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EVOKED POTENTIAL CORRELATES OF SEMANTIC INFORMATION PROCESSING IN NORMALS AND APHASICS

Of Eric Lenneberg's understanding of language there is one aspect that we consider particularly relevant and which we will emphasize in this chapter. This contribution comes from Lenneberg's belief that neurolinguists must search for a fundamental process that occupies a central position in all higher level cognitive functions. As Lenneberg (1970) states, "No psychobiological model of language can be considered to be adequate unless it comes to grips with the notion of language knowledge and its relationship to knowledge in general" (p. 636). Throughout his writings Lenneberg searched for a single process or a set of central processes which were fundamental to all higher-level operations including perception, language, thought, and knowledge. It was from this background that Lenneberg so forcefully argued that "sensory recognition processes were homologous to language processes" (Lenneberg, 1970). Although Lenneberg never described pre-

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cisely what these basic processes were, he nevertheless felt it was important to emphasize that language and logic share the basic property of classification and discrimination (Lenneberg, 1967, 1970). As discussed more completely by Lenneberg (1970), the notions of discrimination and classification were formalized into laws of thought and knowledge by George Boole in 1854. The famous "Boolean algebra" is based on a binary classification scheme which, in essence, creates a formalism of the concepts of "sameness" and "difference." As examined more fully elsewhere (Thatcher, 1976b), the concepts of "sameness" and "difference" are among the most profound known to man. These notions form the basis of order (Bohm, 1969), logic and mathematics (Whitehead and Russell, 1927; McCulloch and Pitts, 1943), and classification in general (Chen, 1973; Sneath and Sokal, 1973). In the context of language and cognition, Lenneberg pointed to the importance of the relational properties of language (Lenneberg, 1974) and emphasized the temporal structure of knowledge where connections are made between succeeding events and the present is compared to the past. Notions of "semantic fields" and "syntactical and semantic structures" involve an elaboration of the concepts of "sameness" and "difference" and the computation of relationships in time (Lenneberg, 1967, 1970).

Physiological Considerations of Language Comprehension

The goal of the present chapter is twofold. One is to introduce procedures that explore the electrophysiological correlates of memory match and mismatch. The procedures involve evoked potential analyses from subjects performing in delayed letter matching and delayed word semantic matching tasks. The evoked potential is particularly relevant since it reflects sensory recognition and cognitive processes held so important by Eric Lenneberg. The second goal is to contrast the electrophysiological results from normal subjects to those obtained from two aphasic patients performing the same tasks. This represents the first efforts by the authors to study evoked potentials and neuropsychological tests of cognitive function in aphasic patients. Evoked potential analyses from such patients may provide a useful measure of cognitive function for studies of language recovery after acquired le-

sions. In contrast to behavioral examinations the evoked potential reflects only early neurological events—e.g., those that follow stimulus presentation but precede motor output. In this way an electrophysiological correlate of sensory and cognitive function may be examined directly in aphasic patients.

The evoked potential test battery, currently being developed, also includes challenges of auditory and visual information processing. In the present chapter, however, only evoked responses to visual (letter and word) stimuli will be described. Although the results from the aphasic patients are preliminary, they are presented in this chapter in order to emphasize the potential scientific and clinical application of these procedures.

Before describing the electrophysiological procedures a brief theoretical discussion of certain physiological aspects of language processing must be considered. This discussion will necessarily be brief, since no clear neurophysiological models of language comprehension have been developed. Only particular aspects of language comprehension will be considered as they pertain to Lenneberg's views regarding classification and discrimination processes.

Representational Systems

The human scalp evoked potential reflects primarily sensory and cognitive processes and has two major components. The early components reflect the physical attributes of the stimuli, whereas the longer latency components reflect later cognitive processes (Regan, 1972). In terms of linguistic information processing afferent information is transformed by specialized nerve endings into coded impulses which are conducted centrally. The physical features of the sensory stimulus (phonemes in the case of an auditory input and lines, edges, angles, etc., in the case of a visual input) are mapped onto a neural representational system in an, as yet, unknown manner. Various neurophysiological models have been developed to explain the mapping process (Hubel and Wiesel, 1962; Pribram, 1971; Barlow, 1972). Most of these models rely on feature extraction. That is, neural elements respond optimally only to a particular feature of the sensory stimulus. The constellation of neural responses corresponding to the salient features of the stimulus constitute a representational system. Feature extraction models are usually hierarchical (see Barlow, 1972) in which there is a hierarchy of levels of greater complexity both of the feature extraction and the representational systems. There are a few nonfeature extraction models (see Gibson, 1969) in which the anatomy of the brain uniquely determines mappings of the external world onto neutral representational systems. Our concern in this chapter, however, is not with how representational systems are formed but rather with cognitive operations that are performed on representational systems once they have been created. There is reasonable consensus among researchers (see Szentagothai and Arbib, 1974) that, at some stage, both the formation and subsequent operations performed on representational systems involve the active interaction of the present with the past. For example, Szentagothai and Arbib (1974) elegantly presented the commonly expressed view (see Sokolov, 1960; Miller, Galanter, and Pribram, 1960; Pribram, 1971) that models of the external world are continually being created and then refined and updated by matching and mismatching the model with memory as well as successive samples of sensory input. This hypothesis of representational match and mismatch is consistent with many of Lenneberg's views and fits two general hypotheses of linguistic comprehension.

Hypotheses of the Comprehension Process

Currently, there are two general categories of theories of speech perception. One category contains the motor or articulatory theories and the other the sensory theories. The motor theory was proposed first by Halle and Stevens (1962) and elaborated by A. M. Liberman and colleagues at Haskins Laboratories (see Liberman, Cooper, Shakweiler, and Studdert-Kennedy, 1967; Liberman 1970). This theory maintains that the mechanism of speech recognition makes use of internal models of speech production, in which acoustic input is correlated with articulatory patterns necessary to reproduce the input. According to this view phonemes are the basic building blocks for speech and speech perception is presumed to occur in a special "speech mode" which involves unique sensory systems and motor mechanisms. However, there are recent experimental data that challenge the motor theory. For example, Fodor, Bever, and Garrett (1974) failed to observe invariant electromyographic correlates associated with particular phonemes. Also, as noted by Wanner, Taylor, and

Thompson (1976), the phenomenon of "categorical perception" * (Liberman, 1970; Lisker and Abramson, 1970) can be explained strictly in terms of acoustic cues without reference to articulation. Similarly, Ades (1974) and Miller, Weir, Pastore, Kelly, and Dooling, (1974) have shown that categorical perception can be obtained to artificially synthesized sounds which are unrecognizable as speech stimuli. Finally, recent evidence indicates that the syllable and not the phoneme may be the basic perceptual unit for speech (see review by Rubin, 1974). The latter finding is important since a motor theory is not necessary to explain context dependent perception if syllables are the basic units (Wanner *et al.*, 1976).

The purely sensory theories can be divided into two broad categories. The first one is called the transformational hypothesis which evolved from the transformational grammar developed by Chomsky (1957, 1965). The transformational grammar provided a means by which the relation between the structural location of a phrase and its grammatical function could be determined. This was accomplished by introducing an abstract syntactical construct, called the "deep structure," which represents the grammatical functions of a sentence. "Transformational rules" were then developed in order to obtain a description of the order of words or phrases in a sentence, which is called the "surface structure."

The transformational hypothesis evolved from Chomsky's formulations by assuming that the meaning or semantic level of comprehension corresponded to the deep structure and that the physical features of visually or aurally presented words corresponded to the surface structure.

Internal transformational rules determined the relationships between these two representational levels. In the present context one might assert that the surface structure of language corresponds to feature extraction or sensory representational systems, whereas the deep

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* "Categorical perception" implies that speech sounds are perceived categorically. That is, discriminable speech sounds are limited to a small number of identifiable categories. For example, syllables such as /ba and /pa differ according to their *voice onset times* or VOT (the delay between the initial sound produced by releasing the lips and the later sound made by vibrating the vocal cords). Sounds with a short VOT (less than about 25 msec) are perceived as /ba, sounds with a longer VOT (greater than about 25 msec) are perceived as /pa. Two sounds which fall on either side of the boundary are easy to discriminate, whereas two sounds which fall on the same side of the boundary are discriminated with slightly better than chance accuracy.

structure corresponds to a long-term memory or semantic representation and the transformational structure reflects a comparator operation involved in matching or mismatching sensory representations at the semantic level (Thatcher, 1976a).

The second dominant view of comprehension can be called the context construction hypothesis. This includes the semantic node hypotheses (Wortman and Greenberg, 1971). However, one of the most promising context hypotheses is believed to be the so-called *augmented transition network* (ATN) developed originally by Thorne, Bratley, and Dewar (1968) and subsequently elaborated by Bobrow and Frazier (1969) and Kaplan (1973). This hypothesis involves a sequential process whereby information at the beginning of a sentence guides the comprehension of later words in the sentence. It is argued that comprehension occurs by formulating hypotheses about the syntactical category of each word, the contextual grouping of words into phrases, and the grammatical function of a phrase. According to this view, sensory input is continually being matched or mismatched with the output of an ongoing hypothesis-refining process.

It is not our purpose to evaluate critically these two hypotheses of the process of comprehension. Suffice it to say that there is experimental evidence favoring both, and conflicts between the two hypotheses are, as yet, unresolved (Wanner, 1974). In the present chapter the sensory theories of comprehension will be emphasized rather than the motoric ones. The evoked potential analyses discussed in this chapter are obtained from widespread scalp regions which include frontal, central (motor), and posterior (sensory) derivations. One might predict that if motor or articulatory processes were involved in letter or word recognition, the principal evoked potential correlates would occur in anterior derivations, rather than posterior ones. However, as will be shown, the largest evoked potential effects observed in our study occurred in occipital, parietal, and posterior temporal derivations. Hence, no evidence for the motoric theory was provided by the evoked potential analysis.

Evoked Potential Correlates of Delayed Letter Matching

Central to the language comprehension hypotheses is the process of representational matching. It is consistent to argue that match–mismatch operations are involved whether surface structure representations are being compared to deep structure representations or whether hypotheses are being confirmed or disconfirmed. This center position of the process of representational matching recently gave rise to experiments designed to obtain evoked potential correlates of memory match and mismatch using linguistic stimuli.

The experiments involve the use of a Background-Information-Probe (or BIP) paradigm (Thatcher, 1974, 1976b). This paradigm permits the evoked potential analysis of background neural excitability changes which precede and follow the presentation of information. The subjects in this paradigm are required to view a series of briefly presented random dot displays, then a letter, then another series of random dot displays, then a second letter. The subjects are asked to make either a match or mismatch choice based on the two successive letter stimuli. This requires remembering the first letter for varying periods (3 to 7 sec) and then matching or mismatching the second with the memory of the first in order to make the correct response. The random dot displays elicit evoked potentials which serve as controls of excitability changes that precede and follow the presentation of the first letter. A major purpose of the experiment was to analyze evoked potentials elicited by physically identical stimuli which differ only in the degree of concordance between the present and the recent past. For example, averaged evoked potentials (AEPs) elicited by the letter *A* preceded several seconds by the letter *A* (match) could be compared to AEPs elicited by the letter *A* preceded several seconds by the letter *B* (mismatch). Figure 1 illustrates the delayed letter matching paradigm in which a series of brief visual displays were presented on an accessory oscilloscope to human subjects. The subjects varied in age from 18 to 32 (one female) and were all either college graduates or college-

Fig. 1. Illustration of trial sequence of computer-generated displays in a delayed letter matching paradigm. There are a variable number of control and ITI displays before and after the first letter (information). All displays are 20 msec in duration and presented at a repetition frequency of 1 Hz. Total luminance and retinal area subtended (1.5°) are the same for all displays. (From Thatcher, 1976a)

bound. These subjects (two left-handed and seven right-handed) had no previous history of neurological dysfunction.

The displays, which were generated by a PDP-12 computer, were 20 msec in duration and presented at a repetition frequency of 1/s. A given trial (Figure 1) involved presenting a variable number (2 to 6) of random dot displays (control) followed by a letter (information display, *A*, *B*, or *C*) followed by another variable number (2 to 6) of random dot displays (intertest interval displays, ITIs) which were followed by a second letter (test) that either matched or mismatched the information stimulus. If the test stimulus was a match, subjects were instructed to delay 1 sec and then move a small lever to the left. If it mismatched, subjects moved the lever to the right. There was a 5-sec delay period between trials, and match and mismatch conditions were equally probable and counterbalanced across a session. There were 24 trials/session and evoked potentials were averaged across four sessions. The direction of lever movement across sessions was counterbalanced and the number of illuminated points and visual angle (1.5°) were the same for all displays. (Further details of the methodology are provided elsewhere: Thatcher, 1976c).

The evoked potentials were recorded from bilateral and midline scalp derivations. The electrodes were applied according to the international 10–20 system (O_1, O_2, P_3, P_4, T_5, T_6, T_3, T_4, F_7, F_8, C_3, C_4, and F_z or C_z) in which the odd numbers refer to left scalp derivations the even to right, and subscript z to the midline (Jasper, 1958). Eye movements were monitored by either F_{p1} and F_{p2} electrodes or by a transorbital bipolar electrode pair. Except when otherwise specified, all recordings were monopolar using linked ear lobes as a reference. The EEG was amplified and band pass filtered (3 db roll-off at .3 Hz and 40 Hz) and evoked potentials were digitized with a PDP-12 computer (5 msec or 6 msec between samples yielding evoked potentials epochs of 512 ms or 640 msec).

An example of one normal subject's AEPs to random dots and letter stimuli is shown in Figure 2. The most common finding was an enhanced late positive component (see horizontal bars, Figure 2) to first letters and also matching second letters. Eight out of the nine subjects showed this enhancement. The mismatch produced significantly less late positivity than the second letter match or first letter AEP. The mean correlation coefficient between first letter AEPs and match AEPs was .72 as compared to .47 for the mean correlation coefficient be-

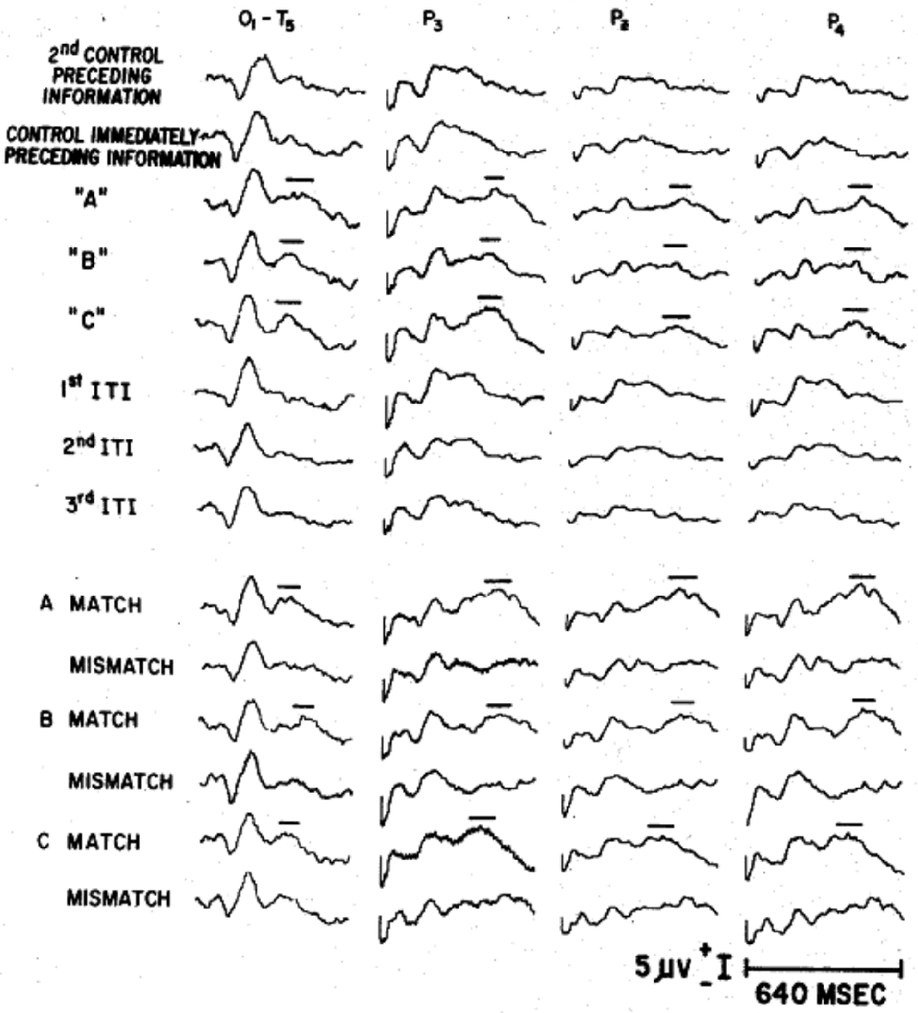


Fig. 2. Examples of AEPs ($N = 24$ for controls and ITIs and 16 for letters) from a subject (J.G.) performing in the letter matching experiment. Bars denote enhanced positivity to first letters and matching second letters. (Positive is up in this and the other figures.) (From Thatcher, 1976a)

tween first letter AEPs and mismatch AEPs. Sign tests showed that first letter AEPs and match AEPs were correlated higher more frequently ($p < .05$) than the first letter and mismatch AEPs. This emphasizes that the mismatch stimulus often results in an attenuated late positive component in comparison to the enhancement observed to both the first letter and the matching test stimuli. It should be noted, however, that a late positive response does occur to the mismatch although it is attenuated with respect to the match. The attenuated late

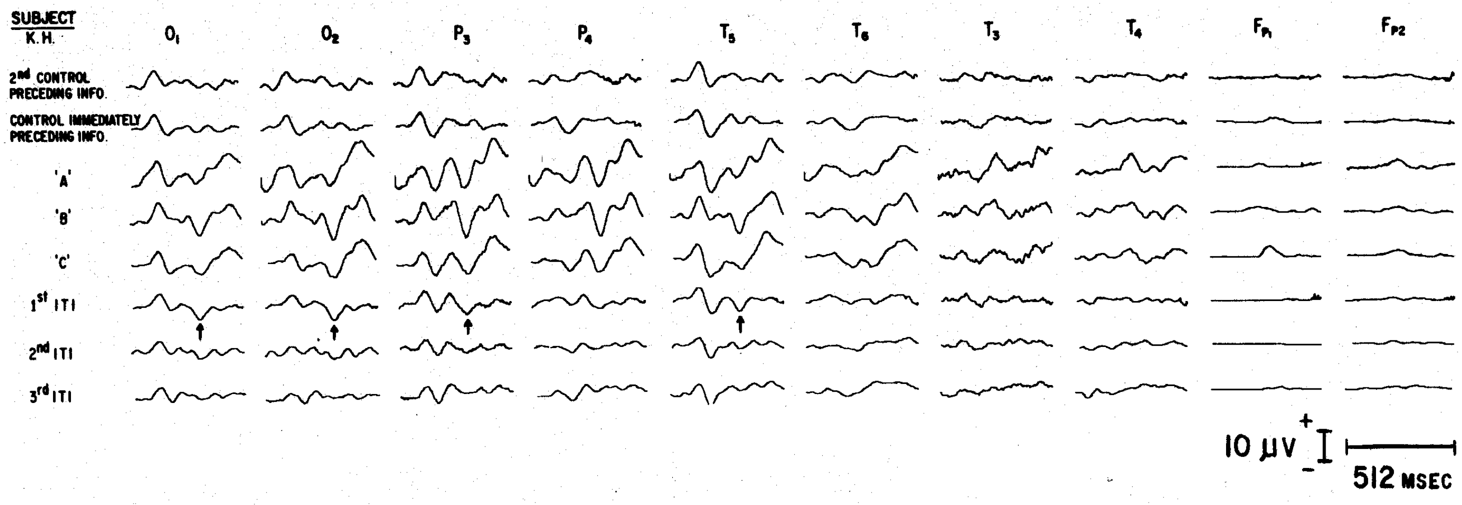


Fig. 3. Examples of AEPs to controls, first letters, and ITIs ($N = 24$ for controls and ITIs and 16 for letters) from a subject (K.H.) performing in the letter match–mismatch experiment. Arrows point to a persistent negative peak to the first ITI following information. Hemispheric asymmetries are evident, particularly in P_3 vs. P_4 and T_5 vs. T_6. Analysis epoch is 512 msec. (From Thatcher, 1976a)

positive component to mismatch stimuli and an enhanced late positive component to the first letter and the match AEP help to explain the results of factor analyses. These demonstrated a shared factor loading between first letter AEPs and match test AEPs (Thatcher, 1974; Thatcher and John, 1975). Another example of late positive component enhancement to first letters in comparison to controls is shown in Figure 3. A clear left–right asymmetry can be seen in this subject, particularly in T_5,T_6 derivations. A persistent AEP change occurred to the first intertest interval display (ITI) which was also asymmetrically distributed (asymmetries emerged in temporal derivations—see arrows). The ITI phenomenon is revealed most clearly in *t* tests between the AEP immediately preceding the first letter (C_1) and the ITI AEPs which follow the first letter. Figure 4 shows latency histograms of statistically significant *t*s for the control_1 versus the ITI_1 through 3 AEPs. It can be seen that most of the significant *t*s were related to the first ITI, the next most to the second ITI, and the least to the third ITI. The latency band for the most frequent significant *t*s was between 300 and

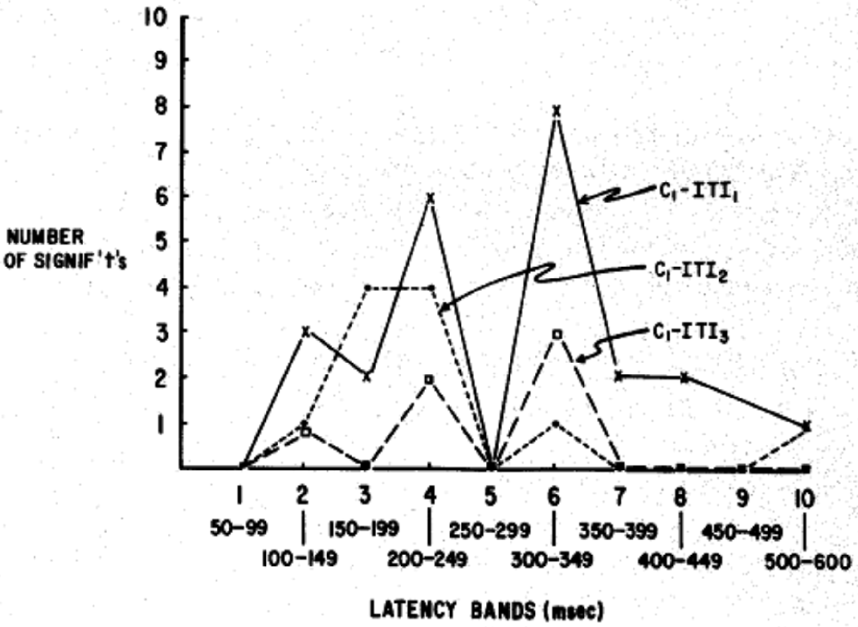
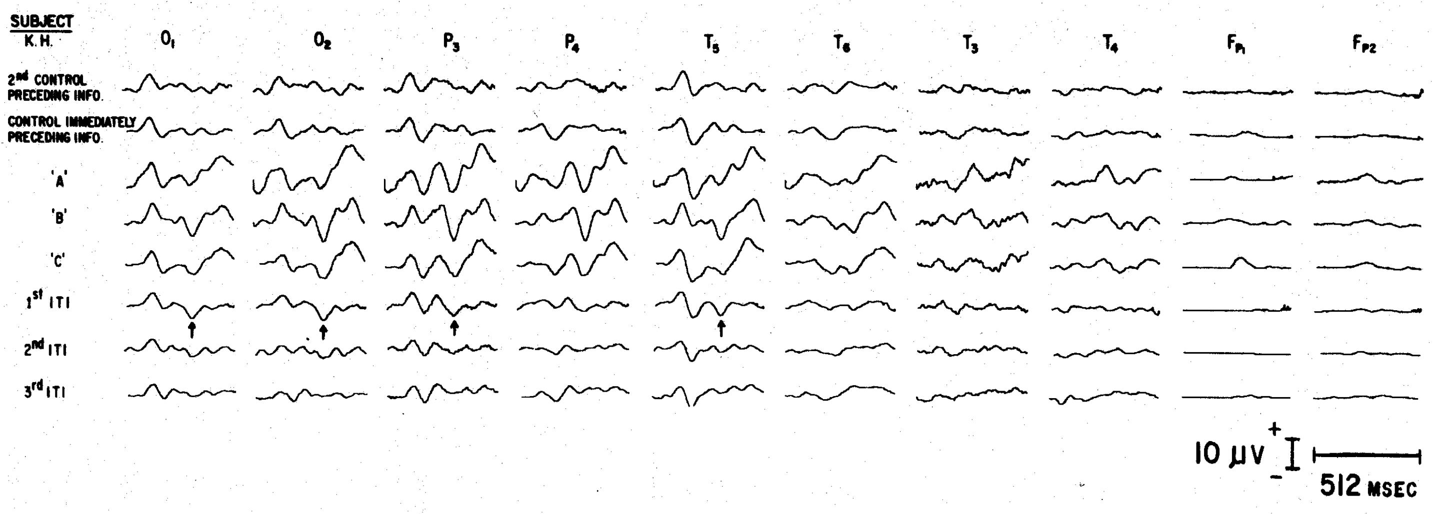


Fig. 4. Latency histograms of significant *t*s for control_1 AEPs versus ITI_1, through ITI_3 AEPs for normal subjects in the delayed letter matching task. The ordinate represents the number of significant *t*s and the abscissa represents the latency bin at which significant *t*s occurred.



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349 msec. These data show that AEP amplitude of waveshape changes occur to the first ITI and then decay back to the control condition by the time of the third ITI (or within about 2 sec). As discussed elsewhere (Thatcher, 1976c) such effects may reflect rehearsal processes.

Table 1 shows the total number of significant *t* tests for the various conditions as a function of derivation. It can be seen that there were only 4 significant *t*s in the control$_1$ versus control$_2$ AEP tests. In contrast, there was a total of 72 significant *t*s between control$_1$ AEPs and first letter AEPs. There were also a decreasing number of significant *t*s between control$_1$ AEPs and the first through the third ITI AEPs (26, 12, and 6). There were nearly twice as many significant *t*s between control$_1$ AEPs versus match AEPs (84) and control$_1$ AEPs versus mismatch AEPs (47). In addition, there was a total of 31 significant *t*s between match and mismatch AEPs. Figure 5 shows latency histograms of statistically significant *t* tests for all of the normal subjects for match and mismatch AEPs and the two control AEPs immediately preceding first letter presentation. It can be seen that significant differences between match and mismatch AEPs occurred primarily at two latency periods (100 to 150 msec and 300 to 400 msec). Table 1 shows that 76% of the significant match–mismatch *t*s occurred in posterior leads (0_1, 0_2, P_3, P_4, T_5, T_6) white 24% occurred in T_3, T_4, and frontal and central leads.

It is important to ask why there are differences in AEPs elicited by letters that match with the past as compared to identical letters when they mismatch. First, could these effects be due to artifacts of experimental design? This is not likely since the conditions of the experiment were counterbalanced and equally probable. That is, match–mis-

Table 1. Number of Significant ts *(3 Successive at $p<.01$) for Normal Subjects in Delayed Letter Matching Task*

Condition	O_1+O_2	P_3+P_4	T_5+T_6	T_3+T_4	C_z	$F_7+F_8+F_z$	Total
Control$_1$ vs. control$_2$	—	2	2	—	—	—	4
Control$_1$ vs. first letter	16	19	20	10	2	4	71
Control$_1$ vs. ITI$_1$	7	6	6	2	1	4	26
Control$_1$ vs. ITI$_2$	4	—	3	3	—	3	13
Control$_1$ vs. ITI$_3$	2	1	3	—	—	—	6
Control$_1$ vs. match	19	19	27	10	3	6	84
Control$_1$ vs. mismatch	12	9	14	8	1	3	47
Match vs. mismatch	7	10	6	2	3	3	31
Total	67	66	81	35	10	23	

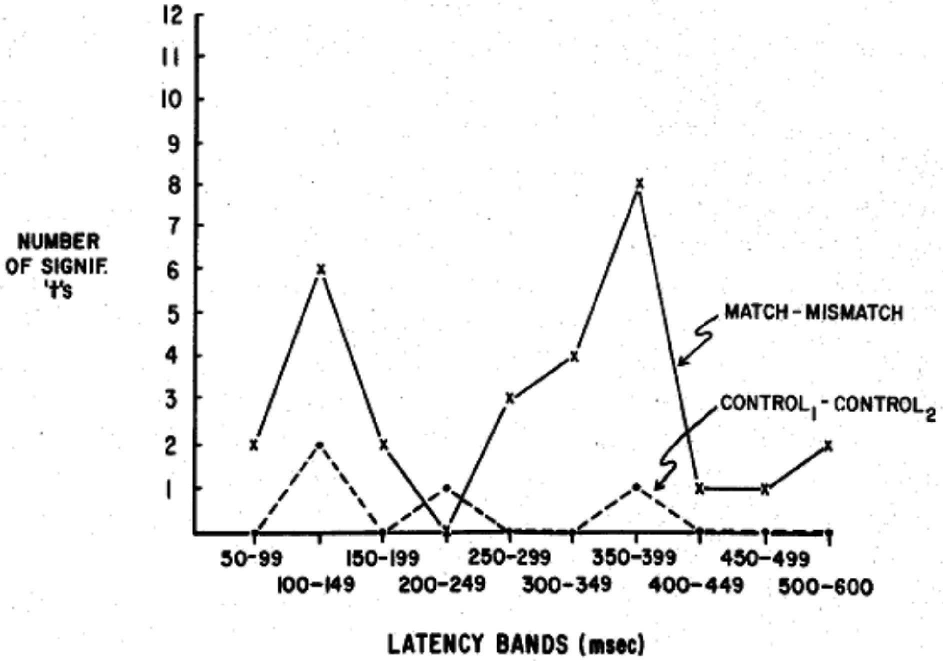

Fig. 5. Latency histograms of significant *t*s for control$_1$ AEPs versus control$_2$—AEPs versus mismatch AEPs for the nine subjects in the delayed letter matching task. The ordinate represents the number of significant *t*s and the abscissa represents the latency bin at which the significant *t*s occurred.

match AEP differences cannot be explained by factors such as differential attention, expectancy, arousal, uncertainty resolution, or cognitive acts of decision. Second, can these differences be due to pathway facilitation? According to this view particular pathways are activated by the first letter resulting in an enhanced late positive component to the matching second letter. However, this explanation is inadequate because there was an enhanced evoked response to the first letter. Third, are these differences due to enhanced variance in the latency of the late positive component to mismatch stimuli? This explanation is also inadequate since the evoked potential variance was slightly greater to match stimuli and analyses of single evoked potentials can discriminate between match and mismatch conditioning (Thatcher, 1976c).

The most parsimonious explanation is that the process of representational matching itself contributes to the enhanced late positive component in the evoked potential.

Evoked Potential Correlates of Semantic Match and Mismatch

One might assume that the enhanced late positive component reflects the match of the physical features and not uniquely the linguistic attributes of the letter stimuli. Considerations of this sort gave rise to other experiments designed to test the linguistic nature of the representational match hypothesis. One experiment involved a match–mismatch paradigm using synonyms, antonyms, and neutral words rather than letters (see Thatcher, 1976a). In this paradigm comparisons are made only at the level of semantic, not physical, features. The prediction was that the late positive component to synonyms and antonyms, comparison of which would involve semantic match or pairing, would be enhanced in comparison to the late positive component elicited by the neutral word pairs which lack a semantic fit. Figure 6 and Table 2 illustrate the synonym, antonym, and neutral word paradigm. The procedure is similar to that shown in Figure 1. This experiment involved eight normal subjects (18 to 37 years of age). Thirty-six different first words and 12 different second words were presented in a session. For one-third of the trials the second words were synonyms, for one-third of the trials the second words were antonyms, and for one-third of the trials the second words were neutral (see Figure 6). Thus, physically identical stimuli (the same 12-second words) served as synonyms, antonyms, and neutrals and were presented in a counterbalanced order within a session. Each subject was given two

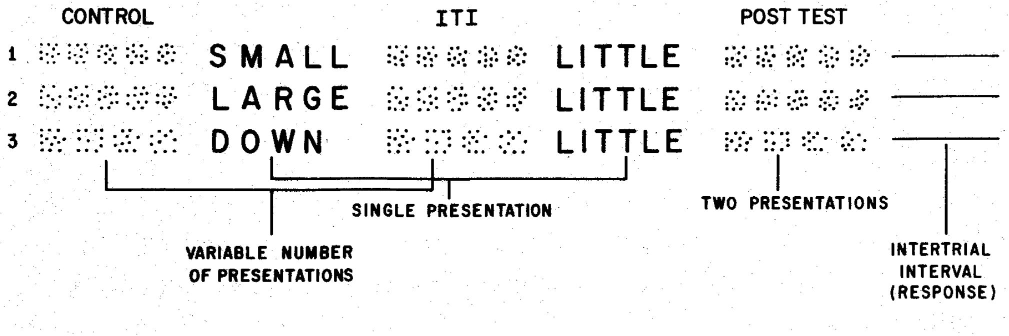

Fig. 6. Illustration of trial sequences and experimental design in the delayed semantic task. Within a session of trials the total number of illuminated dots and the average retinal area subtended was the same for all display conditions. Displays were 20 msec in duration and presented at 1 Hz. (From Thatcher, 1976a)

Table 2. Some Examples of Counterbalanced First and Second Word Pairings Used with Normal Subjects

First word	Second word
Help	Hurt (A)
Easy	Far (N)
Break	Crack (S)
Smooth	Rough (A)
Dark	Black (S)
Neat	Crack (N)
Begin	Finish (A)
Early	Black (N)
Harm	Hurt (S)
Mend	Crack (A)
Near	Far (A)
Coarse	Rough (S)
Lift	Finish (N)
Name	Hurt (N)
Remote	Far (S)
End	Finish (S)
Light	Black (A)
Part	Rough (N)

sessions (≈ 12 min/session) with at least a 30-sec rest period between sessions. The subjects moved a lever to the left if the second word was a synonym, to the right if it was an antonym, and both left and right if it was neutral.*

Examples of AEPs from one subject elicited by first words, controls, and synonyms and antonyms are shown in Figure 7. An enhanced late positive component (440 to 460 ms) occurred only to second words (see arrows, Figure 6). Hemispheric asymmetries (see T_5, T_6, T_3, T_4, Figure 6) occurred in the second word condition but not the first word condition. Note that the late positive component to second words was anatomically widely distributed, appearing even in frontal derivations (F_7, F_8) although less in amplitude. AEP differences between the first word condition might be explained by the fact that retrieval of the meaning of the first word and a comparison with the meaning of the second word only occurred in the second word condition. Figure 8 shows examples of AEPs elicited by second words in the three semantic conditions, t tests between synonym and neutral AEPs

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* The direction of lever movement was counterbalanced across sessions.

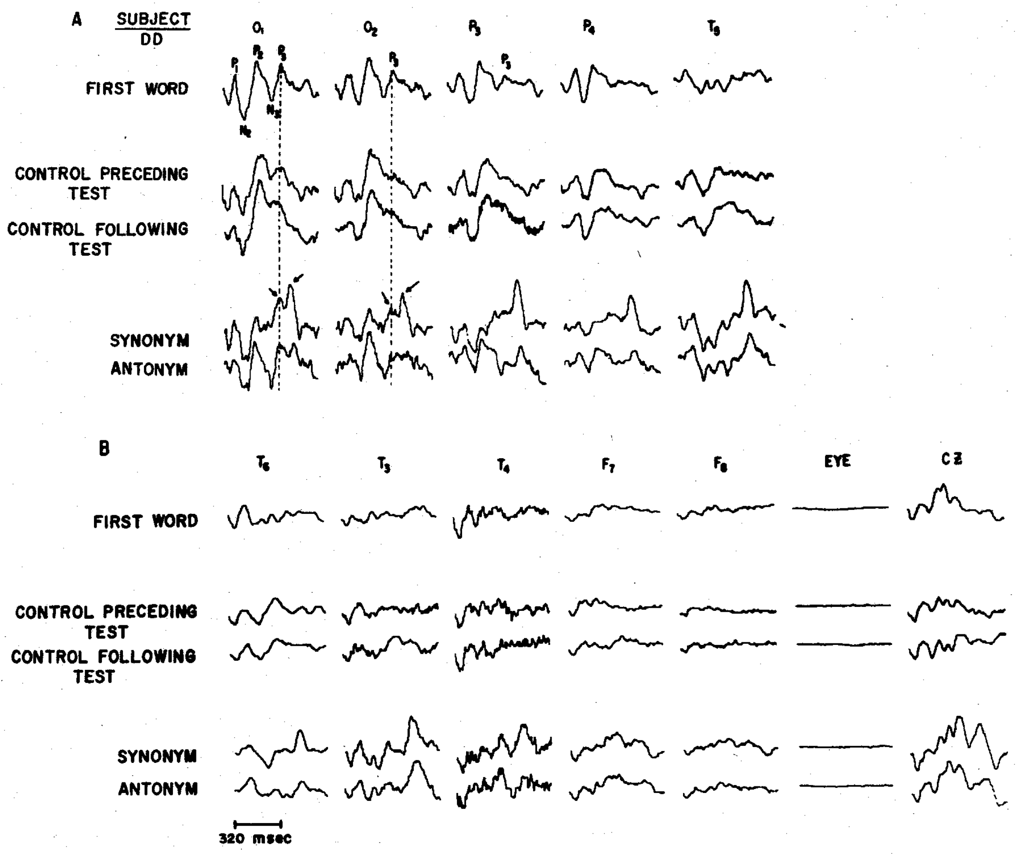

Fig. 7. Averaged evoked potentials ($N = 24$ for synonym and antonym and 48 for the other conditions) to words and random dot controls in one subject. A shows P-300 in occipital regions (dotted line) to both first and second words. Arrows show the P-400 process to synonyms and antonyms which is anatomically and temporally differentiable from the P-300. B, same as A, but showing AEPs from anterior derivations. Note difference between first word and second word responses in T_5, T_6 and T_3, T_4. Note also, asymmetries in the temporal lobe to second words, which are not present in control or first word AEPs.

are shown at the bottom of the figure. The results of this study demonstrated a statistically significant difference ($p < .01$, two-tailed) between synonym or antonym AEPs and neutral AEPs in each of the eight subjects. Significant differences occurred primarily in posterior (O_1, O_2, P_3, P_4, T_5, T_6) derivations with latencies ranging from 405 to 460 ms. In summary, the enhancement of the late positive component to synonyms and antonym AEPs was similar to that seen for letter match AEPs in the first paradigm. The attenuation of the late positive component with neutral word AEPs resembled that for mismatch second letters. This result is consistent with the representational match hypothesis. In terms of the two paradigms an antonym is not analogous to a mismatch. Instead, the words composing an antonym word pair such as *large–little* belong to the same semantic class as the synonym word pair such as *small–little*. The difference is that the antonym and the synonym word pairs represent different ends of the class.

In order to analyze the late positive component (referred to here as the P-4(00)), the absolute amplitude (in μmV) of the maximum late positive peak between 400 and 500 ms was measured with respect to a prestimulus baseline for each condition and each derivation. Using this measure, mean P-4(00) amplitude to random dot displays and words are shown in Figure 9. A repeated measures analysis of variance demonstrated significant differences between synonym and neutral conditions ($F = 80.7$, $df = 1/146$, $p < .001$), as well as between antonym and neutral conditions ($F = 49.3$, df-$1/146$, $p < .001$). No significant differences in mean P-4(00) amplitude were noted between synonyms and antonyms ($F = .28$, $df = 1/146$, $p =$ n.s.). All of the second word AEP conditions were significantly different from the first word AEP condition ($p < .01$). Also the first word P-4(00) was significantly different from the control ($F = 16.7$, $df = 1/46$, $p < .001$). There were no significant differences between C_1 and ITI ($F = 2.8$, $df = 1/146$, $p =$ n.s.), or between left and right derivations when all leads were averaged

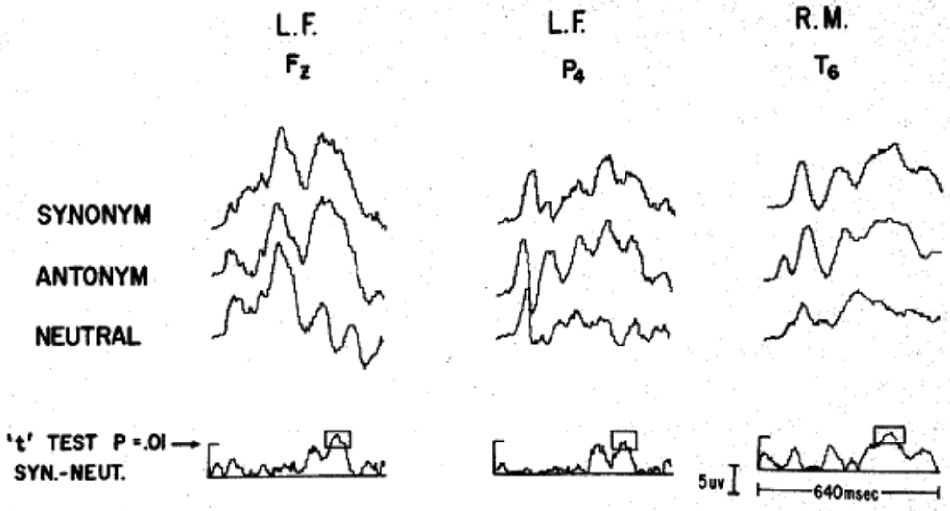

Fig. 8. AEPs ($N = 24$) to physically identical words possessing different semantic relationships. Bottom shows t tests between synonym and neutral AEPs.

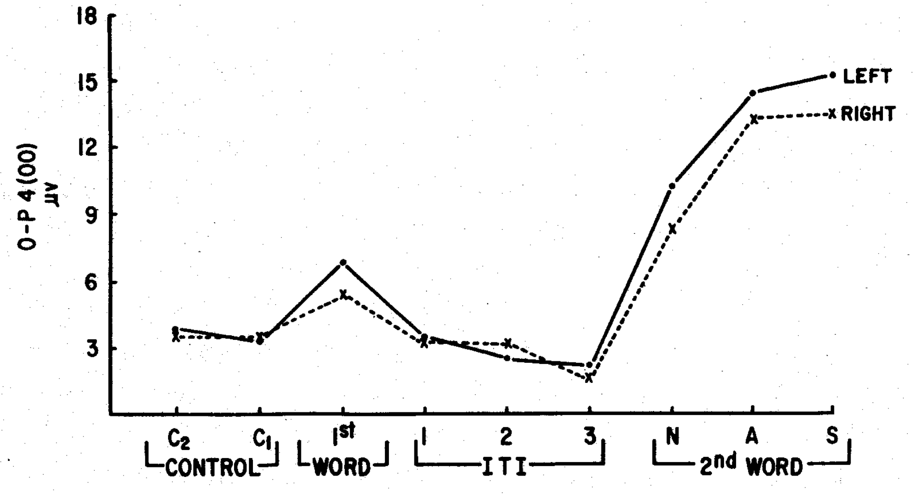

Fig. 9. Mean baseline to P-4(00) amplitude for left and right electrode sites for the various conditions of the experiment. (From Thatcher, 1976a)

together ($F = 3.56$, $df = 1/7$, $p =$ n.s.). However, there was a significant side X derivation interaction ($F = 2.34$, $df = 9/63$, $p < .05$). The latter finding indicates that hemispheric asymmetries, while present, are not uniform across posterior–anterior derivations.

This finding justified additional analyses which showed significant left–right differences ($F = 6.57$, $df = 1/71$, $p < .05$) in posterior derivations ($O_1 + P_3 + T_5$ versus $O_2 + P_4 + T_6$) in the second word condition. No significant left–right differences were noted in anterior derivations ($T_3 + F_7$ versus $T_4 + F_8$) to either the first or second word conditions, nor was a significant difference noted in posterior derivations to the first word condition alone.

Since several workers have reported only rather small AEP symmetries, i.e., 1 to 3 μv (Buchsbaum and Fedio, 1970; Morrell and Salamy, 1971; Wood, Goff, and Day, 1971), a sign test for the side of greatest late positive component amplitude for each subject for control, ITI, and second word conditions was conducted. The results of a binary sign test (Hays, 1963) reveal clear asymmetries in posterior derivations (occipital, parietal, and posterior temporal) during the ITI and first and second word conditions (combined) but not during the control (Thatcher, 1976b). Significant asymmetries always involved left side greater than right (100% of the subjects exhibited left>right in occipital derivations in the word condition). It is interesting that asymmetries are not present to random dot stimuli that precede the first word but emerge to random dot stimuli that follow the first word. This suggests that lateralized operations were active during the ITI or so-called rehearsal period.

In summary, evoked potential analyses from normal subjects performing in delayed letter matching and delayed semantic matching paradigms reveal similar effects, namely, an enhanced late positive component to the match stimuli. Both paradigms demonstrated AEP component and amplitude changes in the random dot display (ITIs) that follow the first word or first letter presentation. Some correlates of hemispheric lateralization were also observed in both paradigms (see Thatcher, 1976b). Also, both paradigms resulted in phenomena that occur largely in posterior derivations (O_1, O_2, P_3, P_4, T_5, T_6) in comparison to anterior regions. These data indicate that motor processes are not responsible for the effects.

Results of Delayed Matching Experiments in Two Aphasic Patients

After the data were acquired from normal subjects, it became possible to examine the performance of some aphasic patients—i.e., those with a localized brain lesion resulting in specific speech–language dysfunction. This approach was felt to be important because it might allow one to examine central representational processes in patients where dysfunction has been described traditionally in terms of specific alterations in input–output functions of language alone (Geschwind, 1972). Since the recovery of function depends on processes in the remaining intact neural substrate (Smith, 1975), observation of task-specific AEPs might give one an opportunity to examine the nature of hemispheric electrical phenomena which parallel the recovery of performance. It is emphasized once again, however, that this method correlates best with the sensory aspect of language and does not give one a measurable correlate of later stage motor processing.

The paradigms used with the aphasic patients were the same as described previously. A complete study with aphasic patients is being planned and only preliminary results from two patients will be presented at this time.

Patient Histories

The two aphasic patients are F.C. (male, right-handed, age 43) and L.F. (male, right-handed, age 25).

F.C. had a sudden onset of aphasia and right hemiparesis in October 1973. A complete diagnostic work-up at the Massachusetts General Hospital revealed the presence of a complete left middle cerebral artery occlusion. The lasting dysfunction consisted of right hemiparesis and nonfluent aphasia.

Language testing at the time of study of the patient's evoked potentials revealed the following. His spontaneous speech was characterized by occasional blocking of complicated sentences, paraphasia, attempts to correct, stammering, and frustration. He was able to read newspapers and books and comprehended both auditory and visual information normally. When given tasks including more than three steps of information, the patient was often confused and had difficulty even repeating manual rhythms tapped by the examiner. He scored 26 on the Symbol Digit Manipulation Test, when the examiner wrote the number that the patient chose on the matching list of symbols. This score represents the mean of score distributions for aphasics tested by Dr. Aaron Smith of the University of Michigan (1973). The patient performed at a high level in the Peabody Picture Vocabulary Test, especially in items involving action pictures. He had no difficulty matching objects, pictures, and words. The functional language problem for this patient consisted principally of going from any input modality to spoken or written output performance. Thus, he was a typical severe Broca's aphasic. A clinical EEG showed very high amplitude intermittent focal delta activity localized at F_{p1}, F_7, F_3, T_3. The patient's clinical neurological course had been complicated by occasional grand mal seizures which were controlled with anticonvulsants.

L.F., a 25-year-old right-handed man, developed headache and the insidious onset of trouble speaking in June 1975. Hospitalization and neurological work-up followed, indicating the presence on cerebral arteriogram of a localized avascular mass in the posterior superior region of the left temporal operculum. On clinical examination there were no abnormalities in cranial nerve function and no lateralizing abnormalities on motor or sensory testing. His spontaneous speech was fluent and there was no paraphasia. When the examiner spoke very rapidly, the patient had difficulty in comprehending the entire meaning of the spoken statement. The patient was unable to follow commands of three-step content. He had difficulty repeating sequences of phonemes (such as, "bee-key-gee") and would say them back erroneously ("pee-key-bee"). More formal language testing revealed errors in phonemic discrimination, but not in reading. WAIS performance IQ was 91. His score on the Raven's Coloured Progressive Matrices was 31/36.* An EEG showed continuous monorhythmic delta activity which was focal at T_3.

The clinical impression was aphasia, Wernicke's type, probably secondary to a left posterior temporal mass lesion, exact nature undetermined.

Task Performance

The scalp electrode locations and recording procedures for F.C. and L.F. were the same as described earlier for the normal subjects. The list of words constituting the delayed semantic task, however, were made much simpler. For example, word pairs such as up–down, high–low, soft–hard, long–short, etc., were used, rather than the pairs in Table 2. F.C. performed above chance on the delayed letter matching task, although his performance was significantly poorer than for normals. For example, only 72% of F.C.'s responses were correct for two sessions as compared to a mean of 98% in normals. F.C.'s performance in the delayed semantic task was even poorer. F.C.'s correct responses were only slightly above chance. However, F.C. clearly understood the instructions for the task and consistently responded correctly to particular word pairs.

A similar performance in the delayed letter matching and delayed semantic matching tasks for F.C. was observed in patient L.F. A primary difference between the two patients, however, was that L.F. was

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* Recently, Kertesz and McCabe (1975) reported the results of scores on the Raven's Coloured Progressive Matrices in a variety of aphasic patients classified according to taxonomic criteria, based on the Western Aphasia Battery scores. The purpose of the study was to correlate nonverbal intelligence with different kinds of aphasia. Interestingly, global, Wernicke's, and transcortical sensory aphasics performed significantly more poorly than did Broca's and other aphasic types. It is therefore of interest to point out that our patient L.F. scored significantly better on the Raven's than did the 18 Wernicke's aphasics in Kertesz and McCabe's series. In fact, his score was superior to that of any of their patients, including controls. Perhaps this relates to the exquisitely localized nature of his pathology.

unable to grasp the concept of antonym and usually confused the antonym and neutral categories. However, L.F. did appear to understand the concept of synonym and did obtain some consistently correct scores to a few synonym word pairs. L.F. scored 76% correct on the delayed letter matching task and only 22% correct in the delayed semantic matching task.

Evoked Potential Results: F.C.

Figure 10 shows AEPs from bilateral parietal (P_3 and P_4) and bilateral frontal (F_7 and F_8) derivations to controls, first letters, and match and mismatch stimuli in the delayed letter matching experiments in patient F.C. It shows that an enhancement of the late positive component occurred in P_3 and P_4 derivations but was poorly developed in the F_7 derivation. The correlation coefficients between the homologous pairs of AEPs is shown at the side in Figure 10. The most notable finding was a deterioration of interhemispheric symmetry of AEPs in the F_7–F_8 derivations to the match–mismatch stimuli. The poor stability of AEP waveforms from F_7 is further demonstrated by the mean correlation coefficient computed for all possible pairs of AEPs. The correlation values at the bottom of each column of AEPs reflect the replicability of AEP waveforms across condition (i.e., C_1–C_2; info–C_1, info–C_2, match–mismatch, match–info, match–C_1, match–C_2, mismatch–info, mismatch–C_1, mismatch–C_2). The F_7 AEPs exhibit marked variability. Table 3 shows the correlation coefficients between homologous pairs in both the letter matching and semantic matching tasks. It can be seen in Table 3 that in the letter matching task the correlation coefficients are reasonably high to the control stimuli but decrease to the letter stimuli showing a decrement in T_5 vs. T_6 and reaching lowest values in F_7 vs. F_8. A similar deterioration of hemispheric symmetry occurred in T_3 vs. T_4 and F_{61} vs. F_8 derivations in the semantic matching task. Table 4 shows the correlation coefficients between AEPs from F_7 and F_8 and AEPs from all other derivations in the two tasks. The significant finding is that the correlation coefficients between F_7 AEPs and AEPs from other derivations is consistently lower than the correlation coefficients between F_8 AEPs and AEPs from other derivations. These data indicate a marked decoupling of the left frontal (F_7) region from other regions, particularly in anterior leads in the match condition. This contrasts with right frontal (F_8) AEPs, which correlate well with all other AEPs and decouple strongly from left anterior AEPs.

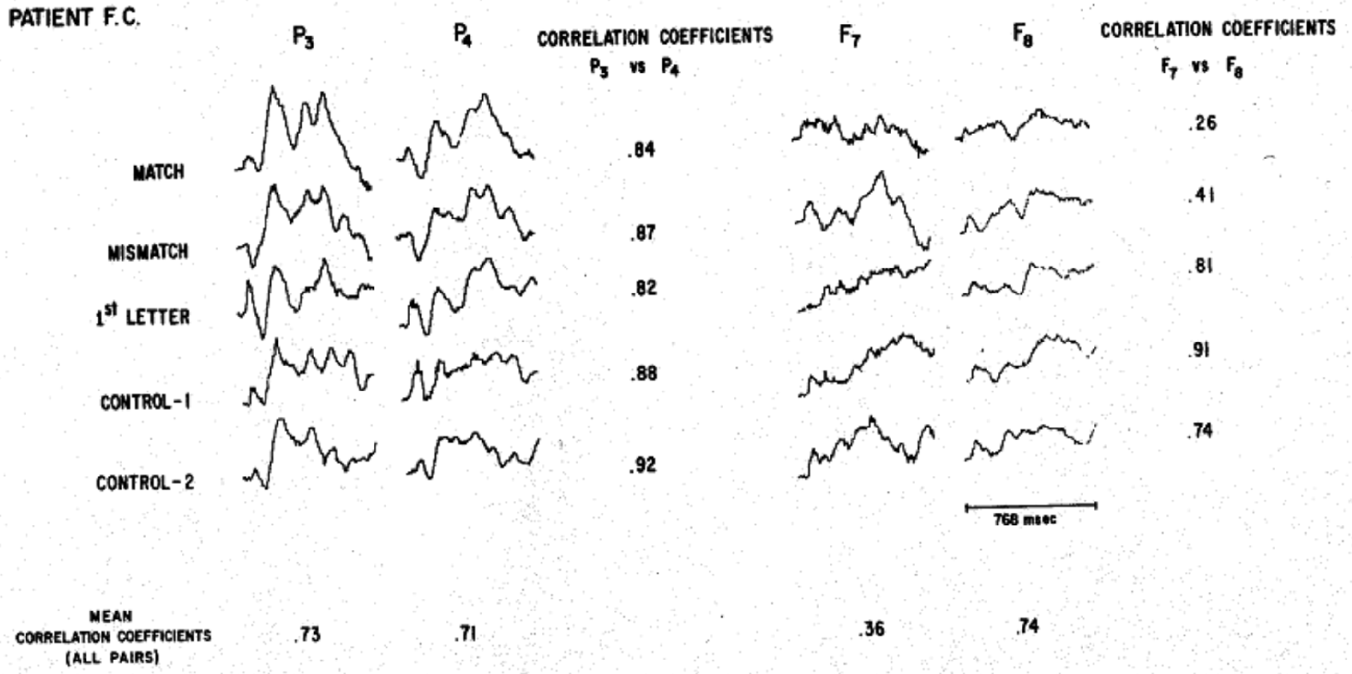

Fig. 10. Average evoked potentials ($N = 24$) from patient F.C. from bilateral parietal (P_3 and P_4) and frontal derivations (F_7 and F_8) to controls, first letters, and match and mismatch stimuli in the delayed letter matching task. Correlation coefficients between homologous derivations is shown at the right of each pair of AEPs. The mean correlation coefficient for a given derivation across conditions (i.e., C_1–C_2, info–C_1, info–C_2, match–*mismatch*, *match*–info, match–C_1, match–C_2, mismatch–info, mismatch–C_1, mismatch–C_2) is shown below each column of waves.

Table 3. Correlation Coefficients of AEPs for Homologous Derivations from Patient F.C.

	O_1 vs O_2	P_3 vs P_4	T_5 vs T_6	T_3 vs T_4	F_7 vs F_8
Delayed letter matching					
Control-2	.96	.92	.78	.75	.74
Control-1	.94	.88	.81	.77	.91
1st letter	.95	.82	.65	.88	.81
Mismatch	.93	.87	.58	.54	**.41**
Match	.94	.84	.69	.61	**.26**
Delayed semantic matching					
Control-2	.91	.86	.75	.12	.25
Control-1	.95	.87	.69	.20	.39
First word	.93	.83	.68	.28	.38
Neutral (2nd word)	.95	.89	.70	.40	**.03**
Syn+Ant (2nd word)	.95	.92	.68	.32	**.08**

These data indicate that a functional deficit begins approximately at T_5 and extends forward, reaching a maximum at F_7.

Evoked Potential Results: L.F.

L.F.'s abnormality appears to be much more localized than F.C.'s. Figure 11 shows AEPs from 11 derivations from both tasks. A marked hemispheric asymmetry was noted in the T_5 vs. T_6 derivations (see arrow at top, Figure 10). In these derivations the mean correlation coefficient was .47 as compared to .86 for O_1–O_2, .88 for P_3–P_4 and .68 for T_3–T_4.

A late positive component occurred consistently in both posterior and anterior derivations (except in T_5) in the delayed letter matching task. However, a late positive component enhancement failed to occur in the anterior derivations (particularly C_3, C_4, and F_z) in the delayed semantic matching task (see arrows, Figure 11). The absence of an enhanced late positive component occurred primarily in AEPs to second words. It should be recalled that L.F. was unable to perform the delayed semantic task. These data may reflect L.F.'s performance deficit.* It is interesting that there is a dissociation between the anterior

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* The absence of a late positive component in the anterior derivations was not due to subject fatigue or habituation. This is known since L.F. subsequently performed in a third task requiring delayed form matching and the late positive components were again present.

and posterior derivations with the posterior derivations exhibiting an enhanced late positive component. A similar dissociation was never observed in normal subjects.

Discussion

Lenneberg was an advocate of simple perspectives although he possessed an enormous capacity to synthesize diverse, complicated facts and to extract the salient invariant relationships. We believe in the importance of Lenneberg's emphasis on the fundamental roles of classification and categorization in the aquisition of language and knowledge. In this chapter and elsewhere (Thatcher, 1976a) it has been

Table 4. Correlation Coefficients of AEPs for Frontal versus All Other Derivations from Patient F.C.[a]

Delayed Letter Matching					
	Left frontal			Right frontal	
	Control	Match		Control	Match
F_7 vs O_1	.46	.43	F_8 vs O_1	.44	.50
F_7 vs O_2	.60	.35	F_8 vs O_2	.60	.60
F_7 vs P_3	.59	.50	F_8 vs P_3	.58	.50
F_7 vs P_4	.72	.25	F_8 vs P_4	.75	.70
F_7 vs T_5	.73	.47	F_8 vs T_5	.75	.47
F_7 vs T_6	.71	.26	F_8 vs T_6	.81	.75
F_7 vs T_3	.81	.62	F_8 vs T_3	.79	.51
F_7 vs T_4	.88	.34	F_8 vs T_4	.95	.84
F_7 vs F_8	.91	.26	F_8 vs F_7	.91	.26

Delayed Semantic Matching					
	Left frontal			Right frontal	
	Control	Syn + ant		Control	Syn + ant
F_7 vs O_1	.14	.32	F_8 vs O_1	.64	.51
F_7 vs O_2	.15	.31	F_8 vs O_2	.62	.66
F_7 vs P_3	.31	.33	F_8 vs P_3	.64	.61
F_7 vs P_4	.18	.34	F_8 vs P_4	.64	.80
F_7 vs T_5	.54	.37	F_8 vs T_5	.56	.40
F_7 vs T_6	.21	.26	F_8 vs T_6	.77	.87
F_7 vs T_3	.77	.58	F_8 vs T_3	.28	.21
F_7 vs T_4	.19	.21	F_8 vs T_4	.90	.96
F_7 vs F_8	.39	.08	F_8 vs F_7	.39	.08

[a] Note more pronounced changes in correlation in left frontal compared to right frontal.

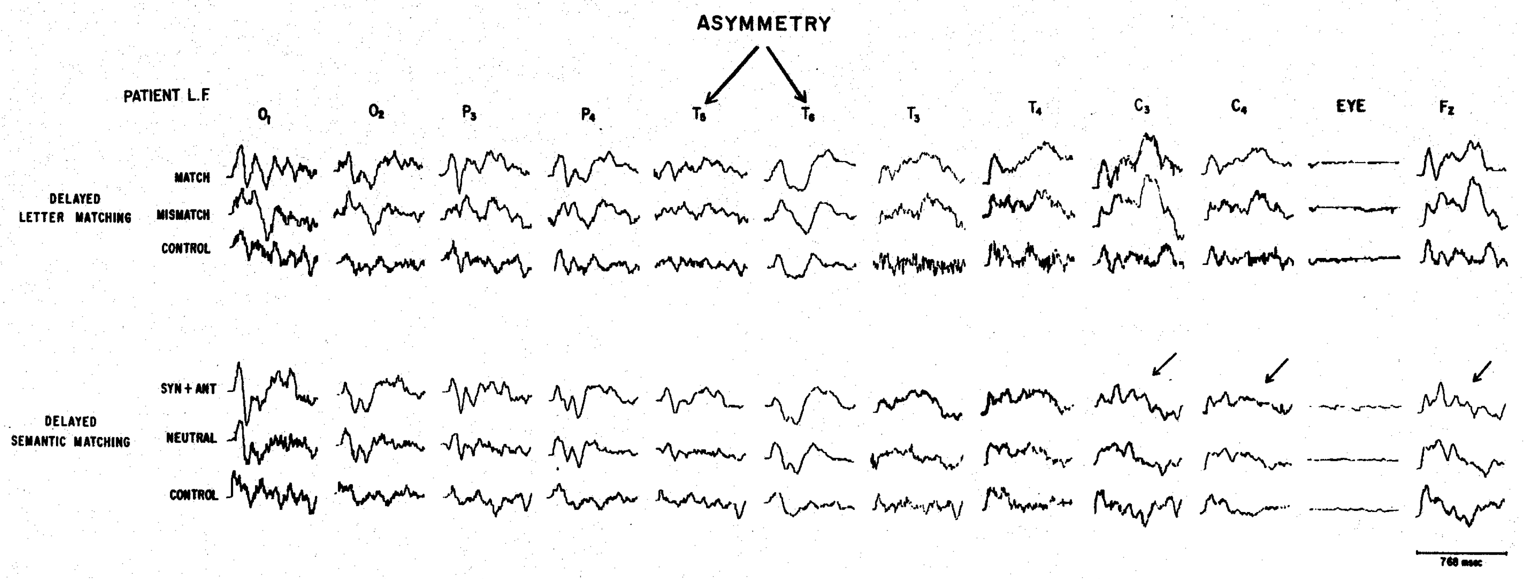

Fig. 11. Average evoked potentials ($N = 24$) from patient F.C. for 12 leads in the delayed letter matching task (top) and the delayed semantic matching task. Arrow above T_5 points to marked asymmetry and attenuated AEPs in the posterior temporal lead. Arrows in delayed semantic task point to an attenuated late positive component in central (C_3, C_4) and frontal (F_z) leads.

emphasized that there is one central concept that underlies the notion of order and classification: namely, the extraction of invariant relations by determining sameness and difference and similarities of such differences. Recently, David Bohm (1969), a quantum mechanist, developed a model of order and information which was based entirely on the extraction of similarities of differences and hierarchies of differences. We argue that one of the fundamental processes for which Lenneberg searched is the perceptual and cognitive operation of determining sameness and difference. This process is believed to be fundamental to logic, language, and mathematics. Classification schemes which arise from the determination of sameness and difference are important not only for semantic categorization and other cognitive functions but also for basic perceptual processes (see Gibson, 1969).

The data presented in this chapter show evoked potential correlates of the match–mismatch process. In normal subjects there are amplitude and waveform asymmetries between evoked potentials elicited by identical physical stimuli that either match or mismatch with stimuli in the past. These effects are observed at different levels of cognitive function—such as, letter feature match–mismatch and word semantic match–mismatch. The match–mismatch AEP asymmetries occurred primarily in the long latency components (300–500 msec), although some differences were also noted between 100 and 149 msec. This major long latency phenomenon indicates that the asymmetries represent processes occurring at the level of memory or semantic representations. That is, the early components of the evoked potential are classically related to the physical attributes of the evoking stimulus and early sensory processing. The late component AEP phenomena related to higher-level processing had a widespread distribution but were maximal in posterior derivations. The strong posterior dominance might be due, in part, to the fact that visual stimuli were used. Future experiments will be designed using both auditory and visual stimuli. Auditory and visual–auditory cross-modal tasks may have more relevance for the study of aphasia.

The paradigms described in this chapter allow precise psychophysical control of the parameters of stimulation. That is, the number of illuminated dots and retinal area subtended were the same for all displays. The paradigm allows the presentation of linguistic or nonlinguistic stimuli (e.g., geometric forms, faces, objects, etc.) and can ascend different levels of complexity and thus challenge specific information processing. In this way a patient with a localized brain lesion might be challenged with tasks which are initially very simple but become successively more complex and can be tailored to the particular domain of neurological deficit. The philosophy behind this approach is that evoked potential diagnosis of functional pathology can be optimized by providing challenges specific to the cognitive deficit as contrasted with classical clinical EEG which lacks cognitive challenges. Not only may the region of pathology be localized more precisely by this method but, perhaps more importantly, specific functional or organizational deficits may appear in brain regions that are normal but which are nonetheless an integral part of a network subserving the probed cognitive function. In this regard there are three findings from the aphasic patients worthy of emphasis.

First, a late positive enhancement failed to occur during semantic processing in patient L.F., who also failed to perform correctly. This gives added support to our hypothesis that late positive enhancement is directly related to correctness of processing rather than to stimulus features themselves.

Second, the enhanced AEP components were bilateral and widespread at many electrodes. Thus, the representational process probed is not limited solely to the traditional language region of the left hemisphere.

Third, we noted striking left–right waveform asymmetries during processing of information loaded stimuli if one of the electrode pairs was situated near the local brain lesion. This points out the value of probing cognitive function with specific stimulus loads in order to uncover maximum lack of regional processing. We refer the reader to Tables 3 and 4, which show that the correlation coefficients were much lower when the stimuli contained information.

More data must be gathered systematically, using a variety of stimulus arrays (geometric form match–mismatch, probes of logic and simple mathematics, cross-modal match–mismatch, etc.). Patients with a variety of local lesions (with and without aphasia) should be chosen. In this way it might be possible to describe systematically central representational processes after cerebral lesions as reflected in components of the AEP.

References

Ades, A. E. Categorical perception and the speech mode. *Cognition*, 1974.

Barlow, H. B. Single units and sensation: A neuron doctrine for perceptual psychology? *Perception*, 1972, *1*, 371–394.

Bobrow, D., and Fraser, B. An augmented state transition network analysis procedure. In D. Walker and L. Norton (Eds.), *Proceedings of the International Joint Conference on Artificial Intelligence*. Washington, D.C., 1969.

Bohm, D. Some remarks on the notion of order. In C. H. Waddington (Ed.), *Towards a theoretical biology*. II. Sketches. Chicago: Aldine, 1969. Pp. 18–58.

Boole, G. *An investigation into the laws of thought*. Cambridge: Cambridge University Press, 1854 (reprinted by Dover Press, New York, 1951).

Buchsbaum, M., and Fedio, P. Hemispheric differences in evoked potentials to verbal and nonverbal stimuli in the left and right visual fields. *Physiology and Behavior*, 1970, *5*, 207–210.

Chen, C. H. *Statistical pattern recognition*. Rochelle Park, New Jersey: Hayden Book Co., 1973.

Chomsky, N. *Syntactic structures*. The Hague: Mouton and Co., 1957.

Chomsky, N. *Aspects of the theory of syntax*. Cambridge: M.I.T. Press, 1965.

Fodor, J. A., Bever, T. G., and Garrett, M. F. *The psychology of language*. New York: McGraw-Hill, 1974.

Geschwind, N. Language and the brain. *Scientific American*, 1972, *4*, 76–83.

Gibson, J. J. *Principles of perceptual learning and development*. New York: Appleton, 1969.

Hays, W. L. *Statistics for psychologists*. New York: Holt, Rinehart & Winston, 1963.

Halle, M., and Stevens, K. Speech recognition: A model and a program for research. *IRE Transactions on Information Theory*. IT-8: 155–159, 1962.

Hubel, D. H., and Wiesel, T. N. Receptive fields, binocular interaction and functional architecture in the cat's visual cortex. *Journal of Physiology (London)*, 1962, *160*, 106–154.

Jasper, H. H. The ten–twenty electrode system of the international federation. *Electroencephalography and Clinical Neurophysiology*, 1958, *10*, 371–375.

Kaplan, R. A general syntactic processor. In R. Rustin (Ed.), *Natural language processing*. Englewood Cliffs. New Jersey: Prentice-Hall, 1973.

Kertesz, A., and McCabe, P. Intelligence and aphasia: Performance of aphasics on Raven's coloured progressive matrices. *Brain and Language*, 1975, *2*(October), 387–395.

Lenneberg, E. H. *Biological foundations of language*. Wiley, New York, 1967.

Lenneberg, E. H. Brain correlates of language. In R. O. Schmitt (Ed.), *The neurosciences: Second study program*. New York: Rockefeller University Press, 1970. Pp. 361–371.

Lenneberg, E. H. Language and brain: Developmental aspects. *Neurosciences Research Program Bulletin*, 1974, *12*(4).

Liberman, A. M. The grammars of speech and language. *Cognitive Psychology*, 1970, *1*, 301–323.

Liberman, A. M., Cooper, F. S., Shankweiler, D. P., and Studdert-Kennedy, M. Perception of the speech code. *Psychological Review*, 1967, *74*, 431–461.

Lisker, L., and Abramson, A. S. A cross-language study of voicing in initial stops: Acoustical measurements. *Word*, 1964, *20*, 384–422.

McCulloch, W. S., and Pitts, W. A logical calculus of the ideas immanent in nervous activity. *Bulletin of Mathematical Biophysics*, 1943, *5*, 115–133.

Miller, G. A., Galanter, E., and Pribram, K. F. *Plans and the structure of behavior*. New York: Holt, Rinehart & Winston, 1960.

Miller, J. D., Weir, C. C., Pastore, R. E., Kelly, W. J., and Dooling, R. J. Discrimination and labeling of noise-buzz sequences with various noise-lead times: An example of categorical perception. *Journal of the Acoustical Society of America,* 1974. In press.

Morrell, L. K., and Salamy, J. F. Hemispheric asymmetry of electrocortical responses to speech stimuli. *Science,* 1971, *174,* 164–166.

Pribram, K. H. *Languages of the brain.* Englewood Cliffs, New Jersey: Prentice-Hall, 1971.

Regan, D. *Evoked potentials in psychology, sensory physiology and clinical medicine.* London: Chapman and Hall, Ltd., 1972.

Rubin, D. C. The subjective estimation of relative syllable frequency. *Perception and Psychophysics,* 1974, *16,* 193–196.

Smith, A. Symbol digit modalities test. Manual. Los Angeles: Western Psychological Services, 1973.

Smith, A., and Sugar, O. Development of above normal language and intelligence 21 years after left hemispherectomy. *Neurology.* 1975, *25,* 813–818.

Sneath, P. H. and Sokal, R. A. *Numerical taxonomy.* San Francisco: W. H. Freeman, 1973.

Sokolov, E. M. Neuronal models and the orienting reflex. In M. A. B. Brazier (Ed.), *CNS and behavior* (Vol. 3). New York: Macy Foundation, 1960.

Szentagothai, J., and Arbib, M. A. Conceptual models of neural organization. *Neurosciences Research Program Bulletin,* 1974, *12*(3).

Thatcher, R. W. Evoked potential correlates of human short-term memory. *Proc. Fourth Ann. Neurosci.* Conv., 1974, p. 450.

Thatcher, R. W. Electrophysiological correlates of animal and human memory. In R. D. Terry and S. Gershon (Eds.), *The neurobiology of aging.* New York: Raven Press, 1976. (a)

Thatcher, R. W. Evoked potential correlates of hemispheric lateralization during semantic information processing. In S. Harnad, L. Goldstein, R. Doty, and J. Jaymes (Eds.), *Lateralization in the nervous system.* New York: Academic Press, 1976. (b). In press.

Thatcher, R. W. Evoked potential correlates of delayed letter matching. *Behavioral Biology,* 1976 (c). In press.

Thatcher, R. W., and John, E. R. Information and mathematical quantification of brain states. In N. Burch and H. L. Altschuler (Eds.), *Behavior and brain electrical activity. New York: Plenum Press, 1975.*

Thorne, J., Bratley, P., and Dewar, H. The syntactic analysis of English by machine. In D. Mitchie (Ed.), Machine intelligence 3. New York: American Elsevier Press, 1968.

Wanner, E. *On remembering, forgetting, and understanding sentences: A study of the deep structure hypothesis.* The Hague: Mouton, 1974.

Wanner, E., Taylor, T. J., and Thompson, R. F. The psychobiology of speech and language—an overview. In J. Desmedt (Ed.), *The cerebral evoke potential in man.* London: Oxford University Press, 1976.

Whitehead, A. N., and Russell, B. *Principia mathematica* (Vol. 1, 2nd ed.). Cambridge: University Press, 1927.

Wood, C. C., Goff, W. R., and Day, R. S. Auditory evoked potentials during speech perception. *Science,* 1971, *173,* 1248–1251.

Wortman, P. M., and Greenberg, L. D. Coding, recoding and decoding of hierarchical information in long-term memory. *Journal of Verbal Learning and Verbal Behavior* 1971, *10,* 234–243.