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Journal

International Journal of Psychophysiology, 6(4)

ISSN

0167-8760

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Publication Date

1988-11-01

DOI

10.1016/0167-8760(88)90011-6

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Peer reviewed

Research Reports

Brain responses to semantic anomaly in natural, continuous speech

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In the present study, brain responses were recorded during the presentation of naturally spoken sentences. In two separate experiments, the same set of stimulus sentences was presented with subjects either being asked to pay close attention in order to answer content questions following the run ('memory instruction' – MI) or to press one of two buttons to indicate a normal or unusual ending to a sentence ('response instruction' – RI). Brain event-related potentials were not averaged across the exact same acoustic information but across 49 different words spoken in natural, uninterrupted sentences. There was no attempt to standardize the acoustic features of stimulus words by electronic means. Rather than splicing stimulus words (and trigger pulse needed for computer averaging) onto sentence stems, consonant–vowel–consonant (CVC) monosyllablic words were selected with voiceless stop consonants in the word initial position. This not only avoids acoustic overlap with the preceding word of the sentence but also allows the point of stimulus word onset to be precisely located. In the MI group, brain responses to the semantically anomalous endings were distinguished by the presence of a late negative wave (N300) followed by a sustained positive wave (P650). Responses to anomaly in the RI group data was not consistently differentiated from normal in the 650–1000 ms range. Within conditions, the MI and RI waveforms were differentiated by the presence of an augmented positive-going slow wave in the RI condition which may reflect an augmented CNV release. The feasibility of averaging brain electrical responses across non-isolated words which differed acoustically but were of similar phonemic structure was demonstrated. This paradigm provides a means of studying speech-activated neurolinguistic processes in the stream of speech and may make complex spoken language contexts available for event-related potential investigations of brain and language functions.

INTRODUCTION

Since the discovery that the human brain emits scalp-recordable electrical activity in response to simple auditory stimuli (e.g. clicks, tones) that are sensitive to cognitive variables, there have been attempts to utilize human speech sounds as eliciting stimuli. However, the use of naturally-spoken words in meaningful context has been severely hampered by the enormous acoustical complexity of human speech. For example, spoken words have many frequency components of rapidly varying amplitudes. Also, acoustic information defining a particular word spoken in context can overlap that defining temporally adjacent words, resulting in 'parallel transmission' phenomena and consequently, boundaries between words and even word onsets are often not clearly defined. Because speech-relevant stimulus parameters such as rise time, frequency composition and duration are known to strongly influence event-related potentials (ERPs), the problems in using real human

speech are formidable. The need to repeatedly present a particular stimulus item as a means of overcoming these problems to obtain an averaged brain ERP further compounds these complications. In commenting on this latter problem, Wanner et al. (1977) noted that "repeated presentations of linguistic stimuli are certainly not normal occurrences in natural language" and suggest that the subject's concept of the same stimulus word may change over a large number of repetitions, complicating an interpretation of results.

Previous attempts to utilize speech sounds in ERP paradigms can be divided into two categories: ERPs to isolated speech sounds (ISSs) and ERPs to whole words. Wood et al. (1971) was among the first to use synthetically produced consonant vowels (CVs) such as /ba/ and /ga/ to demonstrate task-related ERP effects. In a series of studies, Molfese and collaborators (reviewed in Molfese, 1980) have demonstrated the sensitivity of ERP variables to ISSs, showing significant sensitivity of ERP variables to acoustic–phonetic features as well as higher order perceptual processes. Most of the investigators using ISSs have averaged individual ERPs to the exact same stimulus, although a few have averaged ERP trials across different stimuli (Galambos et al., 1975; Tanguay et al., 1977; Dorman et al., 1974). In general, these studies have revealed task-related variations in ERPs. Importantly, ISSs used in these studies incorporated physical/acoustic characteristics that rendered them entirely compatible with design requirements of ERP paradigms. Namely, they have abrupt, defined onsets with very short rise times (less than 10 ms), known frequency composition (in several cases, completely controlled formant transitions) and known durations similar to tones typically used to derive auditory ERPs.

Studies of ERPs to whole words have been less well controlled. Cohn (1971) was the first to average brain responses to isolated monosyllabic words (e.g. 'cat'). In 13 previous studies of word-ERPs, 6 have averaged ERPs to the exact same word, repeated many times (Cohn, 1971; Morrell and Salamy, 1971; Brown et al., 1973; Grabow et al., 1980; Molfese et al., 1975; Brown and Lehmann, 1978) and 7 have averaged across acoustically

disparate stimuli (Matsumiya et al., 1972; Haaland, 1974; Neville, 1974; Friedman et al., 1975; Pace et al., 1978; Okita et al., 1983; McCallum et al., 1984). However, in only one of these (McCallum et al., 1984) were ERPs averaged across acoustically diverse whole words within a natural speech context (i.e. complete sentences). The sentences were "spoken at a slow rate" by a male voice. Sentence-terminal (i.e. stimulus) words were digitised and transposed to the ends of 6 word stems which provided either semantically normal or anomolous contexts. According to previous studies (Harris, 1953; Peterson et al., 1958) 'splicing' of natural speech segments can, however, disrupt the normal rythm of information delivery and might induce processing demands on the listener which differ from those involved in fluent speech. Such factors may have contributed to the broad, diffuse separation between brain responses to anomalous and normal sentences in their waveforms.

In a general sense, there would seem to be two critical design requirements needed to derive long-latency brain ERPs to spoken words for the purpose of assessing natural linguistic (i.e. syntactic, semantic) functions: (1) words serving as stimuli should be spoken in a normal, fluent manner, by a native speaker and should occur within a meaningful context (e.g. a sentence); (2) individual brain ERPs should be averaged across acoustically diverse speech elements (i.e. words). The first condition avoids the possible complications of unnatural speech stimuli inducing novel processing modes not normally associated with spoken language comprehension. The second allows for derivation of ERPs without excessive repetition of stimulus words, which has been a major difficulty in earlier studies. However, it also has the serious disadvantages of inconsistency of frequency composition, sound energy and stimulus duration, all of which are major determinants of at least the stimulus-determined components. It is thus not surprising that some investigators have been hesitant to employ such stimuli, as the different acoustic features could evoke different waveform features.

In the present study, an attempt has been made to overcome the obstacles to using naturally-

spoken words in the stream of speech as stimuli primarily through selection of stimulus words which share critical acoustic features. For this purpose, we limited our choice to monosyllabic words with a consonant–vowel–consonant (CVC) structure where both consonants were voiceless stops (e.g. cake, cook, pipe). These constraints on word structure greatly reduce the variability of word duration and acoustic composition, even when spoken in context. Such CVCs also have clearly definable onsets, being characterized by a brief period of silence, followed by an extremely abrupt burst of sound energy. This latter feature in particular enables an experimenter to unambiguously locate word onset (beginning of stimulus information presentation) and consequently avoid parallel transmission problems. We have employed the paradigm of Kutas and Hillyard (1980) which has been found to invoke an ERP component which reflects the perception of semantic anomaly. The above factors may allow more precise delivery of language-based information, and because of the rapid presentation of stimuli, reduce the amount of time required to derive average signals.

METHODS

Subjects

Twenty-nine young adults (16 female and 13 male, range of 17–26 years) were paid for their participation. All were right-handed, as indicated by the Edinburgh Inventory for Handedness (Oldfield, 1971). Subjects were unaware of the hypothesis being tested and were screened for brain disease.

Stimuli

Forty-eight different words were used as stimuli. Each monosyllable was a CVC one, where both consonants were one of the 3 voiceless stop consonants /p/, /t/ or /k/. Each stimulus word was used once in an anomalous context and once in a normal context, always being located at the end of 7–8-word declarative sentences (e.g., "I planted string beans in my coat", "Winter forced me to wear a coat") spoken by an adult male with clear

articulation. Since stimulus duration was of importance in the present study, the duration of all sentence terminal words was measured individually using a PDP-11 computer and waveform-editing programs at the MIT speech laboratory. Importantly, none of the stimulus words was electronically altered in any way. Also, no attempt was made to standardize the acoustic environment preceding each stimulus word, for example, by using the same prestimulus word in each sentence. Each sentence was spoken with a natural cadence and was preceded by a 4-s pause with a 700 Hz signal tone occurring 1 s before the first word of each sentence. All sentences were recorded in a sound chamber at 15 i.p.s. on one channel of a stereo tape. On the second track of the tape, signal pulses were placed coincident with word onset. This was accomplished by manually controlling tape movement across the playback head until word onset was precisely identified. Trigger pulses used to initiate EEG sampling epochs were 10-ms duration square waves generated by a Tektronix PG 505 pulse generator activated by electrical coupling to the remote control unit of the tape recorder. Variation in the placement of these pulses with respect to word onset was always less than 10 ms, with the average being under 5 ms (measured using a dual beam storage oscilloscope).

Procedure

Subjects were tested while seated in a reclining chair in a sound-dampened room, dimly lit with 25 dB white noise. Each experiment consisted of one run, during which subjects were either instructed to pay close attention to the sentences in order to answer content questions ($n = 17$) after the run ('memory' instruction – MI) or to press one of two buttons ($n = 12$) indicating 'normal' or 'anomalous' meaning ('response' instruction – RI). The memory instruction was used simply as a means of directing the subject's attention without requiring an overt response to each stimulus as it was presented. Note that stimulus sentences and ERP recording procedures were identical for both the MI and RI groups. All sentences were presented binaurally through Sennheiser 414 headphones at 75–80 dB (SPL). The EEG was recorded at 4 sites, Fz, Pz, C3 and C4. These were

referred to linked mastoids with the right earlobe serving as ground. Signals were amplified through Grass P511 preamplifiers with half amplitude frequency cut-offs at 0.15 and 35 Hz. Signals were digitized at 250 Hz and averaged on-line by a PDP-11/34 computer. Sample epochs were 1250 ms in duration, beginning at 250 ms prior to word onset and ending 1000 ms after the onset of the first consonant of the stimulus word. Trials contaminated by movement-related artifacts (e.g. eye blinks) were rejected by computer software. All subjects were instructed to keep their eyes closed during the recording session.

RESULTS

The waveforms derived under MIs (Fig. 1) are unlike those evoked by simple tones and generally dissimilar to those seen in previous reports of word-ERPs. In particular, there is a striking lack of a clear N100–P200 complex. Instead, there is a negative peak which reaches a maximum in the range 250–350 ms, followed by a very broad positive-going wave which develops maximum amplitude in the range of 650 ms. In the semantically anomalous (SA) condition, the negative wave (N300) is augmented, while the late positive response is also enhanced in relation to the response elicited by semantically normal (SN) sentences. In contrast to the waveforms reported by McCallum et al. (1984), the early condition-wise difference ends abruptly in all 4 channels at 350–400 ms. From approximately 400–650 ms, SN and SA responses are roughly parallel. The two responses bifurcate at approximately 650–700 ms. This late difference between the two conditions appears to undergo attenuation by 900 ms in the parietal lead, but is clearly sustained in the other channels until the end of the recording epoch. Manual scoring of individual data plots revealed that 15 of 17 subjects displayed both a greater negativity in the 250–350 ms region and a greater positivity in the 650–950 ms region ($P < 0.01$, using the sign test) in the SA compared with the SN condition. Thus, there were two discrete regions of differentiation between conditions.
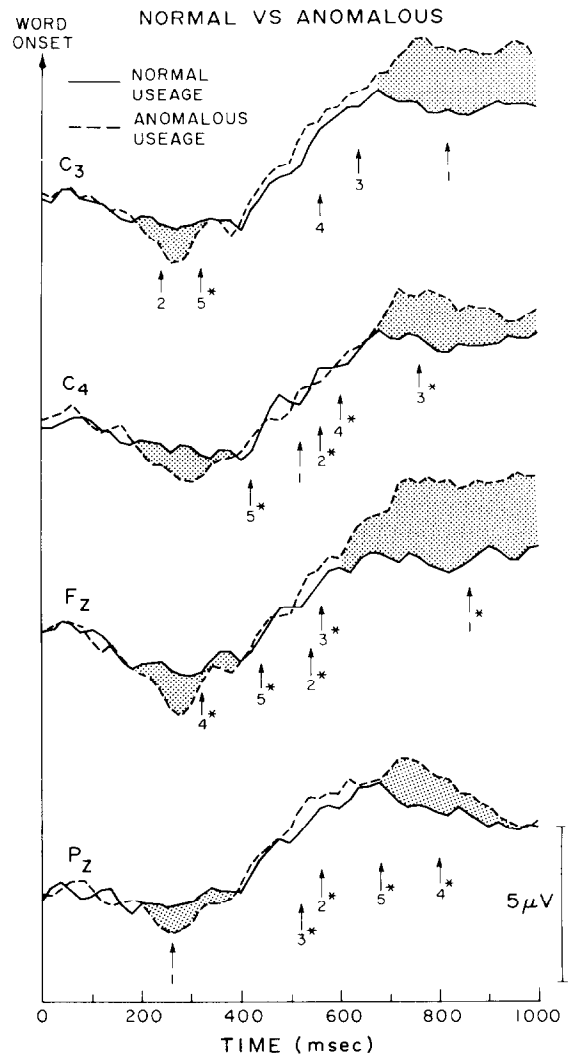

Fig. 1. Comparison of grand average brain ERPs to semantically normal and semantically anomalous declarative sentences in 4 regions under 'memory' instructions. Arrows indicate location of variables selected as discriminators in stepwise discriminant analysis. Asterisks indicate significant F-ratios ($*P < 0.05$).

Stepwise discriminant analysis (SWDA – BMD P7M, Dixon, 1978) was performed on the waveforms after averaging successive sets of 5 adjacent data points to yield 50 total post-stimulus data points. Thirty-nine of these, representing the time interval 150–900 ms (post-stimulus), were used in the SWDA procedure. Only 39 data points were used as this is the region most likely to encompass

TABLE I

Results of SWDA for memory instruction comparing SA and SN conditions

Electrode location	Percent correct classification		Mean latency of time points selected as discriminators (ms post-stimulus)				
	Anomalous	Normal					
C3	82.4	82.4	240	320 *	550	640	820
C4	82.4	82.4	420 *	520	560 *	660 *	760 *
Fz	82.4	82.4	320 *	440 *	540 *	560 *	860 *
Pz	100	100	260	520 *	560 **	680 **	800 *

* $P < 0.05$.
** $P < 0.01$.

brain electrical activity reflective of word comprehension. The first boundary was chosen as it is likely to exclude all the activity which reflects purely stimulus-driven acoustic feature analysis, as indicated in numerous studies of word identification which have shown a lower limit of 175–200 ms (Marslen-Wilson, 1973; Marslen-Wilson and Tyler, 1980). Therefore, electrical activity before this would not be expected to predominantly reflect word meaning (in this instance, the perception of semantic anomaly). The upper limit of 900 ms was chosen as reports of other long latency events, most notably P300, have indicated such processing can extend beyond 600 ms (Donchin, 1977). A 5-step analysis was used based on the recommendations of Donchin and Herning (1975)

and Donchin (1969), who found that the bulk of variance in an ERP data matrix can be accounted for by no more than 6 variables. In Fig. 1, the arrows underlying the waveforms indicate the 5 time points selected (a posteriori) as discriminators. Although there was similarity in the regions selected as discriminators between the 4 electrode locations, their order of entry into the discriminant functions varied. Of interest is the selection of the first variable, which is the single best discriminator between the 2 conditions (displays the highest initial F-ratio). In the cases of the frontal and left–central areas, the first variable selected was of a very long latency (860, 820 ms, respectively). Table I shows the results of the 5-step SWDA for the MI. The percent correct classifi-
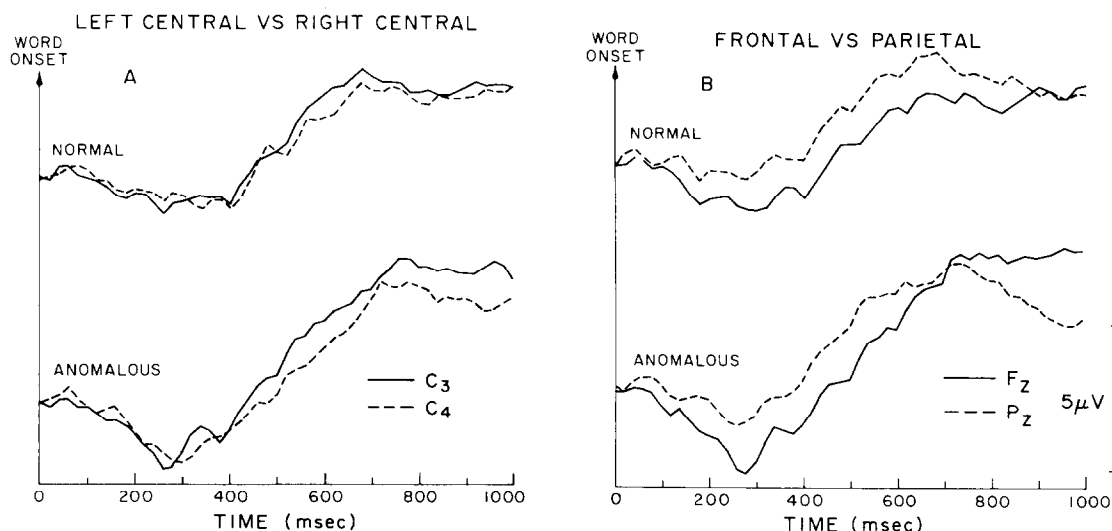

Fig. 2. Regional contrasts of grand average ERPs for MI. Comparisons are between the two central (lateral) placements, C3–C4 and anterior–posterior placements, Fz–Pz. Asterisks indicate significant F-ratios (* $P < 0.05$; ** $P < 0.01$).

cation values ranged from 82% (C3) to 100% (Pz). Thus, the difference between the SA and SN responses was least reliable at C3, where only one of the 5 selected variables was a significant discriminator and most reliable at the parietal site.

For the purpose of comparing regional responses within each condition, ERP waveforms were superimposed for each electrode site (Fig. 2). Grand average responses for both the SA and SN conditions were very similar at both lateral placements. However, waveforms from the frontal and parietal regions showed a marked divergence between SN and SA conditions that appears to begin at 40–80 ms and lasts to 800–900 ms from word onset. It appears to be a very low frequency offset. SWDA performed on these data supported these observations. It was found that the two lateral placements did not yield a single variable with an F-ratio having a probability less than 0.05 (F-ratios for C3–C4 comparisons were all below 2.0). By contrast, percent classifications between Fz and Pz were 77% and 88% for SA and SN conditions, respectively. Every variable selected had an F-ratio with a significant probability level ($P < 0.05$).

The waveforms derived under RIs were similar to those in the memory condition (Fig. 3) in that there was no N100–P200 complex present. These ERPs are, however, distinguished from those in the memory instruction by an augmentation of the late positivity (400–1000 ms). Additionally, the differences between SA and SN conditions are more diffuse. For example, a divergence between conditions begins in all 4 channels at 100–150 ms, but continues until 600–700 ms (Fig. 4). Under response conditions, there isn't a distinctive N300 component in the SA response in comparison to the SN response.

As for the MI, 50 RI data points representing the post-stimulus time period 160–900 ms were entered into SWDA. Overall, the percent classifications between SA and SN conditions were very similar to those under the memory instruction (approximately 87%, on the average). The most reliable difference between SN and SA conditions occurred at the frontal (Fz) position, being 100% (whereas under the MI, classification was highest (100%) at the parietal site). Table II lists these results. As in the memory data, there was ap-
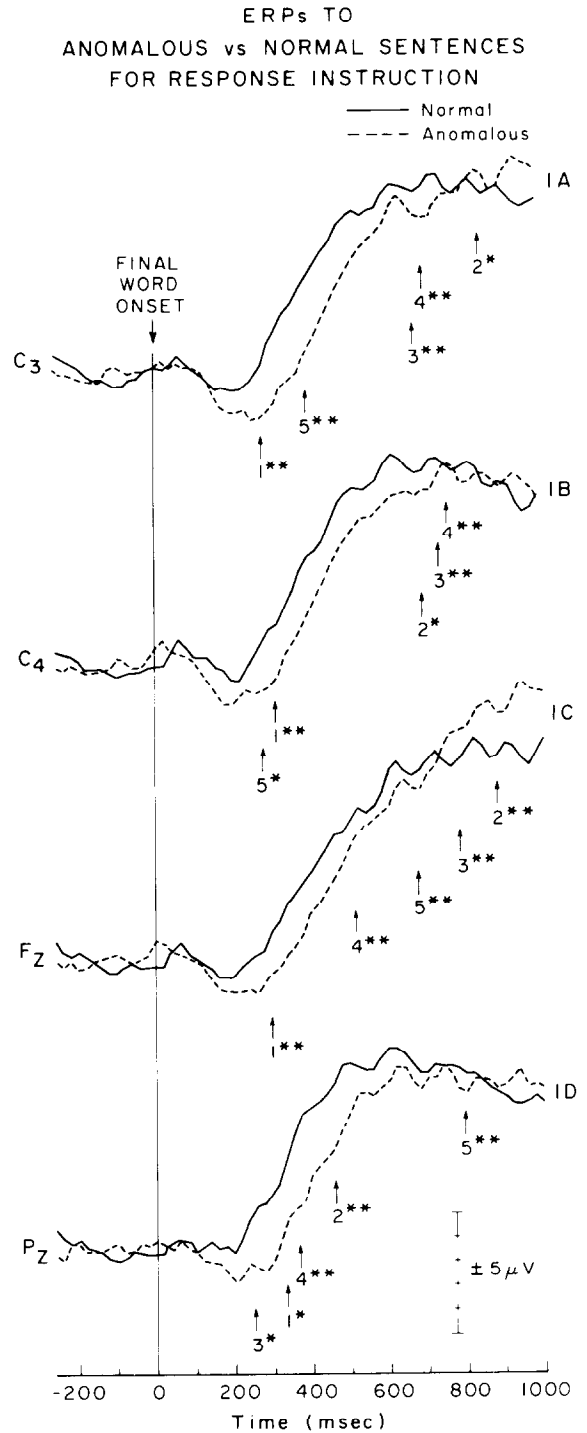

Fig. 3. Comparison of grand average brain ERPs to semantically normal and semantically anomalous sentences under RIs. Arrows indicate location of variables selected in stepwise discriminant analysis. Asterisks indicate significant F-ratios (* $P < 0.05$; ** $P < 0.01$).

REGIONAL CONTRASTS OF
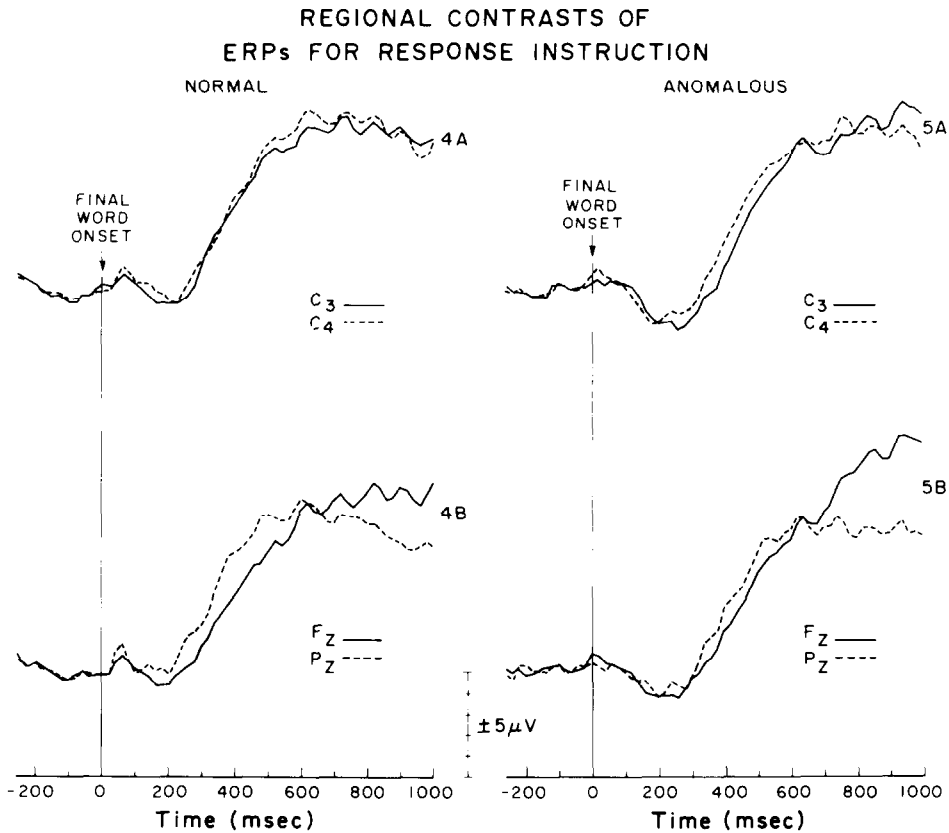## ERPs FOR RESPONSE INSTRUCTION

Fig. 4. Regional contrasts of grand average ERPs for response instructions. Comparisons are between the two central (lateral) placements, C3–C4 and center.

parent consistency across placements in the regions selected as discriminators, particularly in the early and late variables.

All of the variables selected as discriminators in the response instruction experiment had significant F-ratios, with most exceeding the 0.01 level.

This is in contrast to the memory instruction data where many variables did not reach statistical significance and very few exceeded the 0.01 level.

In comparing ERPs within conditions (across electrode locations), there were little or no differences between the lateral placements, with some

TABLE II

Results of SWDA for response instruction comparing SA and SN conditions

Electrode location	Percent correct classification		Mean latency of time points selected as discriminators (ms post-stimulus)				
	Anomalous	*Normal*					
C3	82.4	82.4	260 **	380 *	660 **	680 **	880 **
C4	86.0	86.0	280 **	300 *	700 *	740 **	760 **
Fz	100	100	280 **	520 **	640 **	740 **	840 **
Pz	81.0	81.0	240 *	320 *	340 **	460 **	780 **

* $P < 0.05$.
** $P < 0.01$.
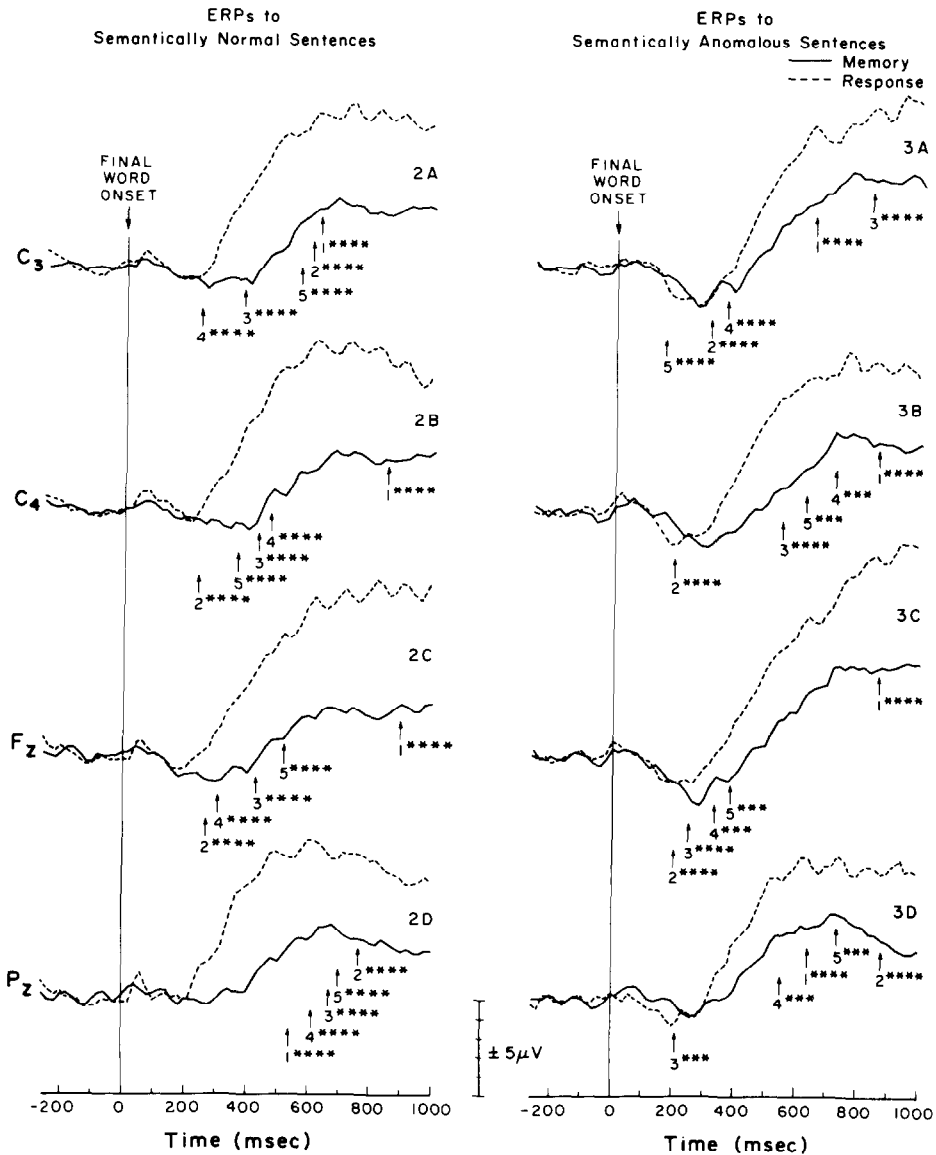
MEMORY vs RESPONSE INSTRUCTION

Fig. 5. Comparison of grand average ERPs for MI and RI conditions within electrode locations and conditions.

divergence between the frontal and parietal (Fig. 4). SWDA performed on these resulted in 60% and 71% correct classification scores for SN and SA conditions respectively, for C3–C4 comparisons and 77% and 88% scores for SN and SA conditions for Fz–Pz comparisons.

In a further set of comparisons, waveforms from both MI and RI paradigms were compared within SA and SN conditions (Fig. 5). As shown in Table III, there was a high degree of separation, ranging from 93 to 100%. F-ratios for the selected variables were all highly significant ($P < 0.001$ for

TABLE III

Results of SWDA in comparing MI and RI paradigms

Electrode location	Precent correct classification	Mean latency of time points selected as discriminators (ms post-stimulus)				
In anomalous condition						
C3	100	260 **	380 **	660 **	680 **	800 **
C4	93	120 **	480 **	540 **	640 **	720 **
Fz	90	120 **	140 **	160 **	260 **	740 **
Pz	100	140 **	480 **	560 **	640 **	740 **
In normal condition						
C3	100	160 **	280 **	500 **	540 **	560 **
C4	100	160 **	280 **	360 **	380 **	720 **
Fz	96	140 **	160 **	280 **	720 **	660 **
Pz	100	440 **	520 **	560 **	580 **	640 **

** $P < 0.001$.

all comparisons). The two paradigms differ in that the RI elicits a faster rising low frequency offset beginning in the 200–250 ms range.

DISCUSSION

In this study, stimulus words were selected which began with one of the 3 voiceless stop consonants, /p/, /t/, /k/, not only to avoid parallel transmission problems and facilitate precise coupling of word onset with computer averaging sequences, but also because of Tobin's work (1968) which suggested that voiceless stops have sufficiently fast rist times (at least when presented in isolation) to generate typical ERP components such as the N100–P200 complex.

The waveforms obtained in this experiment are largely unlike those previously found in studies of speech-evoked cortical potentials. Most notable is the absence of an N100–P200 complex, which is an obligatory electrical response to the abrupt onset of auditory stimuli. Only the waveforms of Cohn (1971) and Matsumiya et al. (1972) have shown such deficiency using speech stimuli. As with their stimulus materials, the lack of a sustained prestimulus silence in our sentences may account for the lack of an N100–P200 complex. That is, because the sound burst denoting onset of the word initial stop consonants does not constitute a sudden large change in stimulus energy

being delivered to the ear (and brain), it may not be sufficient to evoke typical obligatory components. For our stimuli, the silence which precedes closure release varies roughly from 10 to 150 ms, which is much less than the refactory period of N100, which is in the order of several seconds (Nelson and Lassman, 1973). It is apparent that the morphology of ERPs derived under the present procedure are very different from those evoked by pure tones or even isolated, naturally spoken words.

Because of the similarities in stimulus materials, it was unexpected that the present waveforms should appear markedly different than those published by McCallum et al. (1984). Not only did their averaged responses show a distinct N100–P200, but also a more sustained, broad separation between experimental conditions. The reasons for this are unclear but may be due to the different consonants used in stimulus words as well as the lack of any pause between the prestimulus and stimulus words in our sentences. The sentences employed by McCallum et al. were constructed by 'transposing' or splicing the sentence-final or stimulus word, possibly creating an unnatural pause or variable duration.

In comparing these waveforms to those originally published by Kutas and Hillyard (1980) in the visual modality, there is some similarity for the MI (and less for the RI), including a negative deviation from the SN grand mean response and a

later bifurcation between SA and SN conditions. In the visual modality, this latter feature began at approximately 600–650 ms and in the present study, at 600–700 ms. Based on a comparison of the waveforms obtained in these studies, the N300 is probably the auditory analog of the visually-elicited N400. The slightly smaller amplitude of the N300 is probably contributed to by two sources of variability: (1) averaging the ERPs across stimuli which are far more variable with respect to their physical characteristics (i.e. amplitude, frequency composition) than were the visual stimuli; and (2) variation in the time required to uniquely identify spoken words.

In order for anomaly perception to occur, the critical word must first be recognized by a listener. Marslen-Wilson and Welsh (1978) have proposed that "the listener's immediate perceptual decisions about the incoming material represent a balance between two distinct sources of information", where one is the acoustic signal and the other is a "set of internally generated structural constraints" which determine the possible interpretations of this input. The cooperative interaction of these processes is responsible for word recognition times which are appreciably shorter than word duration (down to one-half or three-fourths of word length — approximately 142–213 ms for our stimuli). For naturally spoken words such as these used in this study, there is thus uncertainty from one stimulus to the next, as to the point at which, going from left to right through the acoustic stream, sufficient information has been presented for recognition to occur. Consequently, chronometry of cognition-relevant ERPs which depend on word recognition will vary in accord with these factors. This is in contrast to the visual paradigm of Kutas and Hillyard in which all of the identifying features are simultaneously made available for analysis (words were flashed on a CRT screen). It is not clear why this component evoked by anomaly should occur 100 ms earlier in the auditory modality. Neurologically, afferent impulses from both senses evoke their first cortical potentials in similar time frames (roughly, 50 ms), precluding a purely physiological explanation. Moreover, as mentioned above, sufficient information to define visually flashed words is made available

sooner than for spoken words. Our findings therefore suggest a very rapid sequential analysis of words in context, the time course of which is in close agreement with behaviorally-based estimates (Marslen-Wilson, 1973; Marslen-Wilson and Tyler, 1980), indicating an average of 200 ms for monosyllables (note that the negative component peaking at 300 ms begins to diverge from the SN response at approximately 200 ms). In other words, cortical processing of naturally spoken CVC monosyllables may be more rapid than that for visually presented words. The shorter latency could also be a result of the lack of an extra stage of information processing, namely phonological recording, believed to be required in the transformation of graphemic information to phonetic (Rubenstein et al., 1971; Meyer et al., 1974).

The highly significant difference between RI and MI waveforms must be a result of the tasks, since the same stimulus set was used in both instances. In both sets of waveforms, there is a similar positive-going event that begins in the 200–400 ms region. This component was also prominent in the data of Kutas and Hillyard (1980) who observed a slow negative shift (the Contingent Negative Variation, or CNV) during the entire sentence. Individual ERPs are thus superimposed on the CNV which is resolved upon presentation of the final word. Thus, the ERP of the final word overlaps with CNV resolution and therefore might be expected to be distorted. The apparent augmentation of CNV resolution in the RI waveforms might be explained by a more rapid disengagement of the subject from sentence processing as the MI would be expected to require some sustained memory-related processing of the sentences' syntactic and/or semantic aspects. An alternative explanation for this effect would be that motor potential contribution due to the button-press requirement in the RI condition. Future studies of the N400/N300 component where an RT task is assigned to study chronometric properties must therefore take this effect into account.

Our results demonstrate the feasibility of using an electronically unaltered set of naturally spoken words in ERP paradigms which are acoustically non-identical but of the same phonemic structure (i.e. CVC) and may provide a means for dispens-

ing with the previously perceived need to present the exact same sound stimulus many times and thereby allow for a much greater variety in the number of available word stimuli within meaningful contexts. The present study also suggests the possibility that similar stimulus words presented in a larger discourse format could be used in ERP investigations of neurolinguistic processes. Thus, perhaps we can measure brain electrical activity during normal language processing.

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