

## Brain potentials during reading reflect word expectancy and semantic association

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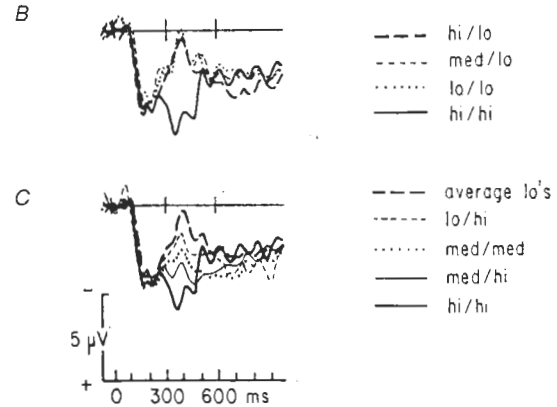
The neuroelectric activity of the human brain that accompanies linguistic processing can be studied through recordings of event-related potentials (e.r.p. components) from the scalp. The e.r.p.s triggered by verbal stimuli have been related to several different aspects of language processing<sup>1</sup>. For example, the N400 component, peaking around 400 ms post-stimulus, appears to be a sensitive indicator of the semantic relationship between a word and the context in which it occurs. Words that complete sentences in a nonsensical fashion elicit much larger N400 waves than do semantically appropriate words or non-semantic irregularities in a text<sup>2,3</sup>. In the present study, e.r.p.s were recorded in response to words that completed meaningful sentences. The amplitude of the N400 component of the e.r.p. was found to be an inverse function of the subject's expectancy for the terminal word as measured by its 'Cloze probability'. In addition, unexpected words that were semantically related to highly expected words elicited lower N400 amplitudes. These findings suggest N400 may reflect processes of semantic priming or activation.

Late negative e.r.p.s resembling the N400 have been observed in experiments that required subjects to make decisions about words based on their semantic attributes,<sup>4-7</sup> and Stuss *et al.*<sup>8</sup> noted an N400-like component following isolated, single words or pictures that required naming. One likely interpretation of these findings would assume that N400 amplitude reflects the extent to which a word is unpredictable or unexpected, regardless of whether or not it is incongruous with a preceding context. Since word expectancy influences how rapidly and accurately words are accessed, recognized and understood<sup>9</sup>, a physiological index of this process would have considerable usefulness for revealing the structure of language comprehension mechanisms.

We examined this relationship by recording e.r.p.s to words that completed sentences in a meaningful way but varied systematically in the degree to which they were expected. The sentences were selected from a set in which the degree of expectancy for alternative terminal words had been determined using the 'Cloze' procedure; that is, by requiring a large group of subjects to fill in the missing terminal word<sup>10</sup>. A word's Cloze probability is defined as the proportion of subjects using that word to complete a particular sentence. The experimental design called for words having different Cloze probabilities (hi, med, or lo) to be placed at the ends of sentences having one of three levels of contextual constraint (hi, med, or lo). Highly constrained sentences were those that led to very predictable endings, while sentences of low constraint did not induce such strong expectations (for examples see Fig. 1A).

A total of 321 sentences were presented, one word at a time, on a video terminal controlled by a microcomputer. Words were presented once every 700 ms for a duration of 132 ms. Fourteen subjects were instructed to read the sentences silently in order to answer a questionnaire about their contents at the end of the experiment. Scalp electrical activity was recorded using non-polarizable electrodes from frontal (Fz), central (Cz), parietal (Pz), and occipital (Oz) midline locations and from symmetrical sites over the anterior temporal (AT) and posterior temporal (PT) regions of the left (L) and right (R) hemispheres, each referred to linked mastoids. Eye movements and blinks were monitored via infraorbital and external canthal electrodes. The midline recordings were amplified with a bandpass of 0-40 Hz; the lateral recordings and electrooculogram with a 0.01-40 Hz bandpass.

A	hi/hi	He mailed the letter without a <u>stamp</u> .
	hi/lo	The bill was due at the end of the <u>hour</u> .
	med/hi	She locked the valuables in the <u>safe</u> .
	med/med	Too many men are out of <u>jobs</u> .
	med/lo	The dog chased our cat up the <u>ladder</u> .
	lo/hi	There was nothing wrong with the <u>car</u> .
	lo/lo	He was soothed by the gentle <u>wind</u> .



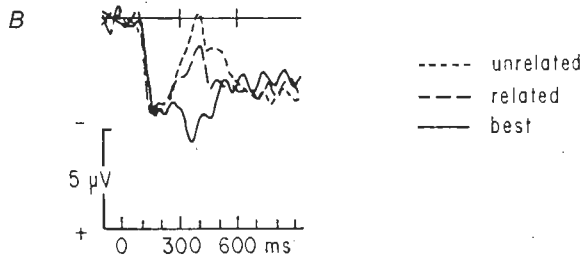
**Fig. 1** A, An example from each of seven classes of sentences that varied in degree of contextual constraint and in the Cloze probability of the terminal word. There were 40-50 of each sentence type. On the left are shown the levels of contextual constraint/Cloze probability for each class. These two dimensions are not wholly independent, since only the more highly constrained sentences have the possibility of being terminated by words of very high Cloze probability. Thus, the level of Cloze probability considered to be 'hi' was relative to the level of contextual constraint, having average values of 0.92, 0.63 and 0.29 for the hi/hi, med/hi and lo/hi sentences, respectively. All of the low Cloze probability sentences, however, had average values of less than 0.03. B, Superimposition of grand average e.r.p.s (across 14 subjects) from the Pz electrode to the low Cloze probability words terminating sentences of high, medium and low contextual constraint, together with the e.r.p. to high Cloze probability words completing highly constrained sentences. C, Grand average e.r.p.s to terminal words of varying Cloze probability terminating sentences of high, medium and low contextual constraint. The e.r.p. to low Cloze probability words was averaged across the three levels of contextual constraint shown in B.

The e.r.p. waveforms in Fig. 1B show that highly probable words at the ends of highly constrained sentences were followed by a broad, late positivity (hi/hi, solid tracing). In contrast, the low probability words elicited a posteriorly distributed negative component (N400) that was superimposed upon the positive shift. The N400 amplitude to the low probability endings did not vary significantly over the three levels of contextual constraint (compare dotted and dashed tracings).

The N400 was measured as the mean amplitude over 300-500 ms post-stimulus, relative to a 50 ms prestimulus baseline. In general, the N400 amplitude was more sensitive to Cloze probability than to the degree of contextual constraint. For example, the e.r.p.s to lo/hi versus med/med words, which were very similar in average Cloze probability (0.29 versus 0.23) but completed sentence fragments of low and medium constraint, respectively, did not differ significantly in N400 amplitude. On the other hand, comparisons of the e.r.p.s to high, medium and low probability words terminating sentences of medium constraint revealed larger N400 amplitudes to the less probable words [main effect of ending Cloze probability  $F(2,26) = 12.94$ ,  $P < 0.001$ ; ending  $\times$  electrode  $F(14,182) = 6.07$ ,  $P < 0.001$ ].

Inspection of the e.r.p.s to all types of terminal words (Fig. 1C) revealed a gradient of potential, with the greatest positivity following hi/hi words and a progressively larger negativity

- A
- (best) Don't touch the wet paint.
- (unrelated) Don't touch the wet dog.
- (best) He liked lemon and sugar in his tea.
- (related) He liked lemon and sugar in his coffee.



**Fig. 2** A, Two examples of sentences with high contextual constraints completed by low Cloze probability words. Above each experimental sentence is the same sentence terminated by its 'best completion', which was or was not semantically related to the word that was actually presented in the sentence below. B, Grand average e.r.p.s from Pz for the best completions (solid waveform), the semantically related (large dashed waveform) and the semantically unrelated (small dashed waveform) low Cloze probability words.

(N400) elicited by words of decreasing Cloze probability. This relationship between Cloze probability and N400 amplitude was also evidenced by the product-moment correlations between the two measures across the seven classes of word endings [for the grand average e.r.p.s, Fz, 0.80; Cz, 0.90; Pz, 0.92; Oz, 0.92; L.AT, -0.82; R.AT, 0.94; L.PT, 0.88; R.PT, 0.97]. At the parietal site, this correlation calculated from individual subjects' data averaged 0.70 (0.21) and reached significance in seven subjects ( $d.f. = 5$ ,  $P < 0.05$ ). This correlation also held when the e.r.p. data were collapsed across the different levels of contextual constraint and re-averaged according to the Cloze probability of the final words [Fz, 0.87; Cz, 0.91; Pz, 0.94; Oz, 0.92; L.AT, -0.60; R.AT, 0.75; L.PT, 0.91; R.PT, 0.93]. The negative correlation observed at the left anterior temporal site could result from this scalp region being located on the opposite side of the dipole field of the N400 generator.

The systematic decline in the N400 amplitude as a function of increasing Cloze probability indicates that semantic incongruity is not a necessary condition for N400 elicitation. Instead, N400 amplitude appears to vary systematically as an inverse function of word expectancy, operationally defined here in terms of Cloze probability.

The influence of context on word recognition has been attributed to the automatic priming or activation of semantic networks, as well as to slower, attention-directed processes<sup>11-13</sup>. Within such a framework, a sentence fragment primes (that is,

activates for faster access) semantically related words whether or not they form acceptable sentence completions. In addition, sentence frames may result in the activation and retrieval of appropriate schemata<sup>14-16</sup>. If the N400 reflects some aspect of this semantic activation, its amplitude should vary according to whether or not an unexpected terminal word is semantically related to the most expected ending of that sentence (that is to the 'best completion' of the activated schema).

We tested this prediction by reanalysing the e.r.p.s to low Cloze probability words that completed highly constrained sentences, now segregating them according to whether or not the terminal word was related to the best completion (BC) of the sentence in which it occurred. The degree of semantic relatedness had been determined by asking a different group of 25 subjects to rate each word pair on a 5-point scale. The mean ratings were 4.03 (0.70) and 1.95 (0.73) for the related and unrelated word pairs, respectively. Sample sentences are shown in Fig. 2A. N400 amplitude was indeed sensitive to the semantic relationship between the eliciting word and the expected best completion (Fig. 2B), with larger N400s following words that were unrelated to the BC [main effect of semantic relatedness  $F(1,13) = 17.37$ ,  $P < 0.001$ ; relatedness  $\times$  electrode  $F(7,97) = 3.14$ ,  $P < 0.001$ ].

These results are in agreement with the hypothesis that the N400 component reflects the extent to which a word is semantically primed, rather than its being a specific response to contextual violations. If the N400 amplitude proves to be a valid index of semantic priming, it should become possible to investigate the timing and spread of activation within semantic networks and knowledge schemata and to identify automatic and attentional components of processing.

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