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Electrophysiological evidence for task effects on semantic priming in auditory word processing

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Abstract

Event-related brain potentials (ERPs) associated with semantic relatedness were recorded in two auditory word recognition tasks. In the Memorize task, subjects listened to a list of words in anticipation of a subsequent recognition test. In the Count Nonwords task, subjects silently counted the number of nonwords occurring within a list of words. Within each list, target words were either semantically related or unrelated to the immediately preceding word. As in comparable visual tasks, the amplitude of a negative ERP component (N400) was significantly attenuated when targets were preceded by semantically related primes. This attenuation was greater in the Memorize than in the Count Nonwords task. These data are consistent with the view that the sensitivity of N400 amplitude to semantic relatedness is modulated by task variables that manipulate depth of processing.

Descriptors: Semantic priming, Lexical decision, N400, Auditory word processing

There is ample evidence that semantic priming plays an important role in word perception. Single target words presented in a sequence are processed faster and more accurately if they immediately follow a semantically related or associated prime than if they are unrelated to the preceding item in the list. These effects have been demonstrated in a variety of tasks including lexical decision (e.g., Becker, 1979; DeGroot, Thomassen, & Hudson, 1982; Meyer & Schvaneveldt, 1971; Neely, 1977), pronunciation (Frost, Katz, & Bentin, 1987), word identification (Morton, 1969), and rhyme monitoring (Donnenwerth-Nolan, Tanenhaus, & Seidenberg, 1981), using both performance (reaction time [RT] and accuracy) and electrophysiological measures (for recent reviews, see Bentin, 1989; Kutas & Van Petten, 1988).

Although semantic priming is mediated in part by automatic processes (Antos, 1979; Fishler, 1977; Neely, 1977), it is also influenced by task-related strategies. For example, in tasks that require attention to the individual letters of the prime, semantic priming effects are smaller than when attention is directed to its phonological structure or lexical identity; the largest priming effects are obtained when semantic attributes of the primes are attended (Henik, Friedrich, & Kellogg, 1983; Smith, 1979; Smith, Theodor, & Franklin, 1983). Such task-related effects can be explained in terms of concepts originally developed within the *levels of processing* framework (Craik & Lockhart, 1972; Jacoby & Craik, 1979). By this view, a "shallow" task (such as the letter search) does not require semantic processing of the stimulus (see also Graf & Mandler, 1984). If the prime is processed only at a shallow level, its semantic context is presumably not included in the formation of the episodic trace. Accordingly, any semantic priming observed in this case would stem only from automatic spreading of activation within the semantic network. However, in a "deep" task that requires semantic processing, it is assumed that more attention is directed to semantic "neighbors" so as to form a durable episodic trace. In that case, semantic priming also may result from the intentional activation of semantic attributes common to prime and target.

According to the logic of the levels of processing theory the level at which the *target* is processed should also influence semantic priming. The effect of varying the level of processing of target words has not been examined as thoroughly, possibly because the standard procedures for assessing semantic priming (such as lexical or semantic categorization tasks) generally require deep processing of targets. However, in the pronunciation task, which can in some cases be performed using shallow grapheme-to-phoneme translation rules, semantic priming effects are either smaller than those in lexical decision tasks or completely absent (Forster, 1981; Lupker, 1984). One benefit of applying event-related potential (ERP) methods to the study of semantic priming is that an expanded range of tasks that do not require any overt behavior can be used.

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Previous ERP studies of semantic priming in visual word perception have shown that the amplitude of a negative (or negative going) waveform peaking at about 400 ms (N400) is attenuated when a sentence-terminating word is semantically related to the expected completion of the preceding sentence fragment (Kutas & Hillyard, 1980, 1984) or when a target word is semantically related to the immediately preceding word in a lexical decision task (Bentin, McCarthy, & Wood, 1985; Rugg, 1985). Thus, the modulation of N400 amplitude was taken as an electrophysiological index of semantic priming. In accord with this proposal, Bentin, McCarthy, and Wood (1984) found that a semantic relationship between two consecutive words in a visually presented study list (in anticipation of a memory probe) produced a similar N400 reduction. These results indicated that in the absence of overt behavior, semantic priming effects between single words can be seen by N400 modulation. In the present study, we employed this ERP measure to examine semantic priming effects while manipulating the amount of semantic elaboration needed during processing of both primes and targets.

Two tasks were chosen that were found in a previous study of visual word repetition on ERPs to have different effects on a positive component identified as P300 (Bentin & Peled, 1990). In one task, subjects studied a list of words in anticipation of a recognition test. In the other task, subjects kept a silent count of nonwords that were occasionally presented within a list of words (i.e., a lexical decision task). Although both the recognition and the lexical decision tasks might be performed successfully without any attention being paid to a word's meaning and/or the relation between words, there is ample evidence from the levels of processing tradition that performance on memory tasks is enhanced by directing attention to meanings during initial encoding (Craik & Lockhart, 1972; Jacoby & Craik, 1979). Thus, we anticipated that the N400s in the recognition memory task would be more sensitive to the activation of the semantic information both within and between words relative to the lexical decision task in which nonwords were counted.

We chose to present the words in the auditory modality for several reasons. First, it was important to expand the scope of N400 research in the area of speech processing; N400 effects during auditory word perception have been examined considerably less often than in the visual modality. The few ERP studies of speech perception suggest that N400s elicited by spoken words are sensitive to semantic priming both during sentence processing and lexical decision paradigms (Holcomb & Neville, 1990; McCallum, Farmer, & Pocock, 1984). Moreover, although behavioral evidence for semantic priming during speech processing is relatively scarce (Frauenfelder & Tyler, 1987), there are some indications that semantic priming facilitates the processing of spoken words in both sentence (Marslen-Wilson, 1975; Marslen-Wilson & Welsh, 1978) and single word (Donnenwerth-Nolan et al., 1981; Milberg, Blumstein, & Dworetzky, 1988; Radeau, 1983) contexts.

Second, a subsequent experiment was planned to evaluate semantic processing in an unattended speech channel using the N400 as an index. However, to integrate the results obtained during dichotic stimulus presentations, we needed to find a task in which semantic relations would reliably modulate N400 amplitudes whenever the stimuli were in the focus of attention but did not require an overt response. This reason motivated both the choice of the auditory modality and the particular two tasks that were used in the present study.

Methods

Subjects

The subjects were 16 paid native English speakers (6 men, 10 women), all with normal hearing and ranging between 19 and 30 years in age. They were all right handed (by self-report) and without any left-handed relatives in their immediate family.

Stimuli

The stimuli consisted of 576 words and 64 nonwords. The frequency of usage of the words ranged between 10 and 2,110 per million occurrences (Francis & Kucera, 1982), with a mean frequency of 83.7. The nonwords were pronounceable phonological patterns without meaning in English. All stimuli were tape recorded in a male voice and digitized (at 10,000 Hz) using the Haskins Laboratories PCM input/output system. Following A/D conversion, each word was edited to eliminate irrelevant noises and silent periods at onset. In addition, differences among word durations were minimized, without affecting intelligibility. The durations of the stimuli ranged from 310 ms to 790 ms with a median of 460 ms, equally distributed across words and nonwords. An IBM-AT compatible computer equipped with a Data Translation 2821 D/A card was used for reproduction; D/A aliasing was avoided by low-pass filtering at output. The stimuli were presented monaurally through headphones at a comfortable intensity either to the right or the left ear, counterbalanced across subjects. The use of monaural stimulus presentation was motivated by our intention to use these data as a baseline for comparison with ERP results in a subsequent experiment using dichotic stimulation. Stimulus onset asynchrony (SOA) was 1,750 ms; interstimulus interval (ISI) varied with stimulus duration.

Procedures

Each subject experienced two tasks. One was a recognition memory task in which subjects were instructed to listen carefully to the words with the understanding that they would be required to recognize them later (Memorize task). The other was an adaptation of a lexical decision task in which subjects were instructed to count silently the number of nonwords randomly interspersed within a list of words (Count Nonwords task).

Two lists of 320 stimuli each were assembled. Each list contained 128 pairs of semantically related words; one word in each pair was designated the prime and the other the target. The semantically related pairs in each list comprised 40 pairs of antonyms and 88 pairs of semantic category exemplars. The strength of the semantic association was determined as follows. Eighty undergraduates (none included in the ERP study) were asked to rate the degree of the semantic association of 408 related word pairs on a scale from 1 (weakly associated) to 5 (strongly associated). Only pairs with a mean rating (across subjects) above 2.95 were chosen for this study. The mean rating of the pairs in List A was 3.339 and in List B was 3.335. The average frequency of the words in List A was 83.64 for targets and 72.8 for primes. In List B, the word frequency was 83.88 for targets and 91.3 for primes. In addition to the related word pairs, each of the lists contained either 64 randomly interspersed filler words (in the Memorize task) or nonwords (in the Count Nonwords task).

Each of the two stimulus lists had two forms designated A1, A2 and B1, B2. In each form, 64 of the target words (of which 20 were antonyms) immediately followed primes to which they were semantically related, whereas the other 64 targets followed unrelated primes. The 64 targets that were presented in the "related" condition in one form were presented in the "unrelated" condition (i.e., following an unrelated prime) in the other form. The serial position of the targets was identical across lists.

Each subject performed one of the two tasks using an A word list and the other task using a B word list, so that words were not repeated. Thus, there were four groups (of four subjects each), each receiving the following word lists during the Memorize/Count Nonwords tasks: A1/B1, A2/B2, B1/A1, and B2/A2. Across subjects, all targets were presented equally often in the related and unrelated conditions. This design allowed ERPs to the same targets to be compared (across subjects) for related versus unrelated primes in each of the two tasks and permitted tests of the effect of semantic priming within subjects.

A testing session started with a tone "oddball" paradigm, in which the subjects were instructed to count silently 64 low-pitch (750 Hz) tones randomly presented among 256 high-pitch tones (1,500 Hz) presented at random ISIs that ranged from 850 ms to 1,250 ms. The purpose of this task was to familiarize the subjects with ERP testing conditions and to provide a measure of their P300 components. The oddball task was followed by the Count Nonwords and Memorize tasks, in counterbalanced order across subjects.

Word recognition was measured immediately after the Memorize condition by presenting subjects with a questionnaire consisting of 120 words, 40 of which were "old" and 80 of which were "new." Among the new words, 40 were semantically related to old words and 40 were unrelated new words. The function of the lures was as an independent source of evidence for semantic activation in the recognition memory task. Subjects were instructed to categorize each word as *old* or *new* and to rate the confidence of their decision on a scale from 1 (not at all confident) to 5 (highly confident).

Electrophysiological Data Collection

Subjects were tested in an electrically isolated sound-attenuating chamber. The electroencephalogram (EEG) was recorded with tin electrodes mounted in a commercially available elastic cap. The recording sites were Fz, Cz, Pz, P3, P4, T5, and T6, and three additional lateral pairs that were placed over symmetrical right and left hemisphere locations: (a) a frontal pair placed midway between F7-8 and T3-4 (approximately over Broca's area and its right hemisphere homologue—BL and BR), (b) a temporoparietal pair that was placed 33% of the interaural distance lateral and 12.5% of the inion–nasion distance posterior to Cz (approximately over Wernicke's area and its right hemisphere homologue—WL and WR), and (c) a central pair that was 33% lateral to Cz along the interaural line (approximately over Brodmann's area 41—41L and 41R). Each scalp site was referred to an average of the left and right mastoids calculated digitally off-line. Vertical eye movements and blinks were monitored via a bipolar montage above and below the right eye; horizontal eye movements were monitored via a left-to-right montage at the external canthi. A fixation point was attached to the center of a video monitor to aid subjects in maintaining fixation while they listened to the auditory input.

The EEG was amplified by a Grass Model 12 polygraph with half-amplitude cutoffs of 0.01 and 100 Hz, digitized on-line at a sampling rate of 170 Hz, and stored on magnetic tape along with stimulus codes for subsequent averaging. About 10% of the trials were rejected prior to averaging because of eye movements, blinks, muscle artifacts, or amplifier blocking.

Results

Prior to statistical analysis, the data from all the channels were rereferenced to an average of the left and right mastoids and equilibrated across scalp locations using the procedure outlined by McCarthy and Wood (1985). Measurements of mean amplitudes between 300 and 900 ms and for 100-ms windows between 300 and 900 ms were taken and subjected to multifactorial analysis of variance (ANOVA) with repeated measures.

The ERPs elicited by both semantically related and unrelated targets contained two major negative deflections, an early component peaking about 100 ms after stimulus onset (N100) and a later component that peaked on the average at about 450 ms at the frontal and central sites and at about 400 ms at the parietal sites (N400). The amplitude of N400 was larger, its latency shorter, and its duration more prolonged in the ERPs elicited by unrelated than by related targets in both tasks (Figures 1, 2). Moreover, the magnitude of the difference between related and unrelated words was larger and started earlier in the Memorize than in the Count Nonwords task. These effects did not differ between subjects who received the words in the left versus the right ear; hence, the data were collapsed across ears for subsequent analyses. We will refer to this difference between the waveforms elicited by related and unrelated targets as the semantic priming ERP effect.

For the main statistical evaluation, the mean amplitude of each waveform between 300 ms and 900 ms from stimulus onset was calculated in each subject. A three-variable ANOVA with repeated measures within subjects was performed using mean amplitude as the dependent variable (Table 1). The variables were semantic relatedness (related, unrelated), task (Memorize, Count Nonwords), and electrode site. When necessary, the degrees of freedom were adjusted according to the Greenhouse-Geisser (GG) procedure.

The ANOVA showed that all three main effects were significant: semantic relatedness: $F(1,15) = 12.94$, $MSe = 11.72$, $p < .003$; task: $F(1,15) = 7.89$, $MSe = 9.01$, $p < .02$; and electrode site: $F(12,180) = 10.10$, $MSe = 6.02$, $p < .001$ (GG $\epsilon = .2166$). Semantic relatedness interacted significantly with task ($F[1,15] = 5.65$, $MSe = 5.36$, $p < .031$) and with electrode site ($F[12,180] = 3.48$, $MSe = 0.52$, $p < .015$ [GG $\epsilon = .3394$]). No other interactions were significant.

Post hoc analyses (Tukey-A) of the interaction revealed that the ERPs elicited by unrelated target words in the two tasks were indistinguishable in overall amplitude; in contrast, for related words the N400 was significantly smaller in the Memorize than in the Count Nonwords task ($p < .05$). Post hoc analysis of the electrode site effect showed that during the 300–900-ms epoch the ERPs were significantly more negative frontocentrally than at the parietal and temporal sites. Although on the average the negativity was larger over right (-1.08 μV) than left (-0.61 μV) hemisphere sites, this difference was not statistically significant.

Because the evaluation of the task effect on semantic priming was planned a priori, the semantic priming effect was analyzed separately for each task. The variables were semantic relatedness and electrode site. These ANOVAs revealed that although the semantic priming effect was highly reliable ($F[1,15] = 13.06$, $MSe = 7.43$, $p < .0025$) in the Memorize task, it did not reach significance in the Count Nonwords task ($F[1,15] = 0.62$, $MSe = 6.94$, $p < .45$) (Figure 3).

To achieve a more detailed characterization of the semantic

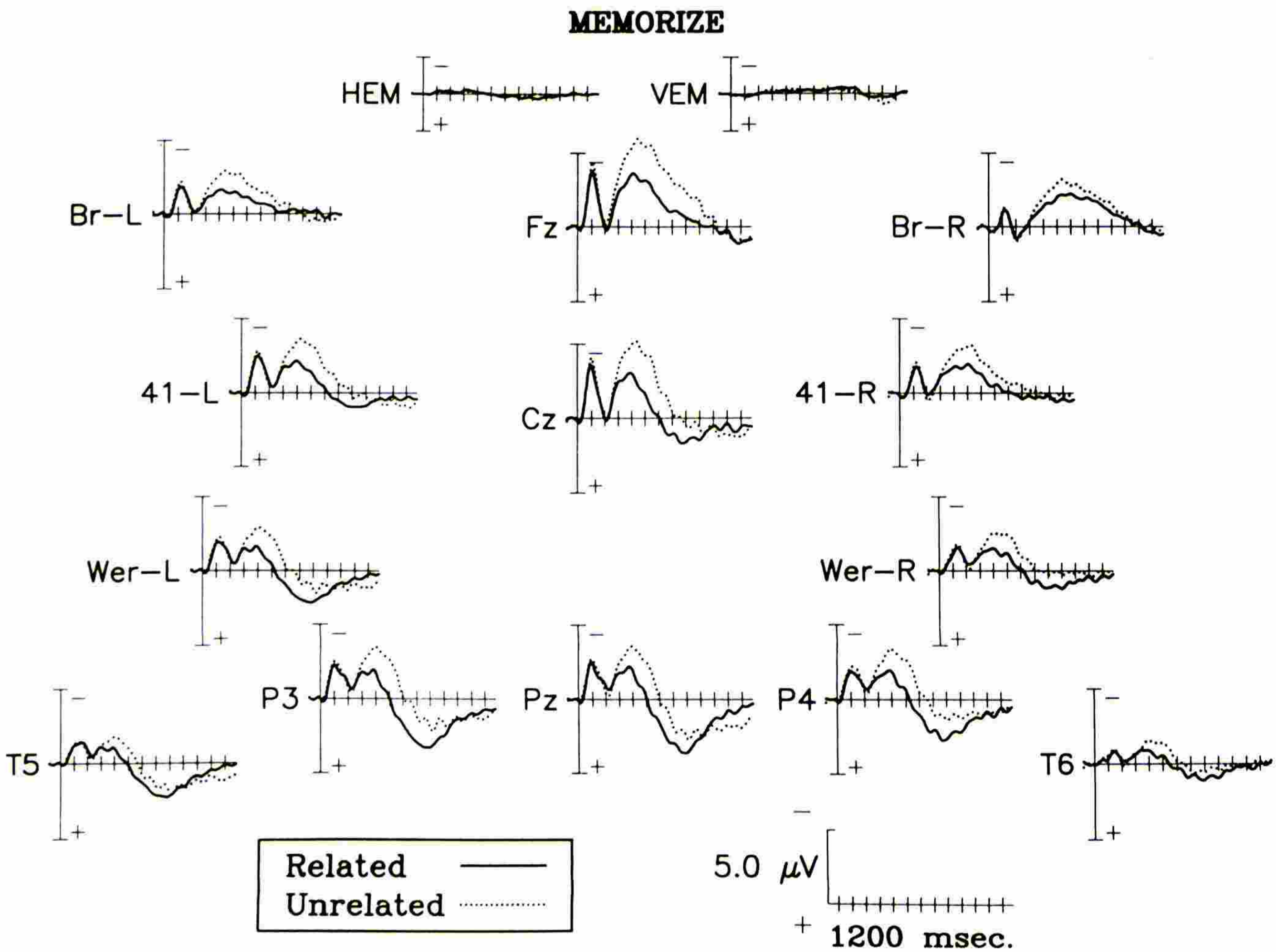

Figure 1. Grand-average ($n = 16$) ERPs elicited by related (solid line) and unrelated (dotted line) target words in the Memorize task. Negativity is up in this and all subsequent figures.

priming effect in both tasks, these analyses were repeated on mean amplitudes over three consecutive epochs: 300–400 ms, 400–700 ms (during which the semantic priming effect in the Count Nonwords task was most conspicuous), and 700–900 ms. A four-way ANOVA was carried out with the same variables as in the initial analysis plus the fourth variable of epoch. The important aspects of this analysis were the interactions between epoch and the other variables. The interaction between epoch and semantic relatedness ($F[2,30] = 6.47$, $MSe = 4.15$, $p < .006$, $\epsilon = .7847$) reflected the fact that the semantic priming effect was larger during the 400–700-ms epoch than during either the 700–900-ms or the 300–400-ms epochs. The interaction between ep-

Table 1. *Mean ERP Amplitudes (μV) Elicited by Related and Unrelated Target Words (300–900 ms) and the Difference Between Them in Two Word Recognition Tasks*

	Scalp recording sites												
Task	BL	Fz	BR	41L	41R	WL	Cz	WR	T5	P3	Pz	P4	T6
Memorize													
Related	−1.0	−1.9	−1.6	−0.4	−1.0	0.5	−0.4	−0.1	0.8	1.1	1.1	0.6	0.1
Unrelated	−1.9	−4.0	−2.2	−1.7	−1.9	−0.7	−2.3	−1.1	0.1	−0.7	−0.4	−0.9	−0.4
Effect	0.9	2.1	0.6	1.3	0.9	1.2	1.9	1.0	0.7	1.8	1.5	1.5	0.5
Count Nonwords													
Related	−1.3	−3.2	−2.0	−1.1	−1.5	−0.5	−2.0	−0.9	0.1	−0.5	−0.6	−0.7	−0.4
Unrelated	−1.8	−4.1	−2.7	−1.5	−2.0	−0.8	−2.7	−1.2	0.0	−0.9	−1.3	−1.3	−0.6
Effect	0.5	0.9	0.7	0.4	0.5	0.3	0.7	0.3	0.1	0.4	0.7	0.6	0.2

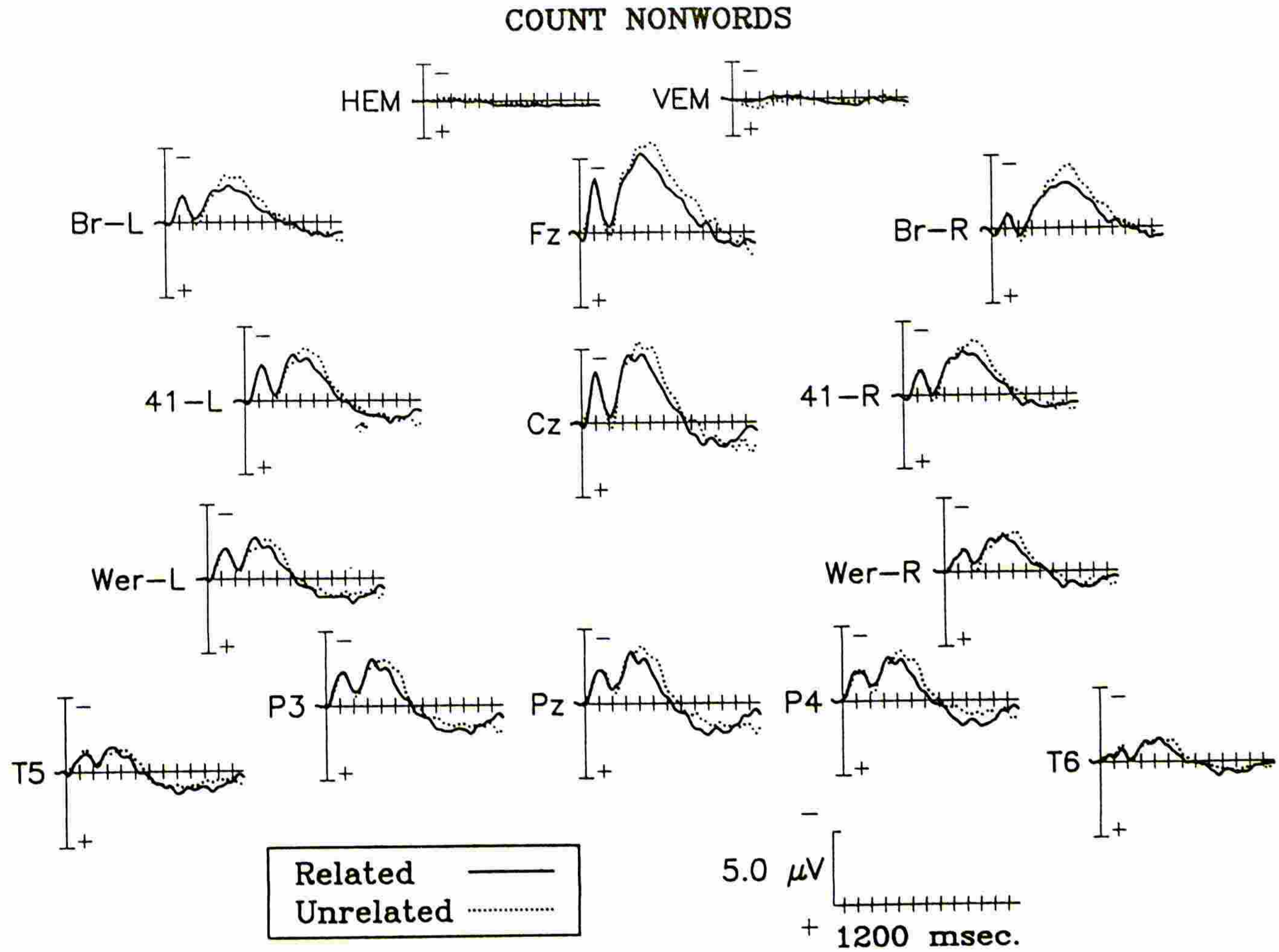

Figure 2. Grand-average (n = 16) ERPs elicited by related (solid line) and unrelated (dotted line) target words in the Count Nonwords task.

och and electrode site was statistically significant ($F[24,360]$ = 17.65, MSe = 2.00, $p < .001$, ϵ = .1540), as was the three-way interaction between epoch, semantic relatedness, and electrode site ($F[24,360]$ = 4.59, MSe = 0.37, $p < .003$, ϵ = .1727). The interaction between epoch and task was not significant ($F[2,30]$ = 1.23, MSe = 4.94, $p < .31$, ϵ = .7627). In addition, as in the one-epoch analysis, the interaction between task and semantic relatedness was statistically significant ($F[1,15]$ = 6.65, MSe = 13.72, $p < .022$), indicating that the semantic priming effect was larger in the Memorize task (1.12 μV) than in the Count Nonwords task (0.36 μV). The three-way interaction between epoch, task, and semantic relatedness was not reliable ($F[2,30]$ = 0.77), suggesting that this two-way interaction between task and semantic relatedness was similar in all three epochs. Accordingly, additional post hoc analyses and planned comparisons of the semantic priming ERP effect were restricted to the Memorize task.

In the Memorize task, the interaction between epoch and semantic relatedness was not reliable ($F[2,30]$ = 1.05, MSe = 6.33, $p > .31$), suggesting that the effect of semantic relatedness was broadly distributed in time. The electrode site effect was reliable ($F[12,180]$ = 6.43, MSe = 9.27, $p < .004$, ϵ = .2058), and this factor significantly interacted with epoch ($F[24,360]$ = 15.00, MSe = 1.18, $p < .0001$, ϵ = .1595) but not with semantic relatedness ($F[12,180]$ = 1.67, MSe = 2.64, $p > .20$). However, as revealed by the reliable three-way interaction ($F[24,360]$ = 2.80, MSe = 0.33, $p < .02$, ϵ = .2118), the interaction between semantic relatedness and electrode site was different during different epochs. This three-way interaction was analyzed in terms of the anterior–posterior distribution at the midline and the interhemispheric sites. The anterior–posterior distribution of the semantic priming effect (the unrelated minus related difference amplitudes) showed a consistent frontocentral maximum during all three epochs (Table 2). The interhemispheric distribution of the priming effect showed consistently larger amplitudes over the left hemisphere in all three epochs, but this lateral asymmetry did not reach significance. The interhemispheric difference was not reliable in the 300–400-ms epoch and in the 400–700-ms epoch, whereas in the 700–900-ms epoch, the right hemisphere was significantly less positive than the left ($F[1,15]$ = 10.50, MSe = 6.23, $p < .006$) (Table 3).

Because behavioral and ERP data suggest that semantic priming effects in reading tend to be bigger for antonyms than for categorically related words (e.g., Becker, 1980), we analyzed the semantic priming effect separately for the two stimulus types. The priming effect was slightly larger for antonyms (1.65 μV)

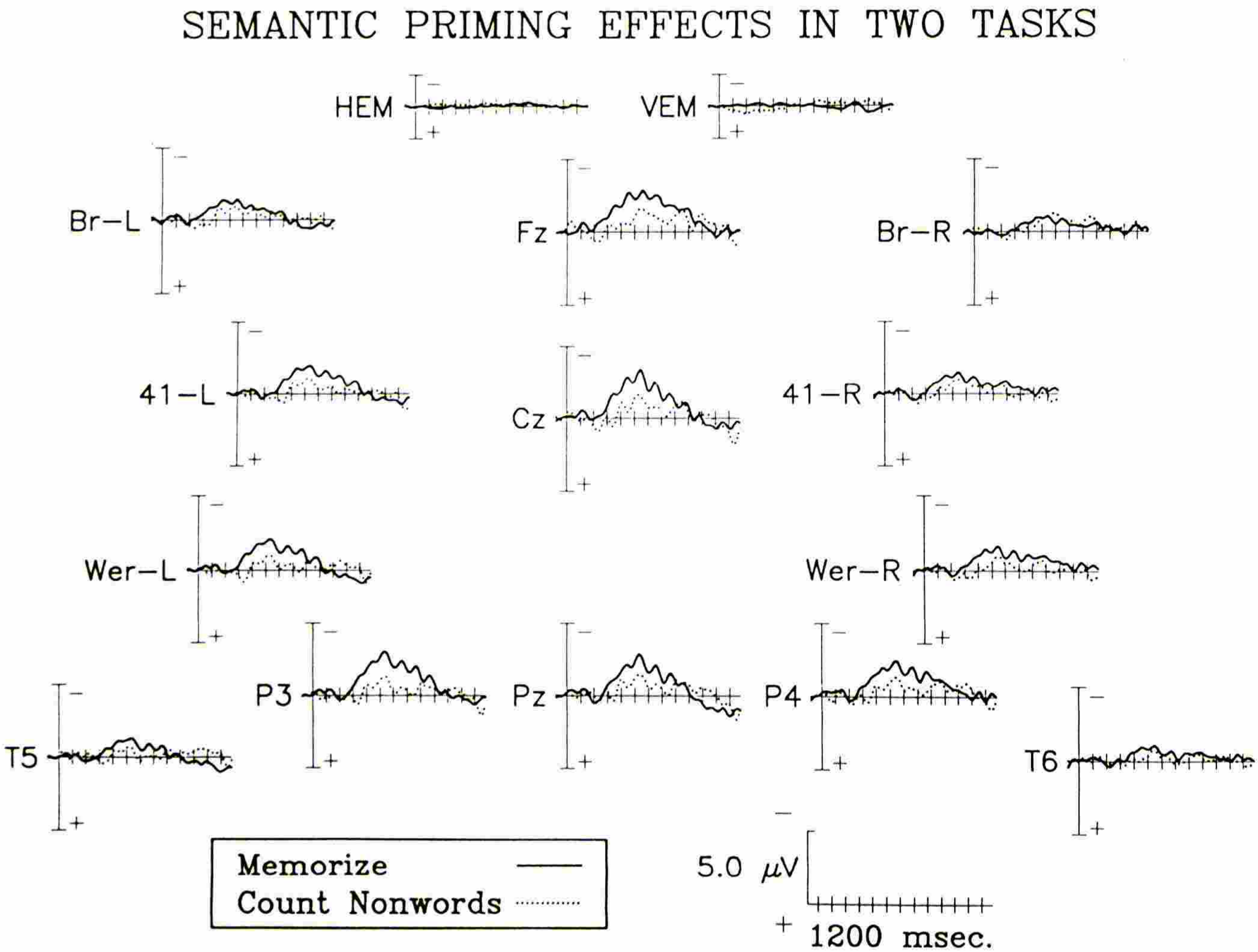

Figure 3. Comparison of the difference waves (unrelated targets minus related targets) in the Memorize (solid line) and Count Nonwords (dotted line) tasks.

than for categorically related pairs (1.04 μV) but not reliably so ($F[1,15] = 2.21$, $MSe = 17.47$, $p < .16$).

Onset and Peak Latency Analyses

Across sites and conditions, the latency of the N400 peak was similar in the two tasks (455 ms and 457 ms in the Memorize and Count Nonwords, respectively). In both tasks, the latency of the peak was shorter for related (439 ms) than for unrelated (473 ms) targets ($F[1,15] = 6.02$, $MSe = 37862$, $p < .03$).

The difference ERP waveforms (unrelated – related) in the Memorize task peaked at 582 ms, approximately 130 ms later than the N400 peak elicited by the unrelated targets. The onset of the difference wave was estimated as the latency of the latest point (between stimulus onset and peak latency) at which its amplitude was smaller than 15% of its peak amplitude. This onset was at about 286 ms, without significant variance across sites.

Memory Performance and Semantic Priming

On the average, 73% of the 120 words in the recognition test list were correctly categorized ($d' = 1.12$). The percentage of false alarms among new words that were semantically related to words in the study list was significantly larger (41.3%) than among unrelated new words (28.8%) ($t[15] = 3.90$, $p < .002$).

Because memory performance might reflect the depth of processing of words in the study list (Craik & Lockhart, 1972) and has been correlated with the magnitude of semantic priming (Smith et al., 1983), we anticipated an interaction between semantic priming (as indexed by the N400 effect) and subsequent recognition performance. To test this hypothesis, we compared the magnitude of the semantic priming effect in the eight subjects with the lowest memory scores (mean $d' = 0.52$) with that of the eight subjects with the highest memory scores (mean $d' = 1.71$). A mixed-model ANOVA (with the d' group as the between variable) indicated that although the semantic priming effect in the high-d' group (1.51 μV) was of larger amplitude than in the low-d' group (0.98 μV), this trend was not statistically significant ($F[1,14] = 1.29$, $MSe = 11.47$, $p < .27$).

Word/Nonword Discrimination and Semantic Priming

The correct nonword counts were between 87.5% and 98.4%, with a mean of 93.8%. There was no reliable relationship between the nonword-count accuracy and the semantic priming effect.

Table 2. *Mean ERP Amplitudes (μV) Elicited by Related and Unrelated Words in the Memorize Task During the Three Measurement Epochs at Fz, Cz, and Pz Scalp Sites*

	Scalp recording site		
Epoch	Fz	Cz	Pz
300–400 ms			
Unrelated	−4.45	−4.24	−3.07
Related	−2.88	−2.75	−1.97
Difference	−1.57	−1.49	−1.10
400–700 ms			
Unrelated	−4.91	−3.34	−1.29
Related	−2.47	−0.83	0.72
Difference	−2.44	−2.51	−2.01
700–900 ms			
Unrelated	−2.44	0.19	2.23
Related	−0.71	1.39	3.18
Difference	−1.73	−1.20	−0.95

Table 3. *Mean ERP Amplitude (μV) Elicited by Related and Unrelated Words in the Memorize Task During the Three Measurement Epochs at Left (L) and Right (R) Hemispheric Scalp Sites*

	Scalp recording sites				
Epoch	Broca	Wernicke	Area 41	Parietal	Temporal
300–400 ms					
Unrelated					
L	−2.05	−2.36	−2.77	−2.92	−1.49
R	−1.19	−1.96	−1.99	−2.79	−1.13
Related					
L	−1.30	−1.49	−1.86	−1.74	−1.02
R	−0.79	−1.34	−1.42	−1.73	−0.86
Difference					
L	−0.75	−0.87	−0.91	−1.18	−0.47
R	−0.40	−0.62	−0.57	−1.06	−0.27
400–700 ms					
Unrelated					
L	−2.38	−1.36	−2.45	−1.50	−0.30
R	−2.56	−1.72	−2.54	−1.63	−0.79
Related					
L	−1.25	0.26	−0.81	0.81	0.66
R	−1.81	−0.49	−1.38	0.25	−0.03
Difference					
L	−1.13	−1.62	−1.64	−2.31	−0.96
R	−0.75	−1.23	−1.16	−1.88	−0.76
700–900 ms					
Unrelated					
L	−1.05	1.00	−0.12	1.55	1.62
R	−1.91	0.06	−0.82	1.05	0.44
Related					
L	−0.40	1.95	0.87	3.01	1.99
R	−1.50	0.97	−0.13	2.32	0.90
Difference					
L	−0.65	−0.95	−0.99	−1.46	−0.37
R	−0.41	−0.91	−0.69	−1.27	−0.46

Discussion

This study was designed to examine the influence of task (depth of processing) on ERP signs of semantic association during the processing of single spoken words. In one task, subjects made a series of independent lexical decisions and kept a running mental count of all pseudowords (Count Nonwords); in the other, subjects listened to a similar list of words in anticipation of a recognition memory test (Memorize). Semantic relatedness was associated with a reduction in the amplitude and peak latency of the N400 component of the ERP in both tasks, but these effects were statistically reliable only in the Memorize task. The divergence between the waveforms in the Memorize task spanned a long epoch starting at about 300 ms and ending at about 900 ms, relative to stimulus onset. More detailed analyses of shorter epochs revealed no important interactions between epoch and any other effects.

In general, these results confirm the existence of a robust semantic priming effect on the N400 component in the auditory modality (Holcomb & Neville, 1990). The strong interaction found between the size of the semantic priming effect and task accords well with previous demonstrations that the amplitude of the N400 priming effect for written words is modulated by the extent to which subjects are urged to attend and utilize semantic relations to improve their performance. For example, Kutas and Hillyard (1989) found that N400 amplitude elicited by the second of two words in a pair varied inversely with the degree of association between them in a delayed letter search task in which subjects had to indicate whether or not a letter presented 1 s following the pair was present in either or both of the words. However, as reported in Kutas and Van Petten (1988), essentially the same stimuli produced a larger ERP priming effect if the task required subjects to rate the strength of semantic association between the words. Hence, although the N400 amplitude could be modulated even by semantic relationships that were incidental to task performance, the priming effect was considerably larger when the semantic relations were attended explicitly. By implication, the amount of attention directed to semantic analysis appears to be important in determining the size of the N400 priming effect.

This hypothesis is supported by a more direct approach taken by Holcomb (1986), who found that the N400 priming effect was significantly larger when 50% of the targets in a lexical decision task were semantically related to their primes and the subjects were told to use a prediction strategy to speed their responses than when only 12% of the targets were related and the primes served only as a warning stimulus. Thus, both studies show that a task that encourages semantic processing of the first (prime) word of a pair enhances the N400 effect elicited by the second (target) word. These findings support the proposed interaction between depth of processing and semantic priming observed in lexical decision tasks (Smith et al., 1983).

Although the present task effect on N400 priming was expected in light of previous behavioral and electrophysiological findings, the absence of a significant N400 semantic priming effect in the Count Nonwords task is intriguing. There is evidence for significant N400 effects of semantic priming in lexical decision tasks in both the visual (e.g., Bentin et al., 1985) and auditory (Holcomb & Neville, 1990) modalities. Moreover, Holcomb (personal communication) found that in some situations semantic priming effects in the auditory modality were even larger than those in the visual modality. The low percentage of errors in the Count Nonwords task suggests that our subjects succeeded in distinguishing between words and nonwords most of the time. Therefore, we must assume that lexical decisions were made in the same manner as those that are usually affected by semantic priming. One factor that might have diminished the semantic priming effect was the relatively long SOA (1,750 ms). Another factor might be the need to keep a silent count of the nonwords, which interfered with elaborate processing of the words to a greater extent than in the more traditional lexical decision task. This silent count and the absence of a requirement to respond to words might combine to reduce the semantic priming effect. However, all these explanations are post hoc and need additional research for validation.

In agreement with Holcomb and Neville (1990), we observed that the difference between semantically primed and unprimed spoken words was a long duration, monophasic negativity (i.e., N400 effect). The long duration and the absence of a laterality effect are especially notable because they contrast with the N400 effect typically elicited by written words; the N400 priming effect in the visual modality is of shorter duration (by 100 ms or more) and is larger over right than left hemisphere sites (e.g., Kutas, Van Petten, & Besson, 1988). At present, we can only speculate on the factors responsible for these intermodality differences.

A possible contribution to the prolonged negativity elicited by auditory words might have been made by the sustained potential, known to track the duration of any elicited sounds, either verbal or nonverbal (Picton, Woods, & Proulx, 1978a, 1978b). This factor, however, cannot account for the duration of the semantic priming effect on ERPs. Another contribution to the prolonged negativity per se and to the duration of the priming effect may arise from a fundamental difference between the processing of spoken and written language. In contrast to the written word, which can be analyzed either sequentially or holistically, an acoustic signal can only be analyzed via sequential analysis. Unequivocal identification of a phonetic signal as a specific word occurs at different points in time for different words ("the recognition point," Marslen-Wilson, 1975). In the present study, the duration of the word stimuli and the locations of the associated recognition points varied across the stimulus set. We do not yet know which aspects of the phonetic information may modulate the N400 (see Woodward, Owens, & Thompson, 1990, for preliminary work on this question). Some N400 activity may be elicited by each relevant bit of information in the acoustic stream, thereby resulting in a prolonged N400 for each eliciting word. Alternatively, an N400 may be elicited at the recognition point of each word, but variability across stimuli can produce latency jitter and consequently a prolonged negativity in the average ERP.

The sequential nature of auditory processing and the obligatory phonetic processing in speech perception may also account for the absence of a reliable right-larger-than-left N400 laterality effect similar to that usually found with visually presented words (e.g., Kutas & Hillyard, 1982). One prominent theory ascribes the dominant role of the left hemisphere in language processing to its specialization for processing of temporal order, of which language is but one special instance (for a review, see Bradshaw & Nettleton, 1983). Certainly this aspect of language processing is accentuated for the analysis of speech relative to written words. An alternative view of the left hemispheric specialization for language suggests that its role in phonetic processing is the key. This skill seems to be missing in the isolated right hemisphere of split-brain patients, rendering them unable to perform various rhyming tasks (e.g., Bogen, 1985). However, this interpretation may only apply to auditory processing of language, because in the visual modality right-larger-than-left effects are found even in phonological matching tasks (Rugg, 1984). Although evidence is mixed concerning the extent to which normal reading invokes phonological decoding, there are data in normal and patient populations showing that words can be read without such decoding (Kay & Patterson, 1985; Seidenberg, 1985). This greater reliance of spoken as opposed to written words on phonological processing may also account for a greater involvement of the left hemisphere in speech perception than in reading. This additional left hemisphere activity may have counterbalanced other factors that cause the right hemisphere lateralization of N400 effects in reading.

The present data differ from those of Holcomb and Neville (1990) in the distribution of the N400 and of the semantic priming effect. Unlike their finding that the N400 priming effect had a temporoparietal maximum, we found that both the overall N400 (i.e., that elicited by unrelated words) and the N400 difference wave were more equipotential over the scalp, with a tendency to be largest over the frontal sites. This difference may be explained in terms of the different task demands. Holcomb and Neville (1990) required their subjects to make a speeded lexical decision, whereas our subjects showed an N400 effect while attempting to memorize the words for subsequent recognition. Thus, both the difference in response mode (speeded RT vs. no overt response) and the nature of the mental operations needed to perform the two tasks (LDT vs. memorize for recognition) could have contributed to the observed differences in the anterior–posterior distribution of the N400 priming effect. The published accounts of the ERP priming effects in word pair studies indicate that the N400 effect recorded during lexical decision tasks typically presents with a posterior maximum (Bentin et al., 1985; Holcomb, 1986; Holcomb & Neville, 1990), whereas that recorded under memory conditions seems to have a more anterior maximum (Bentin et al., 1984). However, the posterior maximum of the N400 effect in the delayed letter search task of Kutas and Hillyard (1989) and for incongruent words in sentences that did not require a motor response to the target word indicates that the absence of a motor response per se cannot account for the differences in scalp topography. Therefore, the question of the scalp distribution of N400 remains unresolved.

The semantic priming effect can be enhanced by instructions and tasks that direct the subject to analyze words to a deep (i.e., semantic) level. In particular, the amplitude of the N400 is apparently modulated by the degree of semantic elaboration that a word undergoes during encoding. Additional evidence that our manipulations affected depth of processing (or semantic elaboration) comes from the subjects' behavior in the recognition test, specifically in the greater number of false alarms among new words that were semantically related to the old words than among new words that were not related to those in the study line. Overall, our results agree with those of a series of studies showing that semantic constraints are a major (although clearly not the only) factor in determining the amplitude of the N400s elicited by open class (content) words in sentences (Van Petten, 1989; Van Petten & Kutas, 1990, 1991).

The amplitude of the N400 to spoken words can be modulated by semantic relatedness even when the subject's task is simply to memorize the words. This finding opens the door for investigation of the extent of semantic processing that is accorded words in an unattended speech channel.

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