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Electrophysiological Perspectives on Comprehending Written Language

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It is no simple question how our brains comprehend written language, but I doubt that it will be answered by investigating words in isolation regardless of the experimental paradigm or measure. It is not that a single word has no meaning but rather that a word in isolation has too many possible meanings. Take, for example, the words 'mean,' 'put,' 'cut,' 'ball,' etc. Each has several distinct dictionary meanings as well as subtly different connotations. Yet, although polysemy and lexical ambiguity are quite common in our everyday language, we rarely experience them as problematic. Why? Possibly, because words do not exist in isolation; they occur in context. Concepts are packaged into words for the purposes of reference but they are generally broader than any one word. Thus, a word's intended meaning at any given moment does not typically emerge from consideration of the isolated word. Likewise, the meaning of a sentence does not emerge from concatenating the meanings of the individual words. Given this particular vantage point, it makes little sense to expect that a description of the comprehension mechanism will prove equivalent to the organizing principles of a static long-term memory store or mental lexicon. By our view, it is indeed unlikely that the mental lexicon is built up of a finite set of single words each coded in terms of a unique meaning and laid down in an accessible store ordered by frequency of everyday usage. We believe that word recognition is not dependent solely upon the search for and access to a static representation (i.e., lexeme), where such a representation is presumed to contain not only the mapping between the written word (i.e., orthographic representation) and its sound (i.e., phonological representation) but also its meaning (i.e., semantic representation). Accordingly, we argue that an experimentally fruitful goal would be to delineate the factors (e.g., perceptual, semantic, structural, experimental, etc.) that constrain how the inputs are processed so as to yield the intended meaning for the purposes of on-line comprehension, integration, inferences and behavior. We believe that this goal is most readily accomplished via a measure that can track the dynamic nature of the emergence of meaning during reading.

One such measure is provided by recording the brain's electrical activity at the scalp, in synchrony with the presentation of words in sentences (for review see Kutas and Van Petten 1988). Although this procedure of presenting words one at a time – the serial visual presentation (SVP) technique – can be questioned on the grounds of its ecological validity there is evidence indicating that it provides a relatively unadulterated view of some processes during reading. Insofar as different text presentation modes have been compared, the SVP method has yielded results very similar to normal reading on a number of tests of reading comprehension and memory (Forster 1970; Aaronson and Scarborough 1977; Potter et al 1980; Juola et al. 1982; McNamara 1982; Cocklin et al. 1984). Chen (1986) actually found that in the case of poor adult readers, rapid serial visual presentation was advantageous over the conventional page presentation method for retention. Further, with the exceptions of opportunities to skip over words and to make regressive eye movements in text, the snapshots of

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input afforded by short duration flashes are similar to those provided by the eyes as they dart across the lines of text on a page (but for limits also see Just et al. 1982; Masson 1983, 1986).

ERP studies with the SVP procedure have demonstrated that each word in a sentence elicits a characteristic series of ERP components which are in no way determined by the specific semantic or even categorical contents of the eliciting word. No parameters of the ERP to any specific word define the eliciting word's identity uniquely. For example, the ERP to the word 'apple' does not differ in any appreciable way from the ERP to the word 'dog.' A similar non-specificity in the electrical signature obtains if the comparison is between the average ERP collapsed across members of the category 'fruit' versus members of the category 'animal.' However, although the ERP does not reflect a word's specific content, various ERP components, especially the N400, have proven to be very sensitive indices of a word's characteristics (e.g., frequency, length, etc.) and the extent to which it is expected within its context.

The typical series of components elicited by words in sentences at locations over posterior temporal sites as shown in Fig. 1 includes the P1 (~110 msec), N1 (~180 msec), and P2 (~280 msec, which is larger and earlier anteriorly) followed by a broad negativity (N400). Whether the reference site is a single mastoid, earlobe, linked mastoids or a non-cephalic site, each of these components with the exception of the N1 has been found to be slightly larger over the right than the left hemisphere. Although we do not know the sources for these asymmetries, we believe that they have at least two different generators based on their differential correlation with family history of left-handedness (i.e., familial sinistrality). In specific, the lateral asymmetry of the amplitude of the N400 component but not that of either the P1 or P2 component is significantly reduced in individuals who have at least one left-handed relative in their immediate family (see Fig. 2 and Kutas et al. 1988). Left-handed individuals per se (without left-handed relatives) do not seem to show a similar reduction in the N400 asymmetry. However, a systematic study of right- and left-handed males and females, with and without left-handed relatives, must be completed before we can be certain of the specific function relating N400 asymmetry to subject handedness. We believe that this may be an especially interesting paradigm in which to examine the effect of familial sinistrality on the fine organization of the two cerebral hemispheres because there are no special task requirements for eliciting the asymmetry; the subjects need only to read.

The asymmetry of the N400 is more pronounced in the ERP responses to 'open' or 'content' words than in the responses to 'closed' or 'function' class of words. This is partly due to the fact that content word ERPs contain a larger negativity between 200 and 500 msec at posterior sites than do function word ERPs. This can be seen in Fig. 3 where the ERPs elicited by function and content words are overlapped; the two columns represent this comparison for sentence initial

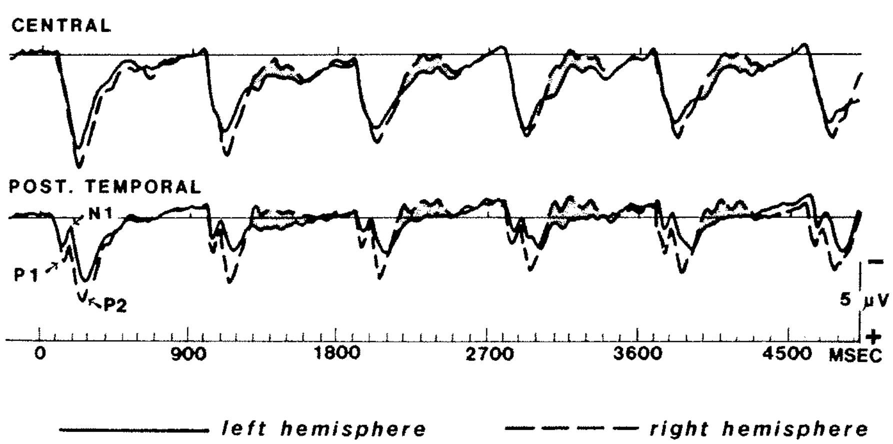

Fig. 1. Grand average ERPs (N = 20) elicited by the first 5–6 words of congruent sentences, presented at a rate of 1 word every 900 msec. From left and right central scalp sites (C3, C4) and a pair of posterior temporal sites, each referenced to the average of right and left mastoids. The P1, N1, and P2 components are indicated by arrows for the ERP to the first word. The asymmetrical portion of the N400 is shaded.

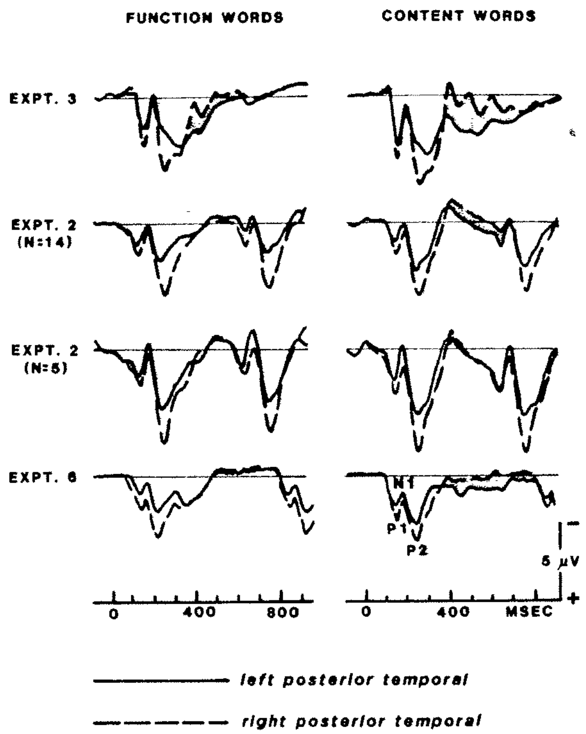

Fig. 2. ERPs elicited by sentence intermediate function and content words at left and right posterior temporal sites. Three different experiments are shown. All subjects were right-handed, but in exp. 2 some of these had left-handed relatives, and their data are shown separately in the third row. Note that the P1 and P2 are larger over the right hemisphere for both content and function words independent of familial handedness. In contrast, the asymmetry of the N400 (shaded) is reduced for right-handed subjects with left-handed family members. Note also the smaller amplitude of the N400 for function than content words.

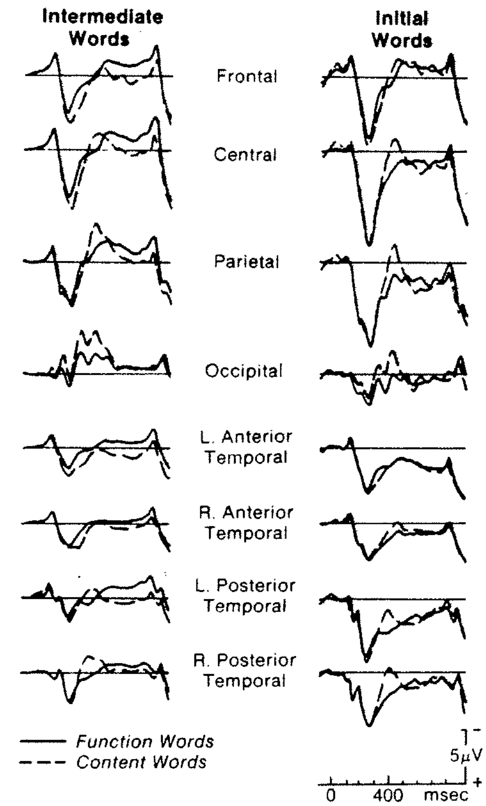

Fig. 3. Grand-average ERPs (N = 16) elicited by words in sentences, according to sentence position and word type. Recorded at sites Fz, Cz, Pz, Oz and 2 pairs of lateral sites.

and sentence intermediate words. At the beginning of a sentence the most striking difference between the ERPs to content and function words is the presence of a large N400 component in the ERP to the former but not the latter. The N400 difference between function and content word ERPs is maintained, albeit somewhat reduced, in the responses to these two lexical classes throughout the course of sentences.

Does this ERP difference reflect the much sought difference in the anatomical addresses of the words that bear meaning (i.e., content words) and the little words in our vocabulary that help parse phrases and sentences (i.e., function words)? Certainly there seems to be some evidence for this distinction between the lexical classes in the aphasia literature (Marin et al. 1976; Friederici and Schoenle 1980; Rosenberg et al. 1985). For example, several investigators have interpreted the disproportionate difficulties that Broca's aphasics have in dealing with closed class items as support for this position. It has thus been suggested that there may be two lexicons: a large repository primarily comprised of nouns, verbs, adjectives and adverbs, always open to the addition of new members and somehow organized according to their frequency of usage and another, smaller closed set consisting of articles, conjunctions, prepositions, auxiliaries occurring so frequently as to shun storage by a frequency code. For some time, Bradley's (Bradley 1978; Bradley and Garrett 1980, 1983) findings of differential frequency sensitivity, non-word interference, and visual field effects for function and content words were cited as strong support for this view. However, despite several independent attempts, these results have not been replicated (Gordon and Caramazza 1982; Segui et al. 1982; Garnsey 1985; Kolk and Blomert 1985; Chiarello and Nuding 1987; Petocz and Oliphant 1988).

An alternative interpretation holds that the difference between open and closed class words is more apparent than real. By this view, open and closed class words are members of a single lexicon with the distinction between them being continuous rather than dichotomous. Compare, for example, the semantic content and structural role of the preposition 'over' in the following sentences:

(a) 'The plane flew over the building.'
(b) 'Let me look over the report.'
(c) 'I guess this affair is over.'

An even more extreme example from English is the word 'have' which may serve as a main verb meaning 'to possess' or as an auxiliary serving only to indicate the aspect of the main verb (e.g., 'have written'). It seems as though it is the role a word plays within a sentence rather than its surface form that determines whether it behaves as an open or closed class word. It may be that the differences in the speed or accuracy of processing open versus closed class words can in large part (and perhaps totally) be ascribed to differences which are *correlated* with lexical class membership but do not determine them. Closed class words tend to be shorter, higher frequency in overall usage, more often repeated, more predictable from context, and less imageable. One of the best ways to test this hypothesis would be to examine the effect of each variable in isolation with the others held constant and in combination with the others *within* a lexical category. This, however, has proven quite difficult, as these characteristics are not orthogonal (e.g., high frequency words tend to be shorter than low frequency words). Depending on the nature of the N400 sensitivity to any or all of these factors, we may want to resort to these relations as an explanation for the difference in N400 amplitude between open and closed class words.

The largest and most robust N400 wave is elicited by an open class word that is semantically anomalous within its context (e.g., Kutas and Hillyard 1980a,b, 1982). This finding holds whether the anomalous word occurs at the end or in the middle of a sentence (see Fig. 4; Kutas and Hillyard 1983). In both cases, the semantically anomalous word elicits a significantly

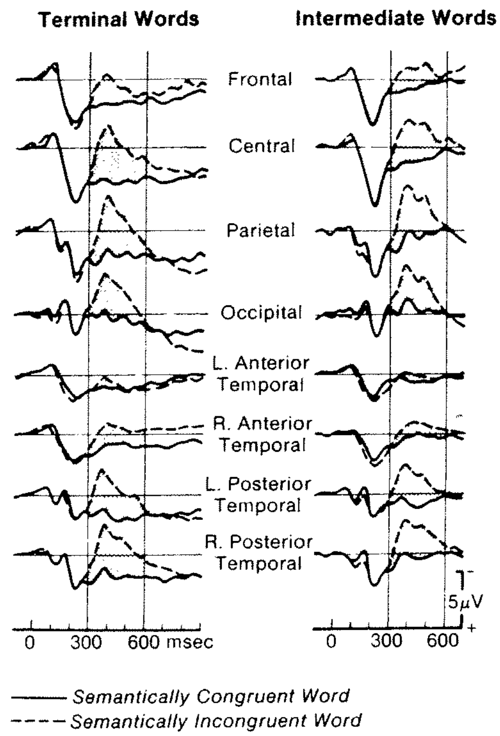

Fig. 4. ERPs to semantically congruent and incongruent sentence words, occurring as the final words of sentences, or in the middle of sentences. Recorded at sites Fz, Cz, Pz, Oz and 2 pairs of lateral sites, from 17 subjects. (From Kutas and Hillyard (1983), copyright Psychonomic Society, reprinted by permission.)

larger negativity which diverges from the response to a semantically appropriate word in the same ordinal position (assuming they are matched on length and frequency of usage) at about 200 msec, peaks between 350 and 450 msec, and has, in the average wave form, a duration of 300–400 msec. Typically, the N400 effect (i.e., the relative difference between congruous and anomalous word ERPs) to words from SVP sentences, while broadly spread across the scalp, is nonetheless larger posteriorly (parieto-occipital) than anteriorly (frontal) and slightly larger over the right than the left hemisphere.

Visual inspection suggests that the N400 elicited by a semantically anomalous word is less peaked and of broader duration than that elicited by a congruent open class word, especially if the latter occurs in the sentence initial position. In the average wave forms, it is impossible to determine whether this difference in duration characterizes single trial as well as average N400s following anomalies, or merely reflects substantial latency variation for single trial N400s elicited by the anomalies. This is an important outstanding question which can only be answered after new, sophisticated techniques for single trial measurement are developed, documented and made accessible to the N400 researcher.

The fact that an N400 wave follows closely upon the heels of a semantically anomalous word, regardless of its ordinal position within a sentence, is most consistent with those models of language processing that emphasize the immediate and on-line nature of comprehension (e.g., Just and Carpenter 1980; Gernsbacher and Hargreaves 1988). Our sentence N400 data do not support models of language processing in which most of the inferential and elaborative processing is buffered for delayed analysis at phrase, clause and sentential boundaries. This is of course not to deny that there is substantial interpretation and integration at the end of sentences and probably other syntactic boundaries as well. Indeed, it is likely that at least a subset of the proposed syntactic boundaries are regions of higher than average processing loads. Eye movement data, click displacement studies, and ERP data all attest to the sense of such a view. For example, Carpenter, Just and their colleagues have shown 'end of sentence' effects on gaze durations (a presumed measure of processing duration), which were on the average 71 msec longer at the ends of sentences in scientific texts (Just and Carpenter 1978, 1980). Reading time studies have also shown that subjects pause longer at phrases that end sentences than those that do not (Mitchell and Green 1978). In the '60s and '70s, several groups found that when subjects were asked to indicate the temporal location of a brief click that had been superimposed on a sentence presented in one ear, they systematically mislocated the click towards certain syntactic boundaries (Fodor and Bever 1965; Garrett et al. 1966). In addition, we always find that the late positive wave of the ERP elicited by sentence terminal words is much larger and more prolonged than that elicited by words earlier in the sentence. For this reason we generally provide subjects with an interval between sentences which is 3 or 4 times as long as that between words. In this way we also give subjects enough time to blink without contaminating the data; on occasion, this requires training as people naturally tend to blink within a few hundred milliseconds after the final word.

Although the N400 seems to be elicited in close synchrony with an anomalous word, we have found that its latency is slightly longer (by about 30 msec) for semantic anomalies occurring in the midst as opposed to the end of a sentence. We take this to indicate that intermediate anomalies are appreciated somewhat more slowly than terminal anomalies. A similar although larger delay in peak latency of the N400 component has been observed following terminal semantic anomalies when the sentences have been presented at the extremely rapid rate of 10 words/sec (Kutas 1987). In contrast to more slowly presented sentences (1–4 words/sec), these N400s both begin and peak approximately 50–100 msec later and have a somewhat more anterior scalp distribution (see Fig. 5). Ten words/sec is faster than normal reading speed, while 4 words/sec is close to the norm for our subject population. Thus, the similarity between the results obtained at this latter rate and those at a slower rate (1 or 2 words/sec) suggests that it is reasonable to draw inferences about normal reading processes from these slow rates. The advantage of allowing more time between words is that it is possible to visualize the entire sequence of ERP components elicited by a single word without confounding by overlapping responses from previous and subsequent words. Of course, we would expect some differences in processing as a function of presentation rate as well as individual differences within a single rate of presentation. For the present, we gloss over these differences; ultimately we hope to develop analytic techniques for extracting overlapping ERP components elicited by words presented at normal reading rates (see Woldorff 1989).

In this regard, it is important to note that while we refer to the N400 (and other ERP components) in terms of its peak latency, this should be taken as an easy reference point rather than an indication that we believe that 400 msec is a critical processing point. In most experiments, N400 amplitude differences are clearly apparent by 200 msec post stimulus. The cellular events underlying word processing and the N400 are not known. It is possible, for instance, that the N400 is elicited at the offset of relevant processes, thereby reflecting activity which began much earlier in time than its peak (or for that matter even its onset). Experimental work on the components of the electroretinogram (ERG) has indicated that evoked potential components may continue well beyond the

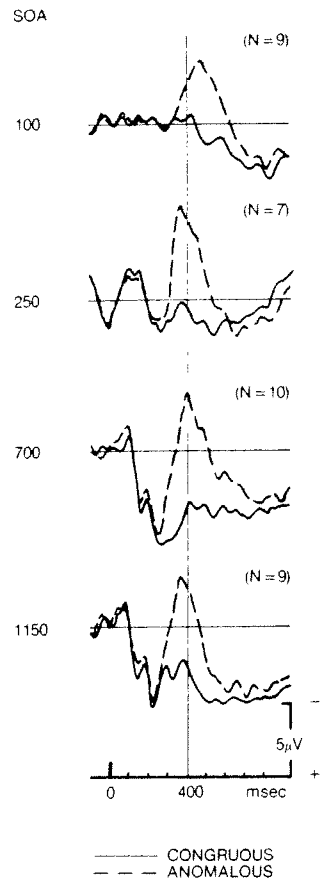

Fig. 5. ERPs to semantically congruent and incongruent (anomalous) words occurring as the last words of a set of sentences which were presented at different rates to partially different groups of subjects; each subject read sentences at 2 different rates. The rates varied between 10 words/sec at the top, to less than 1 word/sec at the bottom. The time in msec between the onset of one word and the onset of the next (SOA) is shown on the left, the number of subjects for each rate is shown on the right. Note that both the onset and peak latency of the N400 response to anomalous words are delayed at the very fastest rate (SOA 100), but not at the rate which most closely approximates a normal reading speed (SOA 250). (Also see Kutas 1987.)

critical cellular events which generate them. The ERG is a complex light-evoked potential generated by the retina. Light absorption by photoreceptors causes a loss of potassium from the extracellular fluid. This ionic change causes the pigment epithelium to hyperpolarize; this hyperpolarization is manifest in the C-wave of the ERG. In contrast to the short duration of the epithelial hyperpolarization, the associated C-wave can last for 5 or so seconds (e.g., Brown 1968). Similarly, we suspect that the relevant cognitive operations *precede* the N400 rather than being immediately coincident with it. In any case, N400 is a convenient label rather than a specific moment of word recognition or comprehension.

Experiments from several laboratories throughout the world have demonstrated that the N400 is elicited by semantic anomalies within a number of input modalities. For example, McCallum et al. (1984) found that whereas an occasional change in the pitch of a speaker's voice was associated with an enhancement in a late positivity, the presence of an occasional semantic anomaly at the end of a spoken sentence elicited an N400-like component. Neville and her colleagues replicated the presence of N400 to semantically incongruous words within speech presented to subjects at either a constant (SOA = 700 msec) or natural rate (Neville 1985; Kutas et al. 1987; personal communication). Both McCallum's and Neville's studies hint at possible differences in the latency of onset, duration, and scalp distribution of the N400 between the visual and auditory modalities. The extent to which the auditory N400 onsets earlier is more frontally distributed, is more bilateral or left hemisphere predominant, and of longer duration than the visual N400 are issues that need to be addressed systematically. Certainly, differences in the time course of visual and auditory information flow and differential amounts of overlap in the processing of successive words could be reflected in different time courses of contextual influences as evident in the associated N400 effects.

Another striking example of the independence of the N400 from surface form has come from the work of Neville and colleagues with congenitally deaf adults. Her studies yielded clear N400s in response to semantic anomalies in American sign language (ASL) in congenitally deaf adults. Such data show that the N400 effect is at a level of analysis beyond the individual letters in a written word, the phonemes or syllables in a spoken word, or the hand shapes in a signed word. Indeed, this is the type of evidence that has led us to emphasize the semantic sensitivity of the N400 component.

Also in line with this general view are data comparing semantic anomalies in the form of words versus line drawings. Fig. 6 shows the ERPs elicited by semantically anomalous words or line drawings completing written sentences as compared with their con-

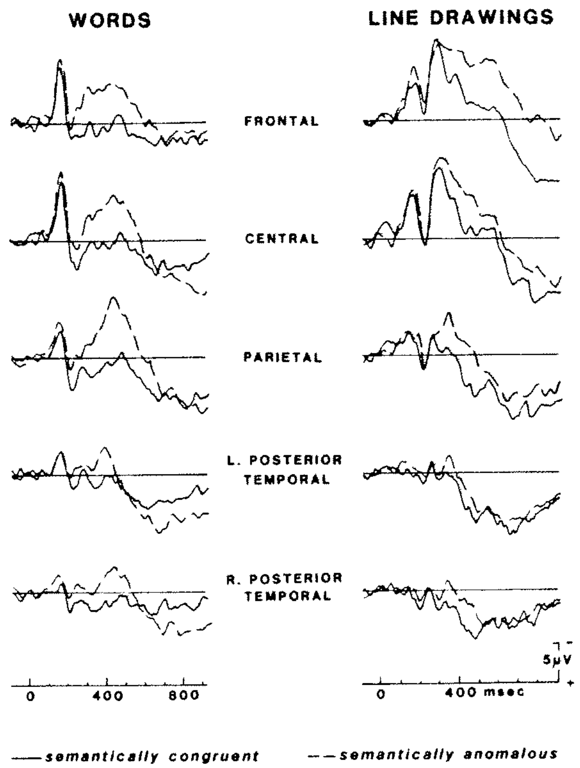

Fig. 6. Grand-average ERPs (N = 8) elicited by semantically congruent and incongruent sentence terminal words are shown in the left column. On the right are the ERPs to line drawings which completed sentence fragments, presented one word at a time at a rate of 1 word/sec, in a congruous or incongruous way.

gruent counterparts[2]. Despite the differences in wave forms elicited by words and line drawings, there is a remarkable similarity in the relative difference between congruent and anomalous endings for words and line drawings. In this data set, the congruity effect at the parietal site for line drawings peaked earlier than that for words. Perhaps this finding argues that line drawings provide a faster route to meaning than written word forms. Certainly, however it is that our semantic concepts develop, they are based more on objects in the visual world than on the decoding written word forms. However, the present data are not clean enough to allow such interpretations. For one, words and line drawings were not matched for imageability; whereas all the line drawings were clearly imageable, all of the words might not have been. Also, because the majority of sentences ended with words, pictures (regardless of their congruity) were relatively more unexpected than the words; this difference might be manifest in the large frontal negativity and/or overlapping P3-like components seen in the ERPs to pictures. Experiments of this sort, properly done, would contribute to our understanding of whether words and visual objects are represented via a common conceptual system or by access to separate systems (e.g., Paivio 1971, 1986; Pylyshyn 1973; Glucksberg 1984; Kolers and Brison 1984; Kroll and Potter 1984). There has been amazingly little ERP research directed at this issue.

After open class semantic anomalies, the largest N400s have been elicited by open class words that are semantically appropriate to their context but not constrained by it. For example, the ERP to a word with a relatively low predictability at the end of a sentence is characterized by a substantial N400 wave (e.g., 'dance' in 'He decided to go shopping after the *dance*'). Sentences of this type that do not lead to strong, consistent expectations for specific words are said to have low contextual constraint. As such, they are terminated by words of low cloze probability. The cloze probability of a word refers to the percentage of individuals who used that very word to fill in a blank slot in a sentence. In this way, cloze probability is used as an operational measure of a word's expectancy. Similarly, congruous words terminating sentences of greater contextual constraint also elicit large N400s insofar as they are not the expected ending (e.g., 'diet' in 'George always kept his dog on a *diet*,' as opposed to the expected ending '*leash*'). Thus, a word can have a low cloze probability because it is unconstrained by its natural context or because an experimenter has violated the natural expectancy[3].

A word's cloze probability and a sentence's degree of contextual constraint are generally correlated. How-

[2] In this experiment, subjects saw 160 sentences one word at a time; their task was to attend to the sentences for a subsequent recognition memory test. One-fourth of the sentences were completed by a line drawing; half of these were semantically anomalous. The remaining sentences were terminated with words; one-sixth of these were semantically anomalous.

[3] In the cognitive psychology literature 'expectancy' and 'predictability' are used in contrast to the terms like 'priming,' 'activation' and thereby generally imply the employment of conscious versus automatic processes. Our use of these terms should not be presumed to carry these implications. At present, we do not know the proportion of 'automatic' versus 'conscious' operation contributions to the elicitation of the N400; nor do we feel that clarifying attributions of this sort will be easy.

ever, when they are dissociated, it is clear that the amplitude of the N400 is determined primarily by a word's cloze probability, rather than the contextual constraint of the sentence (see Fig. 7A). This result rules out an explanation of the N400 as a mismatch detector, reflecting the degree of mismatch from the expected word. Fig. 7B shows that the amplitudes of the N400s elicited by 3 sets of words each with the same average cloze probabilities completing sentences of low, medium and high contextual constraints; note the N400s are indistinguishable. Indeed, our results reveal a strong inverse correlation of about 0.90 between the mean amplitude of the N400 wave and a word's cloze probability (Kutas and Hillyard 1984; Kutas et al. 1984). Words with cloze probabilities greater than 0.70 tend to be associated with positive- rather than negative-going potentials; those with cloze less than 0.70 elicit various amplitude N400s. It is also important to note that this relation between N400 amplitude and cloze probability is more subtle and smaller in amplitude than is the ERP difference between a con-

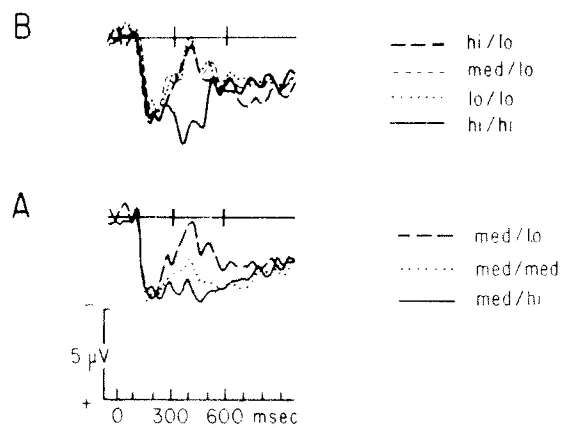

Fig. 7. The dissociable influence of contextual constraint and cloze probability on the ERPs elicited by sentence final words. The first part of the legend indicates the strength of the sentence in suggesting a particular completion (contextual constraint), the second part indicates how well the word presented conformed to this constraint (cloze probability). In A, the contextual constraint of the sentence is held constant. Shown are the responses to the most likely completions ('med/hi'), less likely but still congruous completions ('med/med'), and unlikely but congruous completions ('med/lo'). In B, it can be seen that a constant level of cloze probability results in very similar ERPs even though the contextual constraint of the sentence fragment is varied. All of responses to 'lo' cloze probability words contain large N400s, while 'hi' cloze probability words elicit a late positivity. Scalp site Pz, from a grand average of 14 subjects.

gruous and semantically anomalous word at the end of a sentence. Thus, it is not the type of effect that would be easy to pursue in case studies of normal or brain-damaged individuals.

The effects of contextual constraint, congruity, and cloze probability on word processing have also been assessed via behavioral measures; primary among these are the latencies to decide whether or not a string of letters is a word (i.e., lexical decision task, LDT) and the latency to begin to say the target word (i.e., naming or pronounciation latency task). Typically, subjects are shown the entire sentence context for several seconds followed by the target word 0.5–1 sec later, or allowed to present the sentence to themselves one word at a time. Most often different types of sentence contexts are contrasted to a so-called 'neutral' context, the form of which varies considerably across laboratories. Fast reaction times (RTs) relative to a neutral are referred to as facilitation, while prolonged RTs are referred to as inhibition. Inhibition for semantically incongruous sentence completions is a fairly common finding, especially with LDT. Facilitation for congruent sentence completions seems to be much more elusive. Indeed, there are those who contend that facilitation of word recognition by sentence contexts is restricted to (1) highly predictable final words (cloze probability greater than 0.9; e.g., Fischler and Bloom 1979), (2) degraded words (e.g., Stanovich and West 1979), (3) target words that occur at abnormally long delays after the sentence fragment, or (4) relatively poor readers (e.g., West and Stanovich 1978; Perfetti et al. 1979; Henderson 1982). Those who hold this view also tend to argue that there are no facilitatory effects of context during normal reading (e.g., Mitchell and Green 1978; Henderson 1982, pp. 351–353).

Our N400 data are more consistent with a view wherein semantic context has a gradual, incremental effect rather than a discrete facilitatory or inhibitory impact. In this scheme, it is difficult to define a neutral context. Even intuitively, it seems difficult to accept a row of XXXXs, a blank square or a sentence frame such as 'The next word is' repeated many times as a baseline from which facilitatory and inhibitory effects are to be derived (see De Groot et al 1982; Stanovich and West 1983 for discussion of neutral conditions). A word's predictability within its context is clearly a major determinant in how easily it is processed; and this ease is reflected in the amplitude of the N400 in highly constrained as well as unconstrained sentences. The N400 data suggest that there is a gradient of semantic influences not only for sentence final words but for words throughout sentences.

While cloze probability seems to correlate nicely with N400 amplitude, it would be unwieldy to obtain cloze probability estimates for every word in a sentence for several hundred sentences. Thus in her thesis Cyma Van Petten proposed that for English sentences a word's expectancy can be estimated from its ordinal position within a sentence. The logic is based on the idea that the first open class word of an isolated sentence is subject to few constraints relative to open class words near the end of a sentence. Given the sensitivity of N400 amplitude to contextual constraint, we would expect that the N400 would be larger to open class words at the beginning of a sentence relative to those near the end of a sentence. Van Petten not only confirmed this prediction but also showed that there was a relatively linear decrement in the amplitude of the N400 in a series of congruent sentences averaging 14 words or so (see Fig. 8 and Kutas et al. 1988). Note that these sentences were isolated and presented independent of any narrative structure. Their syntactic structure varied considerably from a simple monoclausal structure to the inclusion of embedded clauses. Word position was considered independent of such factors; it is at present unknown how the relation between word position, degree of contextual constraint, and N400 amplitude may vary with clause structure. Again, these are reliable but small effects that require averaging across many sentences (i.e., around 150) and many subjects (i.e., 20–30).

The sensitivity of N400 amplitude to contextual constraint raises the question of what constitutes contextual constraint. Semantic and syntactic grammatical constraints (e.g., subcategorizations, frames, thematic roles, etc.) are obvious choices. There is now considerable evidence that the N400 is sensitive to semantic constraints. Although a semantic anomaly seems to elicit the largest N400, its amplitude varies with the prior activation of a word or concept that is associatively or semantically related to it. This is the case whether the related word is actually presented or is just suggested by the context and whether the word eliciting the N400 is nonsensical or merely has a low semantic expectancy (i.e., cloze probability). Thus, for example, while both 'butter' and 'chair' would elicit a sizeable N400 if they terminated the sentence fragment 'She made a salami sandwich on wheat ______.', the N400 following 'butter' would be smaller in amplitude because of its semantic association to the suggested (but not received) word 'bread' (see Fig. 9).

A similar reduction in the N400 component is ob-

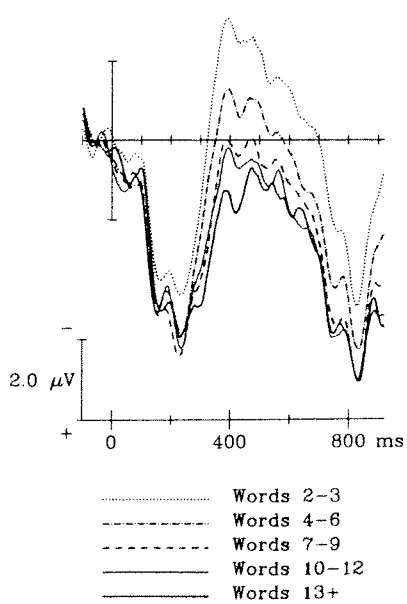

Fig. 8. ERPs to intermediate content words occurring in different ordinal positions of 240 congruent sentences. Scalp site Pz from a grand average of 28 subjects.

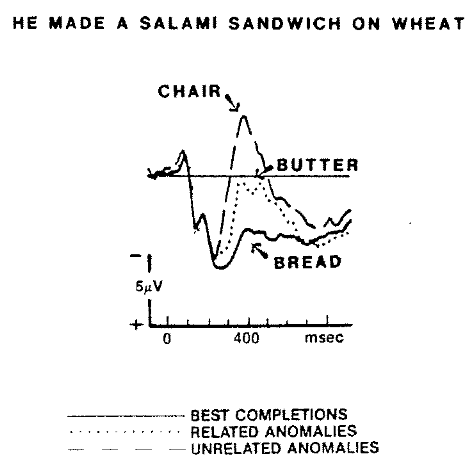

Fig. 9. The effects of sentence and word level context. Subjects saw 1 of the 3 possible completions to the sentence fragment. Scalp site Pz, from a grand average of 10 subjects.

served if the context is a single word instead of a sentence fragment (Harbin et al. 1984; Bentin et al. 1985; Holcomb 1987; Kutas and Hillyard 1988). That is, the N400 component of the ERP to the word 'dog' is significantly smaller in amplitude if it is preceded by 'cat' than by 'table.' Were one to measure either pronunciation or lexical decision latencies with such 'prime-target' word pairs, the speeded reactions for the related relative to unrelated items would be attributed to semantic priming. We follow the same logic to infer semantic priming from the amplitude variation of the N400 component.

In contrast to the overwhelming evidence for the N400's sensitivity to semantic constraints, to date there is little support for the notion idea that the N400 is also sensitive to syntactic constraints. In part, this is due to the fact that there have been relatively few attempts to manipulate syntactic variables in such studies. However, in one study we found that violations of noun-verb number agreement (i.e., 'they is' versus 'they are') and of verb tense (i.e., 'are find' instead of 'are found') did not elicit clear N400 effects (Kutas and Hillyard 1983). Such morphological violations, however, are relatively mild compared to the types of semantic violations that we have used and may well have gone unnoticed.

As part of her thesis work, Van Petten (see Van Petten and Kutas 1990b) examined the extent to which syntactic constraints could account for the amplitude decrement of the N400 across the course of a normal sentence. Specifically, she presented subjects with 3 different sentence types randomly intermixed. These were: (1) congruent sentences, which contained both normal semantic and syntactic constraints, (2) 'syntactic sentences,' which obeyed the syntactic structure of standard American English but were relatively nonsensical; and (3) 'random sentences' comprised of a random ordering of words that violated both the semantic and syntactic constraints of English. The results were very clear on two counts. First, in a global sense the ERPs to the 'random' sentences were markedly different from those to either the congru-

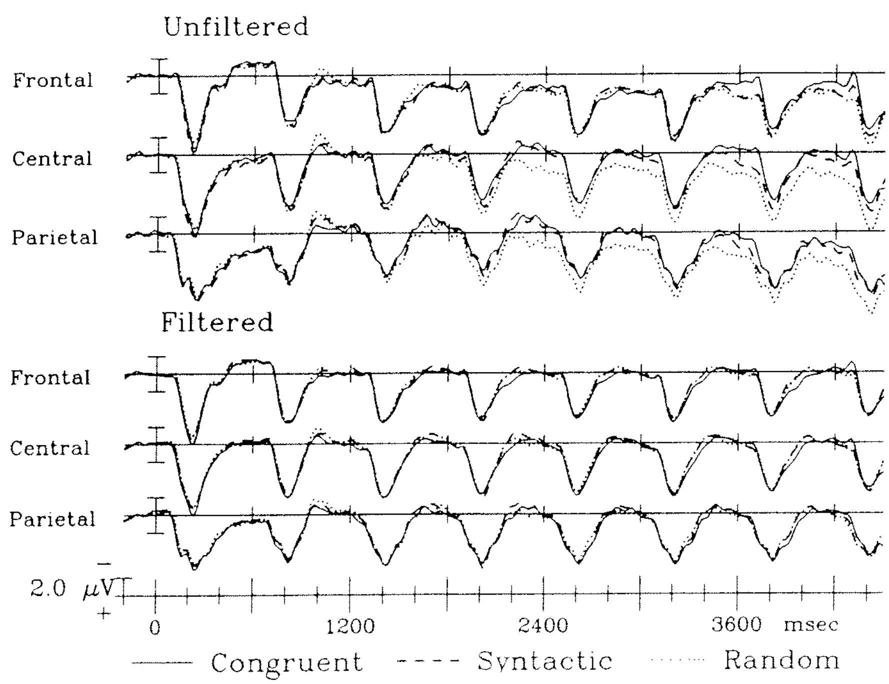

Fig. 10. ERPs to the first 7 words of 3 different types of word strings, presented at a rate of 1 word every 600 msec. 'Congruent' = normal sentences, 'syntactic' = syntactically legal but nonsensical, 'random' = random word strings. The top half of the figure shows the original data recorded with amplifier bandpass of 0.01–30 Hz (half amplitude cut-off). Note the slow positive potential which develops as subjects read random word strings, beginning around the fourth word. The differentially sloping baselines make it difficult to compare ERPs across word positions and sentence types. The bottom panel shows the same data after digital high pass filtering. Removal of the low frequency positive potential has equated the activity immediately preceding each new word, allowing more valid comparisons of the higher frequency ERP components elicited by individual words. Midline sites Fz, Cz, Pz, from a grand average of 38 subjects.

ent or the 'syntactic' sentences. That is, the prolonged slow potential shifts which have been associated with changes in arousal and effort (McCallum 1988) were decidedly positive-going in association with the 'random' sentences (see Fig. 10). It is as if the subjects either intentionally gave up in the 'random' condition or were incapable of calling upon and sustaining the same operations that they summoned in the presence of structural and/or semantic constraints. These findings suggest that such 'random' conditions may be so qualitatively different in the processes they invoke that they do not lend themselves to being good control or baseline conditions.

However, if we focus on the N400 component within the ERP elicited by open class words within each of the sentence types, the differential effects of semantic and syntactic constraints were also quite striking (see Fig. 11). Neither the 'syntactic' nor the 'random' sentences displayed a reduction in N400 amplitude as a function of a word's ordinal position within its sentence; nor were the N400s elicited by open class words in these two conditions significantly different from each other in amplitude (Van Petten and Kutas 1990b). This stands in contrast to the N400s elicited by open class words in the congruent sentences which not only were significantly smaller than those in the two sentence types free of semantic constraints but also were characterized by a cumulative reduction in amplitude with increasing ordinal position. Thus, the processing of open class words as reflected in the amplitude of the associated N400 components seems to be directed by semantic rather than syntactic constraints. This finding may reflect the minor role that structural constraints play in the recognition of open class words in general, or may be a more specific consequence of sentences with relatively high contextual constraint read at a relatively slow rate.

Van Petten also examined the effects of semantic and structural constraints on the processing of closed class words. Remember that closed class words have significantly smaller N400s than do open class words. Nonetheless, it is still possible to compare the N400 region of the ERP to closed class items with varying semantic and structural constraints. As for the open class words, the N400 component of closed class ERPs was smaller if the words were embedded in congruent as opposed to 'random' sentences; that is, the

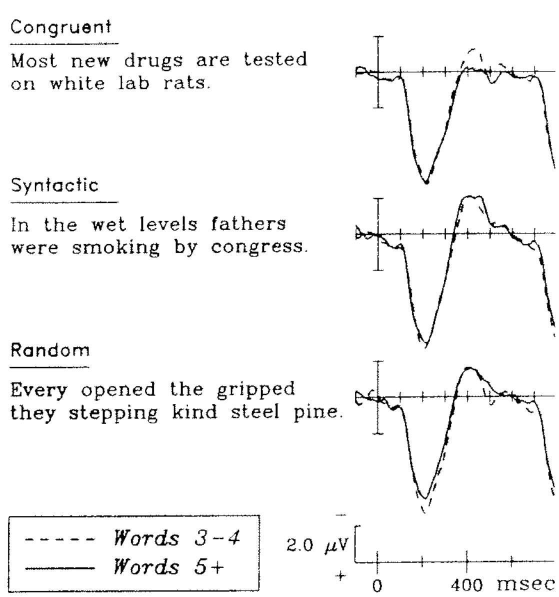

Fig. 11. Single word ERPs from the experiment shown in Fig. 10, after filtering. Shown are the responses to intermediate content words from different sentence positions. Scalp site Cz. Grand average of 38 subjects.

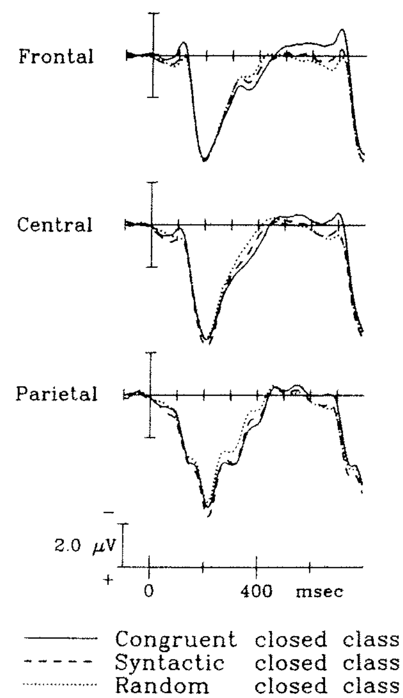

Fig. 12. Closed class ERPs from the experiment shown in Figs. 10 and 11. Two effects of sentence type are apparent: (1) an N400-like negativity which is largest for random words, intermediate in amplitude for syntactic words, and smallest for congruent words; and (2) a later frontal negativity which distinguishes congruent words from function words in the other 2 'sentence' types.

presence of constraints significantly attenuated N400 amplitude for closed class words (see Fig. 12). However, unlike for the open class words, this attenuation was not incremental. It was no greater for words in the latter half of sentences than for those near the beginnings; that is, the effect of structural constraints appears to be more local. Also, in contrast to the open class words, closed class words appeared to be sensitive not just to semantic constraints but also to the presence of structural constraints. N400s were reduced in response to closed class words occurring in 'syntactic' as opposed to the 'random' sentences.

Overall, our findings suggest that contextual constraints are used in word recognition as needed. Within structurally simple sentences, structural factors add little to semantic influences in constraining the meaning of open class words but do aid in the analysis of closed class words. We also find little support for a dichotomous distinction between open and closed class words per se. Further research is necessary to determine whether similar patterns would be observed in more complex sentences and to further define the factors that constitute semantic and structural constraints. The exquisite sensitivity of the ERP to contextual constraints indicates that such questions are amenable to empirical investigation.

References

Aaronson, D. and Scarborough, H.S. Performance theories of sentence coding: some quantitative models. *J. Verb. Learn. Verb. Behav.*, 1977, 16: 277–303.

Bentin, S., McCarthy, G. and Wood, C.C. Event-related potentials associated with semantic priming. *Electroenceph. clin. Neurophysiol.*, 1985, 60: 343–355.

Bradley, D. *Computational Distinctions of Vocabulary Type*. Ph.D. Dissertation, Massachusetts Institute of Technology, Cambridge, MA, 1978.

Bradley, D. *Effects of Vocabulary Type on Word Recognition*. Occasional Paper 12. MIT Center for Cognitive Science, Cambridge, MA, 1980.

Bradley, D. and Garrett, M. Hemisphere differences in the recognition of closed and open class words. *Neuropsychologia*, 1983, 21: 155–160.

Bradley, D., Garrett, M. and Zurif, E.B. Syntactic deficits in Broca's aphasia. In: D. Caplan (Ed.), *Biological Studies of Mental Processes*. MIT Press, Cambridge, MA, 1980: 269–286.

Brown, K.T. The electroretinogram: its components and their origins. *Vision Res.*, 1968, 8: 633–677.

Chen, H.-C. Effects of reading span and textual coherence on rapid-sequential reading. *Mem. Cogn.*, 1986, 14: 202–208.

Chiarello, C. and Nuding, S. Visual field effects for processing content and function words. *Neuropsychologia*, 1987, 25: 539–548.

Cocklin, T.G., Ward, N.J., Chen, H.-C. and Juola, J.F. Factors influencing readability of rapidly presented text segments. *Mem. Cogn.*, 1984, 12: 431–442.

De Groot, A.M.B., Thomassen, A.J.W.M. and Hudson, P.T.W. Associative facilitation of word recognition as measured from a neutral prime. *Mem. Cogn.*, 1982, 10: 358–370.

Fischler, I.S. and Bloom, P.A. Automatic and attentional processes in the effects of sentence contexts on word recognition. *J. Verb. Learn. Verb. Behav.*, 1979, 5: 1–20.

Fodor, J.A. and Bever, T.G. The psychological reality of linguistic segments. *J. Verb. Learn. Verb. Behav.*, 1965, 4: 414–420.

Forster, K.I. Visual perception of rapidly presented word sequences of varying complexity. *Percept. Psychophys.*, 1970, 8: 215–221.

Friederici, A.D. Levels of processing and vocabulary types: evidence from on-line comprehension in normals and agrammatics. *Cognition*, 1985, 19: 133–166.

Friederici, A.D. and Schoenle, P.W. Computational distinction of two vocabulary types: evidence from aphasia. *Neuropsychologia*, 1980, 18: 11–20.

Garnsey, S.M. *Function Words and Content Words: Reaction Time and Evoked Potential Measures of Word Recognition. Cognitive Science Technical Report (URCS-29)*. University of Rochester, New York, 1985.

Garrett, M. Word and sentence perception. In: R. Held, H.W. Leibowitz and H.-L. Teuber (Eds.), *Handbook of Sensory Physiology, Vol. VIII. Perception*. Springer, Berlin, 1978: 611–626.

Garrett, M.F., Bever, T.G. and Fodor, J. The active use of grammar in speech perception. *Percept. Psychophys.*, 1966, 1: 30–32.

Gernsbacher, M.A. and Hargreaves, D.J. Accessing sentence participants: the advantage of first mention. *J. Mem. Lang.*, 1988, 27: 699–711.

Glucksberg, S. Commentary: The functional equivalence of common and multiple codes. *J. Verb. Learn. Verb. Behav.*, 1984, 23: 100–104.

Gordon, B. and Caramazza, M. Lexical decision for open- and closed-class words: failure to replicate differential frequency sensitivity. *Brain Lang.*, 1982, 19: 335–345.

Harbin, T.J., Marsh, G.R. and Harvey, M.T. Differences in the late components of the event-related potential due to age and to semantic and non-semantic tasks. *Electroenceph. clin. Neurophysiol.*, 1984, 59: 489–496.

Henderson, L. *Orthography and Word Recognition in Reading*. Academic Press, New York, 1982.

Holcomb, P.J. Unimodal and multimodal models of lexical memory: an ERP analysis. *Psychophysiology*, 1985, 22: 576 (abstract).

Holcomb, P.J. Automatic and attentional processing: an event-related brain potential analysis of semantic processing. *Brain Lang.*, 1988, 35: 66–85.

Juola, J.F., Ward, N.J. and McNamara, T. Visual search and reading of rapid serial presentations of letter strings, words, and text. *J. Exp. Psychol.: Gen.*, 1982, 111: 208–227.

Just, M.A. and Carpenter, P.A. Inference processes during reading: reflections from eye fixations. In: J.W. Senders, D.F. Fisher and R.A. Monty (Eds.), *Eye Movements and the Higher Psychological Functions*. Erlbaum, Hillsdale, NJ, 1978.

Just, M.A. and Carpenter, P.A. A theory of reading: from eye fixations to comprehension. *Psychol. Rev.*, 1980, 87: 329–354.

Just, M.A., Carpenter, P.A. and Woolley, J.D. Paradigms and processes in reading comprehension. *J. Exp. Psychol.: Gen.*, 1982, 111: 228–238.

Kolers, P.A. and Brison, S.J. Commentary: on pictures, words, and their mental representation. *J. Verb. Learn. Verb. Behav.*, 1984, 23: 105–113.

Kolk, H.H.J. and Blomert, L. On the Bradley hypothesis concerning agrammatism: the nonword interference effect. *Brain Lang.*, 1985, 26: 94–105.

Kroll, J.F. and Potter, M.C. Recognizing words, pictures and concepts: a comparison of lexical, object, and reality decisions. *J. Verb. Learn. Verb. Behav.*, 1984, 23: 39–66.

Kutas, M. Event-related brain potentials (ERPs) elicited during rapid serial visual presentation of congruous and incongruous sentences. In: R. Johnson, Jr., R. Parasuraman and J.W. Rohrbaugh (Eds.), *Current Trends in Event-Related Brain Potential Research. Electroenceph. Clin. Neurophysiol. Suppl. 40.* Elsevier, Amsterdam, 1987: 406–411.

Kutas, M. and Hillyard, S.A. Reading senseless sentences: brain potentials reflect semantic incongruity. *Science*, 1980a, 207, 203–205.

Kutas, M. and Hillyard, S.A. Event-related brain potentials to semantically inappropriate and surprisingly large words. *Biol. Psychol.*, 1980b, 11: 99–116.

Kutas, M. and Hillyard, S.A. The lateral distribution of event-related potentials during sentence processing. *Neuropsychologia*, 1982, 20: 579–590.

Kutas, M. and Hillyard, S.A. Event-related brain potentials to grammatical errors and semantic anomalies. *Mem. Cogn.*, 1983, 11: 539–550.

Kutas, M. and Hillyard, S.A. Brain potentials during reading reflect word expectancy and semantic association. *Nature*, 1984, 307: 161–163.

Kutas, M. and Hillyard, S.A. An electrophysiological probe of incidental semantic association. *J. Cogn. Neurosci.*, 1988, 1: 38–49.

Kutas, M. and Van Petten, C. Event-related brain potential studies of language. In: P.K. Ackles, J.R. Jennings and M.G.H. Coles (Eds.), *Advances in Psychophysiology, Vol. 3.* JAI Press, Greenwich, CT, 1988: 139–187.

Kutas, M., Lindamood, T. and Hillyard, S.A. Word expectancy and event-related brain potentials during sentence processing. In: S. Kornblum and J. Requin (Eds.), *Preparatory States and Processes.* Erlbaum Press, Hillsdale, NJ, 1984: 217–238.

Kutas, M., Neville, H.J. and Holcomb, P.J. A preliminary comparison of the N400 response to semantic anomalies during reading, listening, and signing. In: R.J. Ellingson, N.M.F. Murray and A.M. Halliday (Eds.), *Electroenceph. clin. Neurophysiol., Suppl. 39. The London Symposia.* Elsevier, Amsterdam, 1987: 325–330.

Kutas, M., Van Petten, C. and Besson, M. Event-related potential asymmetries during the reading of sentences. *Electroenceph. clin. Neurophysiol.*, 1988, 69: 218–233.

Marin, O.S.M., Saffran, E.M. and Schwartz, M.F. Dissociations of language in aphasia: implications for normal functions. *Ann. NY Acad. Sci.*, 1976, 280: 868–884.

Masson, M.E. Conceptual processing of text during skimming and rapid sequential reading. *Mem. Cogn.*, 1983, 11: 262–274.

Masson, M.E. Comprehension of rapidly presented sentences: the mind is quicker than the eye. *J. Mem. Lang.*, 1986, 25: 588–604.

McCallum, W.C. Potentials related to expectancy, preparation and motor activity. In: T.W. Picton (Ed.), *Human Event-Related Potentials. Handbook of Electroencephalography and Clinical Neurophysiology (revised series), Vol. 3.* Elsevier, Amsterdam, 1988: 427–534.

McCallum, W.C., Farmer, S.F. and Pocock, P.K. The effects of physical and semantic incongruities on auditory event-related potentials. *Electroenceph. clin. Neurophysiol.*, 1984, 59: 477–488.

Mitchell, D.C. and Green, D.W. The effects of context and content on immediate processing in reading. *Quart. J. Exp. Psychol.*, 1978, 30: 609–636.

Neville, H.J. Biological constraints on semantic processing: a comparison of spoken and signed language. *Psychophysiology*, 1985, 22: 576 (abstract).

Paivio, A. *Imagery and Verbal Processes.* Holt, Rinehart and Winston, New York, 1971.

Paivio, A. *Mental Representation: a Dual-Coding Approach.* Oxford University Press, New York, 1986.

Perfetti, C.A., Goldman, S.R. and Hogaboam, T.W. Reading skill and the identification of words in discourse context. *Mem. Cogn.*, 1979, 7: 273–282.

Petocz, A. and Oliphant, G. Closed class words as first syllables do interfere with lexical decisions for nonwords: implications for theories of agrammatism. *Brain Lang.*, 1988, 34: 127–146.

Potter, M.C., Kroll, J.F. and Harris, C. Comprehension and memory in rapid sequential reading. In: R. Nickerson (Ed.), *Attention and Performance VIII.* Erlbaum, Hillsdale, NJ, 1980.

Pylyshyn, Z.W. What the mind's eye tells the mind's brain: a critique of mental imagery. *Psychol. Bull.*, 1973, 80: 1–24.

Rosenberg, B., Zurif, E., Brownell, H., Garrett, M. and Bradley, D. Grammatical class effects in relation to normal and aphasic sentence processing. *Brain Lang.*, 1985, 26: 287–303.

Segui, J., Mehler, J., Frauenfleder, W. and Morton, J. The word frequency effect and lexical access. *Neuropsychologia*, 1982, 20: 615–627.

Stanovich, K.E. and West, R.F. Mechanisms of sentence context effects in reading: automatic activation and conscious attention. *Mem. Cogn.*, 1979, 7: 77–85.

Stanovich, K.E. and West, R.F. On priming by a sentence context. *J. Exp. Psychol.: Gen.*, 1983, 112: 1–36.

Van Petten, C. and Kutas, M. Semantic versus syntactic context and the word frequency effect. *Psychophysiology*, 1988, 25: 487.

Van Petten, C. and Kutas, M. Interactions between sentence context and word frequency in event-related brain potentials. *Mem. Cogn.*, 1990a, 18: 380–393.

Van Petten, C. and Kutas, M. Influences of semantic and syntactic context on open and closed class words. *Mem. Cogn.*, 1990b, in press.

West, R.F. and Stanovich, K.E. Automatic contextual facilitation in readers of three ages. *Child Dev.*, 1978, 49: 717–727.

Woldorff, G. *Auditory Selective Attention in Humans: Analysis of Mechanisms Using Event-Related Brain Potentials.* Doctoral Dissertation. University of California, San Diego, CA, 1989.