1996).

Conclusions and Future Directions

Psychophysiological data have converged to build a picture of when and where language processes take place in the brain. In some cases, this information also places constraints on how language processing must be occurring.

Perhaps the most striking general conclusion that can be drawn is that language processing is far from a unified phenomenon. Rather, it appears to involve an astonishing array of computational and neurobiological processes that operate on an equally large number of representation types. Much research effort has gone into cataloging and understanding these differences. Both ERP components and fMRI/PET activations have been described that are sensitive to words and no other types of perceptual stimuli. Factors such as word frequency and word class have different ERP signatures. Different ERP indices of semantic and syntactic processing have been proposed.

It is up to future work to piece together the different processes and representations that previous research has defined. That is, while language processing clearly involves a large number of subprocesses, ultimately these must work together to derive meaning from sensory inputs or to instantiate meaning via motor outputs. Understanding language at this level - as an integrated, goal-directed process - will require elucidating the relationships that hold among language subcomponents and between language and other cognitive abilities.

For instance, understanding language utterances necessarily requires that relevant linguistic, contextual, and background knowledge be integrated. Very little is known, however, about the relative importance of immediate context and longer-term background knowledge for meaning construction. The two factors are obviously related: we understand context only because of background knowledge, which in turn is derived (in part) from correspondences we note in various language contexts. How is this relationship instantiated and how are conflicts resolved? We need to design experiments in which both factors are present and to develop measures that can explore their interactions.

It is also important to understand how language representations are built out of both abstract linguistic features and concrete perceptual features. What concrete features allow us to determine that a particular sensory input carries meaning? Do physical features of linguistic stimuli continue to play an important role in language processing beyond the point at which they are classified as words? Do they, for example, help us distinguish nouns from verbs? Does it make sense to talk about a modality-independent language representation at any level of processing?

These questions become especially important when language is taken out of the "white room" - the extremely controlled and fairly artificial setting of the laboratory (Cicourel 1996). In the real world, language processing occurs in a much richer context. Not only are the units of processing larger than those typically studied - discourses, rather than single words or sentences - but there are social and physical cues to guide the language user. In most cases, these cues occur freely interspersed with language; for example, one may point to rather than name an object. In the future we must exploit technological advances to bring more of the world into the laboratory: using tape recorders to study natural conversation, presenting readers with connected texts from natural sources, allowing language users to interact with objects as they process language, and so forth.

Understanding the relationship between aspects of language processing will naturally also entail understanding the role of nonlinguistic factors such as working memory and attention. It is likely that these factors are critical in the integration of more specific language processes, since attentional and working memory capacities may have to be shared across levels of analysis. Furthermore, at least some of the subcomponents of language processing identified thus far may ultimately turn out to be language-specific instantiations of these more general functions. For example, morphosyntactic marking and word order have traditionally been considered purely structural phenomena. However, Langacker (1987) suggested that they - as well as other presumably linguistic phenomena - can be understood more generally as profiling (or attentionally focusing) various aspects of evoked knowledge structures.

This understanding of the relationship between language and other cognitive processes may involve a rethinking of the other processes as well. For example, the exclusive division of cognitive processes into automatic and controlled may not be theoretically useful; rather, one may wish to locate processes on a continuum from automatic to controlled. For example, we briefly reviewed the debate over whether the N400 indexes automatic lexical processing or controlled postlexical processing. Yet the N400 seems in fact to index processes that are automatic in some ways but controlled in others. It has been speculated that semantic priming effects (and associated N400 effects) arise from an obligatory postlexical integrative process (a la Hodgson 1991). This sort of mechanism is neither clearly automatic-modular nor clearly interactive-nonmodular. It resembles modular lexical access in that it is a fast-acting process that acts on every lexical item; in view of large N400 components elicited by pseudowords, it appears moreover to act on every wordlike item. However, it resembles an interactive process in that it is sensitive to high-level inferential information of the sort traditionally associated with attentional processing (as in e.g. Coulson 1996; St. George et al. 1994). By rejecting views of language (or more general) processes that are inflexible and theory-laden, we may derive a more comfortable fit to psychophysiological data and a clearer understanding of language in its cognitive context.

Finally, there is a need to explore connections between language processing and other cognitive feats: the analysis of visual scenes (Sereno 1991), the understanding of diagrams (Hegarty, Carpenter, & Just 1995), and the perception of music (Besson, Faita, & Requin 1994; Besson & Macar 1987). Like language processing, these activities require that meaning be obtained over time from a well-structured source of information. Auditory sentences and music are both inherently structured over time. Diagrammatic processing, like reading, directs attention (and eye movements) from place to place in a surprisingly structured way - in a manner that can be convincingly related to the text that describes them (Hegarty et al. 1995). Visual scenes are less likely to have stereotypical inspection orders, but they are almost as likely to have predictable loci where fixations will occur. By understanding the similarities (and differences) between these types of cognitive processes, we gain insight into the general principles underlying all of cognition as well as an increased understanding of the defining properties of language.

In the future, then, using the various and sundry psychophysiological tools at our disposal, we may yet come to understand how Dickinson used her brain to generate poems ... which we use our brains to decipher and appreciate.

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