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Event-related potentials of the human brain during incidental learning

Robert Mitchell Rothbart
Yale University

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EVENT-RELATED POTENTIALS OF THE HUMAN BRAIN DURING INCIDENTAL LEARNING

ROBERT MITCHELL ROTHBART

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Robert Rothbart
Signature of Author

4/13/78
Date

EVENT-RELATED POTENTIALS OF THE HUMAN BRAIN DURING INCIDENTAL LEARNING

by

Robert Mitchell Rothbart

B.A., Stanford University, 1973

A thesis submitted in partial fulfillment
of the requirements for the degree of
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To Dr. Tom Roth

whose encouragement, guidance, and support were invaluable assets in the successful completion of this project. I hope that I shall continue to work with colleagues and friends of Tom's quality throughout my medical career.

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I. INTRODUCTION

The ongoing electrical activity of the human brain, recorded from the scalp as the electroencephalogram (EEG), is relatively insensitive to external environmental events. Although sensation may elicit frequency and amplitude changes in endogenous rhythmical brain activity, no specific waveforms attributable to the occurrence of auditory, visual, or somatosensory stimulation are demonstrable in the EEG of most individuals. However, if one averages the electrical activity recorded following repeated presentations of a stimulus, the relatively high amplitude background activity, whose form and time course are essentially unrelated to the evoking event, tends to average towards zero. Electrical potentials that are temporally associated with the stimulus progressively augment and emerge as a series of positive and negative waves known as the evoked potential (EP). The number of averaging events necessary to reveal a given wave is related to its amplitude relative to that of the background noise, i.e., the signal-to-noise ratio. For a more thorough discussion of signal averaging see Regan (1972).

Evoked and other potentials with relatively inflexible associations to environmental stimuli or motoric behaviors are more generally referred to as event-related potentials (ERP). The contingent negative variation (CNV) is a surface negative slow ERP that develops in the interval between two successive stimuli. In most CNV paradigms the first stimulus serves as a warning while the second requires a motor response or cognitive action on the part of the subject.

Both the CNV and a late positive component of the evoked potential known as P3 or P300 have been extensively studied in terms of their relationships to psychological processes. A number of studies (Hillyard, 1969; Hillyard et al., 1971; Cohen, 1973; Donald and Goff, 1973) have suggested that the CNV and P3 monitor perceptual efficiency, in that their amplitudes were greater in averages of presentations of threshold stimuli correctly detected or discriminations correctly made, than for trials that resulted in erroneous responses. In addition, there is much evidence that CNV and P3 are related to psychological attention (Donald and Goff, 1971; Tecce, 1972; Ford et al., 1973). It is reasonable to assume that perceptual efficiency or level of attention may, in turn, determine the quantity and quality of information available for central processing in the brain. The present study was undertaken to investigate the possibility that ERPs would reflect the amount of information stored by subjects viewing tachistoscopically presented English words in the acquisition phase of an incidental learning paradigm. This introduction provides a review of the relevant literature in four areas: A) the CNV and psychological processes; B) P3 and psychological processes; C) ERPs and behavior; and D) the electrophysiological investigation of human memory.

A. The Relationship of the Contingent Negative Variation to Mental Processes in Humans

Experimental paradigms employed in the study of the CNV generally include two temporally associated successive stimuli; the CNV develops in the interval between the stimuli. The most

basic of these and the one responsible for the initial demonstration of this phenomenon is the constant period reaction time task (Walter et al., 1964). During each trial of this paradigm the subject is presented with a warning stimulus (S1) followed by a constant interval, which in turn is followed by a second stimulus (S2). The subject is instructed to respond as rapidly as possible after detecting the onset of S2. During the experimental session his electroencephalogram (EEG) is recorded using either a DC coupled amplifier or AC amplifier with long time constant to prevent significant attenuation secondary to filtering of the low frequency CNV wave. In single trials, ongoing random EEG activity obscures the CNV developing between S1 and S2; averaging of segments of EEG time-locked to the onset of S1 allows for cancellation of the random background activity and enhancement of the stimulus-related CNVs. CNV averages consist of not less than 6 but more often 12-20 underlying trials. Its morphology in the constant foreperiod reaction time task is that of a negative ramp, which begins approximately 250-450 milliseconds (ms) after S1, reaches maximum amplitude of approximately 10-20 microvolts (uv) just prior to S2 and returns to baseline in an abrupt positive shift approximately 120 ms after S2, called the resolution of the CNV. Modifications in experimental design may be reflected by changes in morphology; for instance, introduction of a variable rather than constant interstimulus interval yields CNVs with increased steepness in the negative-going limb and decreased latency to peak negativity. The distribution of the CNV across the scalp is typically central and frontal; maximal negativity is recorded at the vertex, a smaller but substantial amplitude at

frontal leads, and minimal or absent magnitude from posterior recording (Walter, 1967).

A bewildering variety of experimental designs has evolved from modifications of the basic CNV paradigm. Stimuli of every modality and intensity have been used as S1 and S2; single trials may involve 1, 2, 3, or more stimuli; a simple, complex, or no motor response at all may be demanded by the task. Hillyard (1971, 1973) has devised a classification of all CNV paradigms into 4 basic types: a) holding a motor response in readiness; b) preparing for a perceptual judgment; c) anticipation of a reinforcer (positive or negative); and d) preparing for a cognitive decision. Although this scheme does conveniently differentiate some of the major themes in CNV research, it does so by sacrificing recognition of the full complexity and range of experimental situations in which CNVs have been observed. For instance, Roth and coworkers (1975) recorded CNVs during a Sternberg memory task which required that subjects press one of two telegraph keys to indicate whether S2, a visually presented digit from 0-9, had or had not been in a previously studied set of digits. This design has characteristics of both Hillyard type A and type D paradigms. An important feature to note in Hillyard's classification and in fact in all such schemes proposed to date is that the divisions are based on arbitrarily chosen aspects of the experimental situation; there is no direct relationship between characteristics of the various categories and characteristics of the CNVs observed in each. In fact, a categorization with true functional significance may not be possible at all. This depends, as Rebert (Rebert and Tecce, 1973) has suggested, on the still open question

as to whether the CNV can be differentiated into a family of task-specific event-related slow potentials, or whether a single unitary process, common to all situations in which it is observed, will be demonstrated. The current level of understanding allows only for classification schemes having value principally as mnemonic devices which summarize the diversity of preparatory acts accompanied by the CNV.

As a relatively large amplitude, consistently and easily recorded cerebral potential sensitive to task demands, the CNV, from the time of its initial demonstration, has encouraged investigation and speculation into its meaning and function. The theoretical concepts most closely associated with CNV research are expectancy, conation, motivation, attention, and arousal. Hillyard (1973) in discussing the utility of psychological constructs such as these, pointed out that each term has been assigned multiple definitions dependent upon the particular experimental context in which it is invoked as an explanation. In order to be useful, definitions must be precise and have clear operational ties to observable events.

As investigation into the CNV progressed, it became apparent that one needed to account for the effects of response-variable manipulations in any explanation of the phenomenon. Low (1966) suggested that the factor common to all situations in which the CNV occurs is conation, which he defined as the mental preparation to make some response. He was particularly impressed both by his inability to reliably demonstrate maintained CNVs in the absence of a motor response and by the presence of CNVs in a Sidman-type avoidance task in which

subjects were required to respond within a 2 second window every 15 seconds in order to avoid a noxious auditory stimulus. Low asserts that since no stimuli were employed at all in this paradigm, one could not appeal to such concepts as expectancy or contingency to explain the occurrence of CNVs. However, he is ignoring the fact that the occasional shock received by the subject set up a definite temporal contingency. One might regard internally generated signals impelling successive responses as correlates of S1 and S2. Furthermore, the averaging techniques employed by Low may have led to measurement of readiness potentials rather than CNVs. Nonetheless, other investigations both prior and subsequent to Low's have lent support to his hypothesis; ample evidence exists that CNV is significantly greater when a motor response is required to S2 compared to when it is not (Walter et al., 1964; Irwin et al., 1966; Rebert et al., 1967). However, this is again an incomplete explanation since a number of studies have demonstrated development and maintenance of CNVs in paradigms in which response to S2 was not required, specifically when S2 was novel (Gullickson, 1970), informational (Donchin et al., 1975), or noxious (Miller et al., 1973).

Motivation, as "an index of the general drive state of the organism" (Rebert et al., 1967), has also been advanced as a concept which integrates various CNV findings. These include the observation of increased CNV amplitude when either the effort required to effect a motor response is increased or detection of S2 is made more difficult (Rebert et al., 1967), when monetary rewards are offered for rapid RTs (Tecce and Scheff, 1968, described in Tecce, 1970), when slow responses

to S2 are punished with painful shock (Cant and Bickford, 1967), and when subjects voluntarily alter their motivational state (McAdam et al., 1966). Once again a variety of CNV findings cannot be explained by this unitary concept. These include increased amplitude with increase in complexity of S2 (Walter, 1965a) decreased amplitude with distracting stimulation and thus presumed increased effort (Miller et al., 1973), and decreased amplitude with increase in the interval between S1 and S2, a manipulation that should have no effect on motivation (McAdam, Knott, and Rebert, 1969).

The most recent and most ambitious hypothetical formulation designed to explain all previous CNV data with a limited number of psychological constructs is the attention-arousal theory originally proposed by Tecce (1972) and extended and modified by subsequent investigations (Tecce and Hamilton, 1973; Tecce et al., 1976) into the distraction-arousal hypothesis. Tecce defines attention as "a hypothetical organismic process characterized by steering functions, which facilitates the selection of relevant stimuli . . ." and arousal as ". . . a hypothetical process that energizes behavior unselectively and affects only intensity of response." In his scheme the magnitude of the CNV bears a positive monotonic relationship to attention and a non-monotonic relation (inverted U) to arousal. Both high and low levels of arousal are associated with decreasing CNV amplitude relative to an optimal central range. This hypothesis does integrate an impressive fraction of the CNV literature. Manipulations which seem to demand increased attention to S2, such as requiring a motor response to S2 (Low et al., 1966; Walter et al., 1964), decreasing S2 amplitudes

(Rebert et al., 1967), selecting for trials with the shortest latency reaction times (Rebert and Tecce, 1973) or providing complex or novel S2s (Gullickson, 1970), yield increases in CNV amplitude. Signal detection theory allows for computation of perceptual sensitivity as a measure of selective attention during detection of signals at threshold. Analysis of such tasks has demonstrated a relationship between CNV amplitude and this measure thereby lending support to Tecce's attentional hypothesis (Hillyard, 1973). In addition, task modifications designed to result in divided attention or distraction, also produce decreased CNV amplitude (Tecce and Scheff, 1969; Tecce and Hamilton, 1973; Tecce et al., 1976).

The evidence concerning the effects of arousal on the CNV is substantially less firm and extensive. In most of the previously mentioned studies whose findings were explained on an attentional basis, one could hypothesize that the manipulations described resulted in increased phasic arousal in the S1-S2 interval rather than, or in addition to, changes in attention. Unfortunately, no objective measurements of autonomic arousal were obtained. If such an arousal effect does occur, Tecce suggests that it accounts for the ascending limb of his inverted U function. More evidence exists to support the descending limb of the proposed relationship. Some of the data comes from Tecce's own lab where he has shown autonomic arousal in the form of increased frequency of eyeblink and heart rate acceleration associated with decreased CNV amplitude during distraction (Tecce et al., 1976). This has led him to posit a reciprocal relationship between increasing distraction and increasing arousal, which tends to result in a reduced

CNV. The fact that CNVs are smaller during extremely difficult, and thus perhaps arousing, tasks (Delse, Marsh, and Thompson, 1969) provides support for Tecce's proposal.

The concept that arousal bears both a direct and inverse relationship to the CNV in different ranges of absolute arousal level, if applied in a non-rigorous fashion, will suffice to explain virtually any CNV change resulting from an experimental manipulation. Physiologic measures associated with autonomic arousal must be monitored independently if this theoretical construct is to be applied intelligently.

While Tecce's scheme is consistent with much more of the available data than previous proposals, the great diversity of CNV findings resists explanation by a limited set of psychological concepts. For instance, dissociations have been observed between autonomic measures and CNV. Administering tranquillizers to experimental subjects decreased autonomic hyperactivity but had no effect on CNV (Walter, 1966). In another study (Knott and Irwin, 1968) changes in CNV were observed in high and low stress conditions without concomitant GSR changes.

Although no single theory is yet available which accounts for all of the observed associations between the CNV and psychological factors, the explanations presently being advanced converge upon a limited area of mental function. Clearly, CNV does access higher mental functions which are involved in the cognitive processing of environmental events of importance to the individual. This property allows the CNV to function as an especially useful tool in human brain research.

B. The P3 Component of the Human Evoked Potential and Psychological Processes

P3 is a late positive wave of the human evoked potential which typically reaches peak amplitude approximately 300 ms after stimulus onset; however, latencies ranging from 250-600 ms, reflecting varying experimental designs, have been reported (Hillyard, in press). The very occurrence of P3, as well as its amplitude and latency, are determined by psychological processes concerned with the reception and evaluation of the evoking stimulus. Strictly speaking, this wave is not evoked by a stimulus, but rather is emitted in response to certain types of events in the environment. It represents what Donchin, Ritter, and McCallum (in press) have called an endogenous component in that its characteristics are dictated more by the mental state of the subject than parameters of stimulus delivery. This quality of P3 is particularly evident in paradigms which allow recording of brain potentials generated to omission of an expected stimulus. Ford, Roth, and Kopell (1976) reported an experiment in which subjects were presented with a series of tone pips at a rate of four per second, occasionally and randomly interrupted by a tone of different frequency or an omitted stimulus. Late positive waves with the classical scalp distribution of P3 were elicited by both of these events. Thus P3 is related to a cognitive process which may occur in the presence or absence of actual sensory input. Further evidence supporting the notion that P3 reflects the psychological evaluation of a stimulus rather than pure perceptual phenomena comes from innumerable experiments in which physically identical stimuli are presented in different contexts. Corby and

Kopell (1973) found that P3 was present in auditory and visual EPs when stimulus occurrence was unpredictable, but absent when subjects could predict the identity of each stimulus prior to its presentation. Ford et al. (1973) recorded greatly enhanced P3s for a given type of stimulus when subjects were required to respond to its occurrence than when they were asked to respond to other types of stimuli. Similar findings have been consistently and virtually universally reported (Sutton, 1965; Donald and Goff, 1973; Picton and Hillyard, 1974). The P3 component is stimulus-independent in another sense, inasmuch as it is not modality-specific. Visual, auditory, and somatosensory stimuli yield P3s with virtually identical topographic distributions across the scalp (Hillyard et al., 1976; Ritter, Simpson, and Vaughan, 1977).

Given the observation that cognitive factors are important determinants of P3, a great deal of work has focused on defining exactly which factors are involved. Unfortunately, each time that P3 has been identified in a previously untried experimental paradigm, a new psychological construct has been invoked to account for the findings. These have included information delivery (Sutton et al., 1965), selective attention (Donchin and Cohen, 1967; Ford et al., 1973; Hillyard et al., 1973), signal detection (Hillyard et al., 1971), salience (Paul and Sutton, 1972), the orienting response (Ritter and Vaughan, 1969), expectancy (Duncan-Johnson et al., in preparation), cognitive matching (Squires, Squires, and Hillyard, 1975), and task relevance (Courchesne, Hillyard, and Galambos, 1975). Many of these concepts are poorly defined in the psychological literature and add

nothing, either in an explanatory or predictive sense, to the basic observations themselves. Gradually, some order has been emerging from the plethora of experimental findings. Recent reviews (Donchin, Ritter, and McCallum, in press; Hillyard, in press) have managed to organize and explain most of the reported P3 data in terms of a limited number of reasonably well-defined concepts.

The probability of stimulus occurrence has clearly emerged as an important determinant of P3 amplitude. In one paradigm (Sutton et al., 1965) the subject predicts the nature of the stimulus he will receive on each trial. P3 amplitude is directly related to the *a priori* experimenter-defined probability of a given event as well as to the subject's expectancy, that is, his prediction of trial outcome. Unexpected, low probability events yielded the largest P3s. Another task that has been widely used in the study of the relationship between P3 and probability is one which requires detection of target stimuli embedded in a series of non-targets. Over a wide range of probabilities, P3 amplitude is inversely related to the relative frequency of the eliciting event (Hillyard et al., 1973; Courchesne, Hillyard, and Galambos, 1975; Ford, Roth, and Kopell, 1976). The evidence suggests that the subject's assessment, whether conscious or unconscious, of the likelihood of occurrence of a particular event is an important modulator of P3 amplitude. This notion is more precise than and can replace past analogous explanatory constructs such as novelty, expectancy, and saliency.

Although many P3 findings can be explained on the basis of stimulus probability, this clearly is not the entire story. When

subjects are asked to respond to one of two stimuli occurring with equal frequency, P3 will be elicited only by the response-requiring sensory event (Corby and Kopell, 1973; Hillyard et al., 1973). The decision to classify stimuli as targets or non-targets may be based upon a simple sensory dimension, such as intensity (Picton and Hillyard, 1974) or a complex cognitive judgment, such as whether or not a test item was contained in a previously defined set (Gomer, Spincuzza and O'Donnell, 1976). These and other studies indicate that a stimulus must have some degree of task relevance in order to elicit a P3 component. In an occasional study, a particularly infrequent or subjectively obtrusive stimulus, even when unattended, will elicit a prominent P3 (Roth et al., 1973; Vaughan and Ritter, 1970).

Both task relevant targets and obtrusive or rare stimuli are subjected to cognitive evaluation. In the case of the former there is a match between an internal representation and a detected environmental event; for the latter, there is a profound mismatch between psychological expectations and sensory input. Both events give rise to a P3 wave.

The process of comparing sensory input with information stored in memory to facilitate stimulus selection and responding was called "response set" by Broadbent (1970) and was one of a number of modes of attention proposed by him. Hillyard (in press) has been most active in applying Broadbent's concept of response set selective attention to analysis of P3 findings. Working with a signal detection task (Hillyard et al., 1971) he has demonstrated that P3 amplitude is directly related to D', a measure of perceptual sensitivity, and thus reflects selective

attention. In dichotic listening tasks (Schwent, Snyder and Hillyard, 1976; Schwent, Hillyard, and Galambos, 1976; Picton and Hillyard, 1974), P3 enhancement served as a sensitive indicator of selective attention to a target stimulus both within and between sensory channels. Studies from Hillyard's laboratory employing both very infrequent and task-relevant stimuli suggest that the P3s to these two types of events may be discriminable in terms of scalp topography (Squires and Hillyard, 1975). Two sub-components were identified: P3a, a probability dependent fronto-centrally distributed wave with a latency of 220-280 ms, and P3b, a centro-parietal wave occurring from 310-380 ms and associated with task relevance. Ford, Roth, and Kopell (1976) have reported additional data supporting the existence of more than one type of P3 wave.

The contribution of behavioral measures to analysis of ERP experiments will be discussed in detail in Section I-C of this introduction. Here it is appropriate to briefly consider the impact of the work concerning P3 latency and reaction time (RT) on psychological theories concerned with the meaning of P3. If P3 in fact reflects the outcome of a cognitive process whereby sensory input is evaluated with respect to subjective expectancy and stored stimulus representations, then the latency of this wave should vary with the time needed to make such a judgment. To the extent that RT is sensitive to the decision time, it should behave in a similar fashion to P3 latency. One would predict that as cognitive tasks involving target selection are made more complex and thus require increased processing on the part of the subject, P3 latency and RT should increase and thus should be positively correlated with one another. Such findings have in fact

been commonly reported. Ritter, Simpson, and Vaughan (1972) investigated tone identification tasks of increasing difficulty and identified concomitant P3 and RT increases of approximately equal magnitude during the more difficult tasks. Roth, Ford, and Kopell (1976) generated EP averages on the basis of RT to a target. P3 latency was greater for the slowest RT trials when compared to the most rapid. In a Sternberg short term memory experiment, Gomer and his coworkers (1976) demonstrated that manipulations known to increase cognitive processing time resulted in longer P3 latency. However, other authors (Karlin and Martz, 1973; Squires et al., 1976) have failed to observe the expected covariation of RT and latency of P3. These discrepant findings can probably be attributed to the failure of P3 to index all of the multiple determinants of RT. P3 is most closely associated with stimulus evaluation processes while RT encompasses those mental activities related to responding and events producing the actual muscular contractions. Minor variations in experimental design may have profound effects of differential strength on the various factors contributing to RT and thus would tend to modify the correlation of P3 latency and RT. Support for this hypothesis comes from the work of Kutas et al. (in preparation, as described in Donchin, in press), which demonstrated a high correlation between P3 latency and RT when the subjects received instructions emphasizing accuracy, but a low correlation when instructed for speed. Viewed as a whole, the data suggests that to the extent RT is determined by cognitive evaluation of sensory input, a positive association between P3 and RT is maintained.

In summary, P3 is an endogenous component which can be identified in the ERPs elicited by infrequent and/or task-relevant stimuli or the absence of expected stimuli. It indexes cognitive processes related to stimulus identification and as such can serve as an investigative tool of psychological events which are only poorly accessed by behavioral measures.

C. Event-Related Potentials and Behavior

Most studies concerned with investigating the association of psychological factors and human cerebral potentials have effected manipulation of mental processes through verbal instructions or by modifying the conditions of stimulus presentation. This places the experimenter in the less than ideal position of formulating *a priori* hypotheses as to the nature of the effect of his intervention on the psychological state of the experimental subject. In a restricted subset of these studies experimental design has included objectively quantifiable behavior on the part of the subject. Event-related potentials can and have been correlated with a number of these including physiological measures, reaction time, perceptual accuracy, and cognitive performance. Use of such measures allows the experimenter to verify the operation of a given mental phenomenon in his paradigm and assess its contribution to systematic changes in ERP features.

Measurements of response latency have commonly been obtained in experiments concerned with ERPs, especially in CNV paradigms, the very first of which was a constant foreperiod reaction time task (Walter et al., 1964). Two reviews of the literature (Tecce, 1972; Rebert and

Tecce, 1973) reported consistently negative correlations between CNV and reaction time (RT), i.e., larger amplitude CNVs associated with increased speed of response; however, the mean correlation of -.365 for the 19 studies reviewed (Rebert and Tecce, 1973) indicated that only a small portion of RT variability (13%) can be accounted for by the CNV variation. Moreover, although numerous studies have demonstrated changes in the expected direction of RT and CNV with various experimental manipulations (Tecce and Scheff, 1969; Irwin et al., 1966; Walter, 1966), an approximately equal number have shown dissociations between the two measures (Hillyard and Galambos, 1967; Rebert et al., 1967). Rebert and Tecce offered the tentative conclusion, based on the small average magnitude of the CNV-RT correlation and the many dissociations, that "CNV and RT are essentially unrelated and reflect different and relatively independent psychological processes." They cited data establishing a low order correlation between physiological measures of arousal and RT and implied that arousal might mediate the CNV-RT correlation.

Prior formulations equating RT and CNV have been derived from simplistic notions of reaction time as a unitary concept. A more realistic view recognizes that a number of components including perceptual factors, motor readiness, learning, and motivational variables operate in reaction time tasks; consequently, dissociations between RT and the CNV, which cannot possibly be related to all of these factors, are not unexpected. Nonetheless, when a single process is manipulated with adequate control of the others, RT can provide valuable information concerning the interpretation of ERP changes.

In general, electroencephalographers have viewed bioelectrical phenomena generated by structures other than the brain as possible contaminants of the EEG, and much work has been directed towards definition of the contribution of various biological potentials, especially those arising from the globe of the eye and the skin, to the EEG recorded from scalp electrodes (for a review see Papakostopoulos, 1973). However, a few investigators have explored the use of physiological measures of autonomic arousal as a means of more precisely defining psychological states during experimental investigation of EEG and event-related potentials. This approach has been used in studies of CNV and psychopathological states. McCallum and Walter (1968) found that neurotic subjects had higher basal heart rates and smaller CNVs than normal controls; however, CNV amplitude decrements produced by the addition of extraneous stimuli were not accompanied by heart rate changes. Galvanic skin response (GSR) was not reliably associated with CNV either on a tonic or phasic basis.

The effects of frontal leukotomy on CNV and cardiac rate in psychotic and neurologic patients has also been studied (Lurin and Homskaya, 1970; Walter, 1966). Comparison of pre- vs. post-operative recordings revealed decreased basal heart rate, decreased heart rate reactivity to sensory stimuli, and increased CNV amplitude into the normal range from its initially depressed level.

Autonomic measures have also contributed to investigations of psychological processes and event-related potentials. Tecce's (Tecce and Scheff, 1969; Tecce et al., 1976) elegant experiments, which demonstrated decreased CNV during distraction, provide examples of

three effective uses of behavioral measures: 1) in these studies the presence of enhanced arousal accompanying distraction was verified by monitoring EKG and eyeblink frequency; 2) accurate recall of the distracting items presented in the S1-S2 interval was required in order to assure the subject's attention to these stimuli; and 3) lengthened reaction times validated the efficacy of the experimental manipulation. Dissociations between ERPs and autonomic measures have also been reported. Knott and Irwin (1968) found decreased CNV amplitude for subjects with high manifest anxiety (Bandig scale) but no GSR changes relative to subjects who scored much lower.

Convincing associations between ERPs and perceptual accuracy have been reported from a number of laboratories. The most comprehensive studies are those performed by Hillyard concerning auditory signal detection. In a preliminary experiment involving detection of near-threshold tone pips following a warning tone (Hillyard, 1969), CNV amplitude was greater preceding correctly identified signals when compared to signals that were missed. Subsequently, he (Hillyard et al., 1971) showed that P3 varied in amplitude directly as a function of D' (perceptual sensitivity). Thus, these averaged EEG features seemed to index spontaneous fluctuations in the efficiency of auditory processing. Donald and Goff (1973) have demonstrated that accuracy of performance on a difficult auditory discrimination was related to CNV and P3 amplitude to S2. Comparison was made between blocks of trials with the most accurate performance and the block with the poorest accuracy. In the former CNV was greater and P3 to S2 increased relative to the latter. Again, these results suggest that the CNV

is related to efficiency of auditory sensory processing. Studies of the visual modality have yielded similar results. Cohen (1973) investigated CNVs preceding words and pictures presented tachistoscopically to subjects near their thresholds for identification. CNV amplitude was greater before correctly perceived stimuli. In a similar experiment (McAdam and Rubin, 1970) the readiness potential was increased prior to stimuli that were correctly identified with high confidence when compared to stimulus presentations that resulted in responses rated by the subjects as guesses.

Cognitive tasks and the behavioral measures of performance they provide can also be useful in research involving event-related potentials. Donald (1970) investigated the resolution of the CNV by interpolating mental arithmetic or a short term memory procedure between S2 and the motor response in a constant foreperiod reaction time paradigm. McAdam and Whitaker (1971) demonstrated lateralization of the readiness potential during a verbal task, but not during one involving only facial expressions. Johnson and Chesney (1974) found that a single ambiguous stimulus produced different EPs when meaning to the subject is manipulated by changes in context. In addition, ERPs have been studied during a variety of learning and memory paradigms (Roth et al., 1975, 1977, 1978; Rubin and McAdam, 1972; Gomer et al., 1976). These will be discussed in Section I-D.

D. Electrophysiological Investigation of Human Memory

The body of literature devoted to electrophysiological studies of human memory processes is quite limited, both in terms of the actual

number of studies reported and the range of issues which have been approached. The principal lines of investigation in this area have followed three research strategies: a) observation of EEG changes during tasks which require the activation of memory processes; b) determination of the relationship between EEG activity during learning and retention of information in memory; and c) investigation of the effects of arousal, as determined by skin conductance changes, during learning and memory. A few authors have reported obtaining averaged event-related potentials during learning paradigms.

The suggestion that human mental activity is reflected by changes in electrical activity of the brain was initially made by Berger (1930) soon after his first descriptive studies of the human EEG. The intervening 50 years have seen a great deal of effort expended by many researchers in attempting to delineate the association between mentation and EEG; the results have generally been confusing, contradictory, and difficult to interpret.

Special attention has been directed towards the alpha rhythm, cyclical activity of 8-12 cycles per second, observed in the EEGs of most people. The findings have been somewhat ambiguous. Decreased alpha activity has generally been associated with the performance of mental tasks; however, not infrequently, increased activity in the alpha band with mentation has been reported (for a review see Stigby, 1977). These discrepant findings may be partially attributed to the diversity of techniques and devices used to quantitate the EEG as well as to the variety of conditions under which it is recorded (e.g., eyes open vs. eyes closed). A reasonably consistent finding has been a

global increase in average EEG activity with mental activity (Surwillo, 1971a).

In an extensive study designed to allow the simultaneous analysis of a wide range of frequencies at a large number of scalp locations during a variety of mental tasks, Giannitrapani (1971) demonstrated a global decrease of alpha activity and an increase in beta activity in the temporal and prefrontal areas. Based on these findings he proposed that alpha activity be regarded as a search for sensory stimulation; decrements in alpha proportional to the degree of structure of the stimulus occurred in the presence of a broad range of percepts. Beta activity increased during presentations of unstructured stimuli and could be regarded as a correlate of an internal scanning and organizing activity which subsided after structuring of the stimulus.

Application of these techniques to human learning was first reported by Thompson and Obrist (1964). In their research employing a serial anticipation task, alpha wave incidence was decreased and beta (>12 cps) wave incidence increased over the entire learning session compared to a nonlearning control condition which contained some but not all of the stimulation and response characteristics of the experimental period. These results can be interpreted in terms of perceptual scanning and structuring of percepts, concepts discussed above with respect to Giannitrapani's work (1971).

Freedman and his coworkers (1966) analyzed the EEG in a number of frequency ranges during a paired-associate paradigm. Yoked control subjects received stimulus sequences identical to those presented to their respective experimental counterparts but for these controls,

feedback information was unrelated to responses, and thus, no learning was possible. Alpha activity increased in the experimental group over trials, but decreased for the controls. Lower frequency components of the EEG behaved in a reciprocal fashion to the alpha activity. No significant variation was observed in the higher frequency bands. The authors explained their findings by suggesting that prevalence of alpha is directly related to level of arousal. Thus, as learning progressed, decrements in arousal were accompanied by increases in alpha activity. They hypothesized that the control group experienced frustration as a consequence of the feedback devoid of informational content thereby leading to increased arousal and a progressive decline in alpha activity as the experiment continued. A hypothetical perceptual scanning mechanism associated with alpha is not consistent with the findings reported in this study. Since EEG sampling was interdicted during stimulus presentations, the authors are probably correct in ascribing their results to tonic characteristics of the experimental situation such as arousal, rather than specific perceptual processes.

Surwillo (1971a) measured the average frequency of the EEG obtained from adolescent subjects during performance of a short term memory task with variable memory load (the reverse digit span subtest of the Weschler intelligence scale for children). Using as a control an auditory reaction time task, which provided sensory stimulation and required attention and motor responses on the part of the subjects, he demonstrated increased mean EEG frequency during the experimental task. No reliable frequency differences were noted with different

memory loads. Unfortunately, in this study no attempt was made to determine activity in standard frequency bands, thereby preventing direct comparison with previous studies; however, these findings are consistent with Thompson and Obrist's (1964) observation of decreased alpha and increased beta activity during learning, which would translate to a mean frequency increase.

More recently, a large number of EEG features were analyzed during an auditory memory task and compared to a control auditory rest condition in which white noise was presented to the subjects (Stigby, Risberg, and Ingvar, 1971). It should be noted that the experimental task, which required subjects to press a button whenever three consecutive odd numbers occurred in a series of random auditorily presented digits, made minimal demands on memory processes. Prevalence of alpha activity decreased while alpha, delta, and theta amplitude and overall waveform power increased in the experimental condition. The observed changes in alpha activity are analogous to the previously cited findings of decreased alpha occurring during learning and other types of mental activity. Due to a paucity of previous research, the data concerning amplitude measures cannot be specifically explained in terms of psychological processes. This type of analysis merits further investigation and may contribute another dimension to the investigation of mentation and the EEG.

The studies which initially purported to establish associations between measures of EEG activity and memory were those of Thompson and Obrist (1964) and Freedman, Hofner, and Daniel (1966) discussed earlier. In the first, alpha activity to presentations of nonsense syllables

declined during the learning period and then recovered. The second demonstrated a linear increase in alpha for individual items over trials as contrasted with behavioral curves showing all or none learning with virtually perfect performance occurring after the last error. In both of these studies, the alpha changes are confounded with time and may be attributable to habituation effects or tonic changes in arousal over the experimental session rather than to specific memory processes.

A more convincing report by Gale (1974) concerned measurement of EEG abundance (power) in a band of 11.5 to 12.5 Hz during a short term memory task which involved recall of strings of nine digits presented in the auditory mode. Task errors in recall increased and EEG power during acquisition decreased as a function of serial position. Total abundance during acquisition was positively correlated with subsequent recall. In addition, abundance during a pretrial resting period predicted the level of subsequent performance. As in the case of the previously cited studies, serial position and thus time was a confounding factor in a number of the reported analyses; however, for others this argument cannot be invoked. The striking consistency of the finding that poor performance on the memory task was associated with increased EEG abundance holds up for a number of comparisons of different type and warrants further investigation. The authors equated EEG arousal (decrease in alpha) with psychophysiological arousal, asserting that arousal as measured by their techniques was impairing task performance.

Issues involving arousal and memory were further explored in a study by Warren and Harris (1975). These authors simultaneously recorded EEG activity in the band of 8-12 Hz and skin potential during auditory presentations of lists of nouns in a free recall task. Records obtained during the presentation of each word were scored for the presence or absence of a decrease in alpha activity (an alpha block) or a skin potential response. Subjects to whom the recall task was administered immediately after learning showed increased recall of words that were associated with an alpha block, skin potential response, or both when compared to words to which no change in the electrophysiological measures was noted. Subjects given a delayed recall test 45 minutes post list presentation demonstrated no significant difference in recall across the categories. Thus electrophysiologic measures of phasic arousal were associated with enhanced recall as assessed by immediate but not delayed testing. This interaction can be construed as supporting a two-stage model of memory consolidation (Walker, 1958), a suggestion advanced by the authors, or it may reflect the retrieval phenomenon of output interference (Parker and Warren, 1974) in which cues for the retrieval of one category interfere with those of another; in this case, the words associated with physiological arousal interfere with retrieval of the non-arousal words. The observed pattern would be obtained if this effect simply diminished over time.

A number of tasks in which changes in basal skin resistance level (BRL) were measured during learning focus on the role of physiological arousal in human memory. The findings of one group

(Kaplan and Kleinman, 1963, 1964; Walker and Tarte, 1963) suggest that associations learned under low arousal exhibit high immediate recall but rapid forgetting; conversely, high arousal associations exhibited a marked reminiscence effect, i.e., low immediate recall and high permanent memory. Controlling for serial position in the data analysis failed to alter the pattern of the findings. Independent replication (Butter, 1970) has been reported; however, similar work from two other laboratories failed to demonstrate a reminiscence effect for high arousal items. In the first (Maltzman, 1966), recall for high arousal associates was superior for both immediate and delayed tests of retention. The second (Corteen, 1969) found superior recall for high arousal items only on the delayed test.

The question of the role of attention in human memory processes has not been approached at all by electrophysiological techniques. Behavioral data in the form of performance on a dichotic listening task, which required subjects to attend to one ear while simultaneous verbal input occurred in both ears (Wickens, Moody, and Shearer, 1976; Massaro, 1970), is relevant to this issue. Even with the use of extremely sensitive measures of information storage, these studies failed to demonstrate any learning whatsoever of verbal input to the unattended ear. This established at least a minimal requirement of some attention for learning to occur. The interesting question that remains is whether discrete levels of attention can be quantified during learning and related to subsequent recall performance.

A limited number of laboratories have reported findings concerning ERPs recorded during learning paradigms; nevertheless, due

to deficiencies in design and analysis, it is impossible to draw any firm conclusions concerning the relationship between ERPs and memory from these studies. Rubin and McAdam (1972) investigated the readiness potential during a recognition task. This potential is a slow negative shift which is time-locked to motoric, rather than sensory, events. Subjects were allowed five minutes to freely study a printed list of words and then the EEG was recorded during tachistoscopic presentation of words, half of which had been studied. For each trial the subject pressed a single response button as soon as he had arrived at a decision. This was followed by a verbal report of his judgment as to whether the item had been on the study list, as well as a rating of his confidence in that judgment. Averages of the EEG synchronized with respect to the button press were computed solely on the basis of the subject's confidence rating. No consideration was given to whether a word had or had not been on the study list nor to the accuracy of recognition. The readiness potential was significantly greater for "on list" judgments made with high confidence than for guesses. Insufficient "not on list" high confidence responses were obtained to permit averaging. Clearly, as analyzed, this is not a memory experiment since attention was paid not to the actual recall of the items, but only to the subjects' confidence in their responses. In addition, although no precise recall data is provided, the paper does mention that the confidence ratings of the subjects were unrelated to accuracy of recognition performance. Thus, the comparison in this experiment was between categories related to different levels of subjective certainty; it was not an investigation of memory processes.

Roth and coworkers (1976, 1977, 1978) have presented a series of studies dealing with ERPs during a Sternberg memory task. Subjects were presented with a memory set of one to four digits and then responded to a test digit by determining whether it was or was not in the memory set. They demonstrated that the amplitude of the CNV preceding the test digit decreased monotonically as memory set size increased. This effect was attributed to enhanced distraction related to rehearsal of increasing numbers of items in memory. Furthermore, the latency of the resolution of the CNV increased with increasing set size. Sternberg (1966) has demonstrated that the larger the set size, the greater the time needed to scan it before a decision concerning the test stimulus can be made. Thus, CNV resolution in this paradigm appears to monitor the cognitive decision as to whether the test digit was in or out of the memory set. In a similar experiment reported by Gomer et al. (1976), P300 latency rather than CNV resolution reflected the decision time. These and other findings reported by the two groups relate to the complex cognitive aspects of the Sternberg task rather than to issues of information storage. Since performance was virtually perfect, no data concerning acquisition or retention of memory traces could be obtained.

This review of the literature concerning the electrophysiological investigation of memory reveals a number of significant methodological difficulties retarding progress in the field. First, most of the work has been done by researchers whose primary training is outside the field of cognitive psychology; the result all too frequently has been selection of inappropriate learning tasks, omission of necessary controls,

and generally poor experimental design. Second, limited and idiosyncratic methods of EEG analysis are often employed thereby preventing meaningful comparisons between the work of different laboratories. Finally, the studies frequently confound tonic and phasic changes. These difficulties contribute to the high incidence of failures to replicate and the notable absence of followup studies on many initially interesting findings. Nonetheless, taken as a whole, this literature represents a significant beginning in a line of investigation that will eventually expand our understanding of the psychological and neural underpinnings of memory.

II. MATERIALS AND METHODS

A. Subjects

Sixteen paid subjects (7 males and 9 females) with a mean age of 23.1 years (range 21-30) were tested in this experiment. Payment was at the rate of $5 per hour. Fourteen of the subjects were right hand dominant; two were left hand dominant.

B. Recording Apparatus

The EEG was recorded from Grass subdermal pin electrodes inserted at frontal, vertex, and left occipital locations [Fz, Cz, and O1 respectively, 10-20 International System (Jasper, 1958)] and referenced to linked Beckman Ag-AgCl disk electrodes placed on the earlobes. This technique eliminates the skin potential artifact which may be obtained when disk electrodes are used at scalp recording sites (Corby, Roth, and Kopell, 1975). The electrooculogram (EOG) was recorded from Beckman disk electrodes placed on the mid right infraorbital and supra-orbital ridges each 3 cm from the pupil. Recording of the EOG is necessary due to the fact that an electrical potential field exists across the globe of the eye; eye blinks and vertical shifts of gaze result in voltage changes detectable at the scalp which may confound the interpretation of the EEG if their source is not recognized. All electrodes had an impedance of less than 10,000 ohms. Amplification was provided by Princeton Applied Research amplifiers with a gain of 10,000X for the EEG and 2,000X for the EOG and set to a bandpass of 0.03-100 cycles/second, the end frequencies being 3 db points of 6 db/octave rolloff curves. A 10 uv calibration pulse was added to the signal at

the beginning of each trial (Macpherson and Kopell, 1968).

C. Experimental

Subjects were informed that they were participating in an experiment investigating the manner in which the mind processes different types of visual stimuli. The relevant technical aspects of EEG recording were described and consent obtained. The scalp and EOG electrodes were then applied and the subject was seated in a comfortable chair in an electrically shielded audiometric testing booth. The front wall of the booth contained a window behind which an oscilloscope screen was placed for presentation of visual stimuli. The subject was centered with respect to the eye level screen at a distance of 100 cm. He rested the index finger of his dominant hand on a response key which was adjusted so that 100 grams of force would close the circuit after a 1 mm depression. A period of 20 minutes was allowed to pass to permit the electrodes to stabilize. Instructions were then read to the subject informing him that he was participating in an experiment designed to measure the electrical response of the brain to relevant and irrelevant stimuli. He would be presented with a series of four-letter nouns, some of which would be animal names and constitute the relevant targets. His task was to press the key as rapidly as possible whenever he detected one of these targets. Subjects were also instructed to maintain their gaze on a fixation point, which was continually present in the center of the screen, throughout the experiment and to refrain from blinking during or just after stimulus presentation.

A PDP-12 digital computer controlled the display of stimuli. Each trial was initiated by a 100 ms warning tone (frequency = 1000 Hz; intensity = 70 db SPL relative to .002 dynes/square cm). The tone was produced as a square wave, passed through a Krone-Hite filter and audio amplifier, and delivered to the subject by means of earphones. 900 ms after the offset of the tone, the fixation point on the screen was replaced by a word which was displayed for 200 ms.

A presentation list was prepared comprising one hundred and twenty of the most commonly occurring English four-letter nouns, twenty of them animal names, selected from the norms of Thorndike and Lorge (1944). All had frequencies of greater than 5 parts per million. In order to partially control for order effects each of the items was randomly assigned to one of 4 sublists such that each sublist contained 5 of the target animal names and 25 non-targets. Each subject was presented with all four sublists in one of their possible 24 permutations. The 16 different list permutations used were selected so that each sublist appeared equally often in every position. The four letters composing a word were each generated as points in a 5 x 7 matrix by the computer and displayed on an oscilloscope equipped with a fast relaxation cathode ray tube to prevent persistence of the image after stimulus offset. The letters measured 2 x 2.8 cm and subtended a visual arc of 1.6 degrees.

If the word presented was a target (animal name), the subject pressed the response key as rapidly as possible. If not, he continued to direct his gaze at the fixation point and wait for the next warning tone. Reaction times up to 1.5 seconds were recorded by the computer

and each trial was categorized as to whether it represented a correct identification of a target (hit), lack of response to a non-target (correct rejection), response to a non-target (false alarm), or a lack of response to a target within 1.5 seconds (miss). The interval between the initiation of successive trials was randomly distributed between 4.7 and 8.7 seconds.

Three channels of EEG and the EOG were collected for each trial and stored individually on computer tape. The initial 600 ms of the record, including a 100 ms baseline prior to warning tone onset, was digitalized with a dwell time of 5 ms/point. During the subsequent 600 ms, that is, the period preceding the onset of the word, each successive group of four points was averaged and stored as a single point giving an effective sampling time of 20 ms/point. This rate provided ample resolution of the CNV, the only feature present in this segment of the record. Finally, 625 ms of activity following word onset were sampled with a dwell of 5 ms/point. In all, 1725 ms of data were collected for each trial.

The experimental session began after the EEG and EOG recordings had stabilized, with 2 runs of a practice list of 20 three-letter nouns, four of them targets. At this time the instructions for speed of responding were emphasized. Subjects were required to wear corrective lenses if they normally used them for distant vision. The main list, which required 13.5 minutes to complete, was then presented. Immediately after the final item the subjects were distracted with a brief conversation about their schooling or work in order to eliminate the recency effect of improved memory for the last

few items of a list (Postman and Phillips, 1965). The electrodes were then removed and the subject told that we were interested in his memory for the words he had just seen. A forced choice recognition task was administered employing 120 randomly ordered file cards each containing four words, one word that had been on the presentation list and 3 distractors drawn from those remaining of an original list of 480 high frequency four-letter nouns after 120 had been randomly selected for use in the target identification task. In addition to selecting a response the subject was required to provide a confidence judgment for each item where 1 represented absolute confidence, 2 reasonable confidence, 3 little confidence, and 4 signified a guess. At the end of the session inquiries were made about any suspicion on the part of the subjects with respect to the delayed recognition test. All denied making any attempt to memorize the words during presentation.

D. Data Analysis

The EEG and EOG collected and stored for individual trials was summated to yield 3 distinct types of averages:

1) A Correct (C) average for list nouns that were recalled on the recognition task;

2) An Incorrect (I) average for nouns not recalled; and

3) A Target (T) average for the target items, i.e., animal names.

For each subject C, I, and T averages were generated from the 3 EEG channels plus the EOG channel to produce 12 curves/subject.

Two additional considerations guided the choice of items for averaging. The first was the need to eliminate correct guesses from

the C averages. The principal comparison in this experiment is between electrical events occurring in the brain around presentations of words in 2 categories, those yielding strong memory traces versus those yielding weak ones. Correct guesses represent items which were poorly enregistered in memory when presented. Including these in the C average, which is meant to contain well-enregistered items, confounds the two categories and would tend to obscure any effects that might be present. The second consideration was the need to delete from the I average those items to which an incorrect response was made with a high confidence rating on the grounds that such items almost certainly reflect the operation of different memory processes as compared to items which are simply not recalled. For instance, assume that the presentation list had included the words "wine" and "king" and the subject was subsequently presented with an item on the recognition task with "king" as the correct answer and "beer" as a distractor. He might choose "beer" with high confidence based upon semantic information stored when he had originally seen "wine". Such a choice fails to provide precise information concerning the memory strength of the trace associated with the item "king" and should be eliminated from data analysis. For each subject, the percentage of correct responses at each confidence level was computed and used to decide whether items should be apportioned to the C average, the I average, or deleted entirely. For a confidence rating of 1, all subjects had a recognition accuracy of greater than 80%; thus the correct items assigned a confidence rank of 1 were included in the C average in all cases and the incorrect items with a confidence judgment of 1

were eliminated. At a confidence level of 2, recognition accuracy ranged from 40-95%; at levels 3 and 4 accuracy was always below 65%. The items assigned a confidence rating of 2, in subjects whose recall at this level was greater than 65%, were treated the same as items at confidence level 1. For all other items, the incorrect ones were included in the I average, and those that were correct were omitted in order to exclude guesses from the C average. In summary, the C averages represent those items correctly recalled with high confidence when the high confidence was associated with high recognition performance (>65%). The I averages represent those items incorrectly recalled with low confidence; such items were invariably associated with poor recognition performance (<65%). This scheme produced averages with 13-68 underlying trials (Mean: C average=42.8; I average=29.4). The T average consisted of all the target items (n=20).

III. RESULTS

A. Statistics

Unless otherwise indicated the statistical test employed to determine significance of differences observed was a two-tailed t test with repeated measures.

B. Behavioral Measures

TABLE 1

Percent correct recognition by confidence level on incidental memory task and mean number of responses per subject in each category.

Confidence Rating	Non-Targets		Targets	
	N	% Correct	N	% Correct
1	39.5	94.8	15.7	99.6
2	27.0	57.3	2.7	80.0
3	22.5	42.7	1.2	52.6
4	11.0	38.1	0.4	33.0

Table 1 presents the data from the recognition task partitioned on the basis of confidence ratings. Overall mean percentage of non-target items correctly recognized was 67.3%±standard deviation (SD) of 11.9. Recognition performance decreased with decreasing confidence, but remained well above chance level, even when the subjects believed themselves to be guessing at a confidence level of 4 ($t=2.16$, $df=15$, $p<.05$). Targets were correctly identified with a mean accuracy of 92.8%±8.

Serial position curves (Figure 1) demonstrate a clear primacy effect, i.e., enhanced recall for the non-target items from the initial portion of the list, a finding generally reported in the verbal learning literature with tasks of this type (Kintsch, 1970, pp. 153-62). The target items, however, yield a flat serial position curve. Distraction immediately after list presentation was effective in suppressing a recency effect, as neither curve manifests enhanced recognition of the last few items. The curves presented in Figure 1 also demonstrate that a disproportionately large share of the items contributing to the C averages and an unexpectedly small fraction of those comprising the I average were drawn from the initial one third of the presentation list.

Error rates in the target identification task were extremely low. Ten of 16 subjects had perfect performance. In all 2.8% of the targets were missed; false alarms occurred to 2.2% of non-target items. Mean reaction time to the targets was 559.6 ms±58.6.

C. Event-Related Potentials

Figure 2 presents the superimposed averaged curves of EEG and EOG for 8 subjects plus a set of Grand Average curves summated across all 16 subjects. The major features to note are: 1) the auditory evoked potential to the warning tone; 2) the contingent negative variation (CNV) apparent after the evoked potential to the tone and rising to a maximum just before the presentation of the word; 3) the visual evoked potential to the word; riding on 4) the resolution of the CNV, a positive shift subsequent to the onset of the word. Four

Figure 1. Serial Position Curves

A. Mean number of subjects demonstrating correct recognition per item vs. serial position plotted for successive groups of 10 non-target items and 2 target items.

B. Mean number of items included in Correct and Incorrect averages vs. serial position.

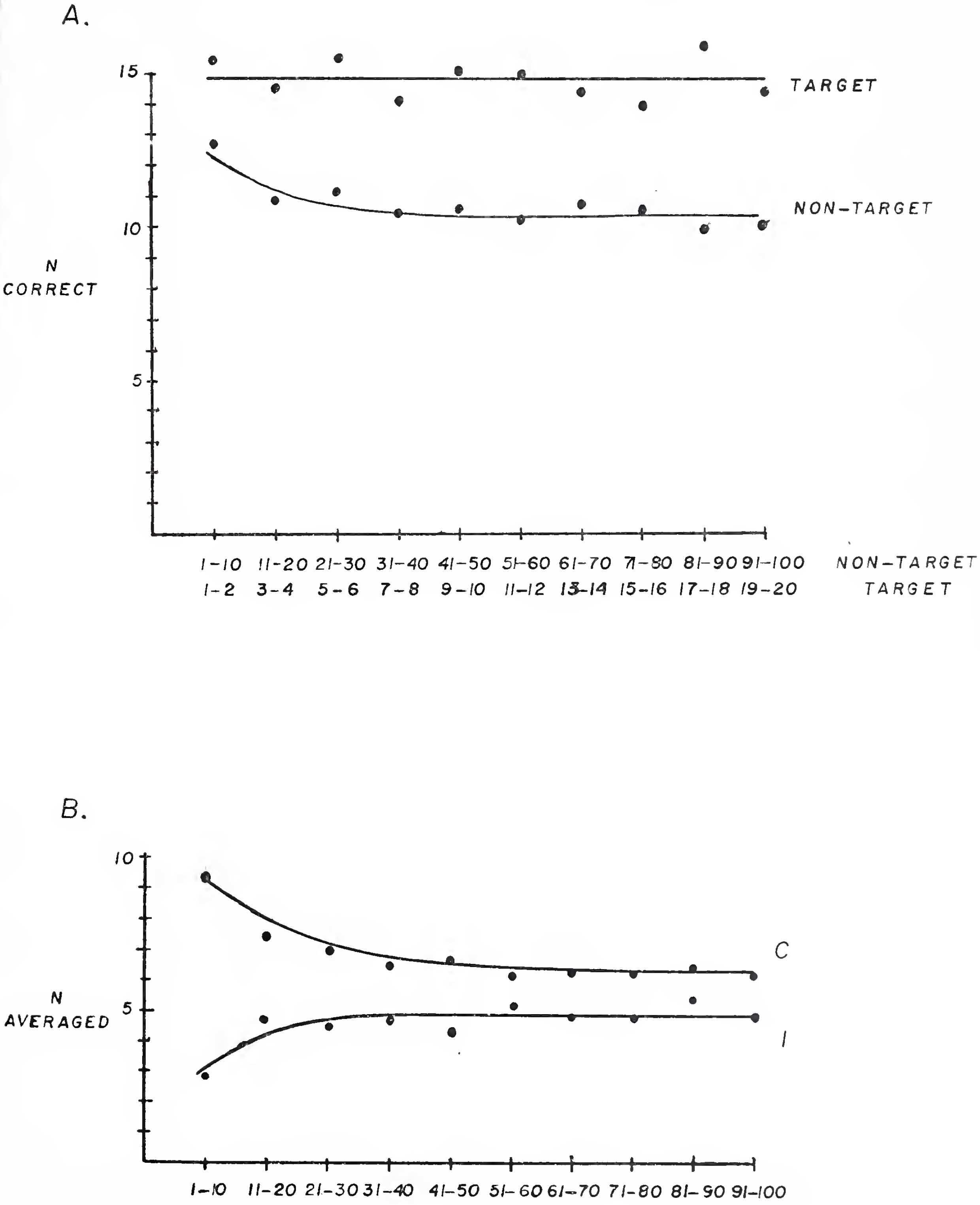


Figure 2. Event-Related Potentials. Negative upward in all curves. Onset of warning tone and word indicated by arrows on time scale.

A. ERP features shown for a representative averaged curve from an individual subject.

B. Superimposed averaged EEG and EOG curves of 8 subjects at lead. Cz for correct, incorrect, and target items depict variability of data.

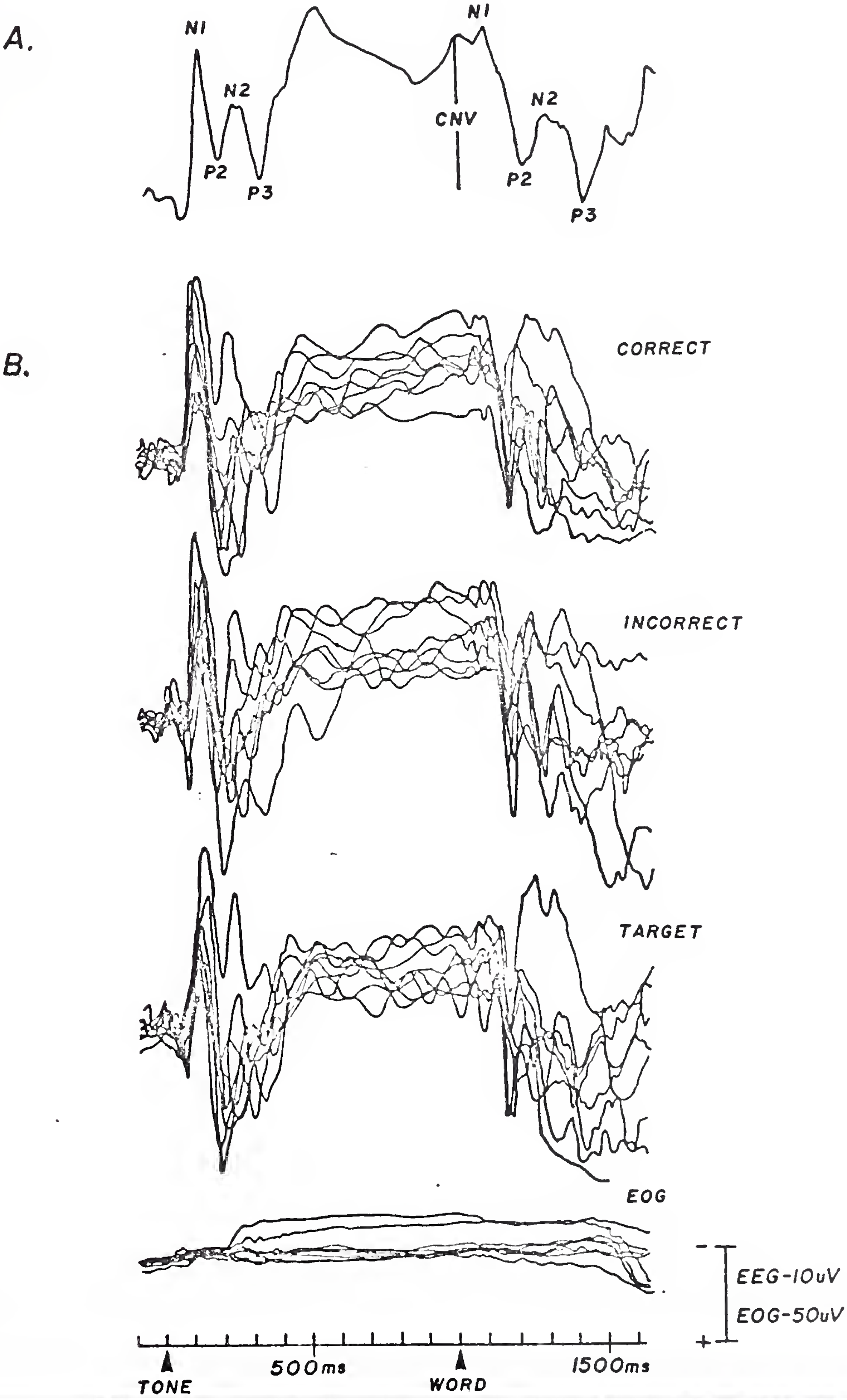
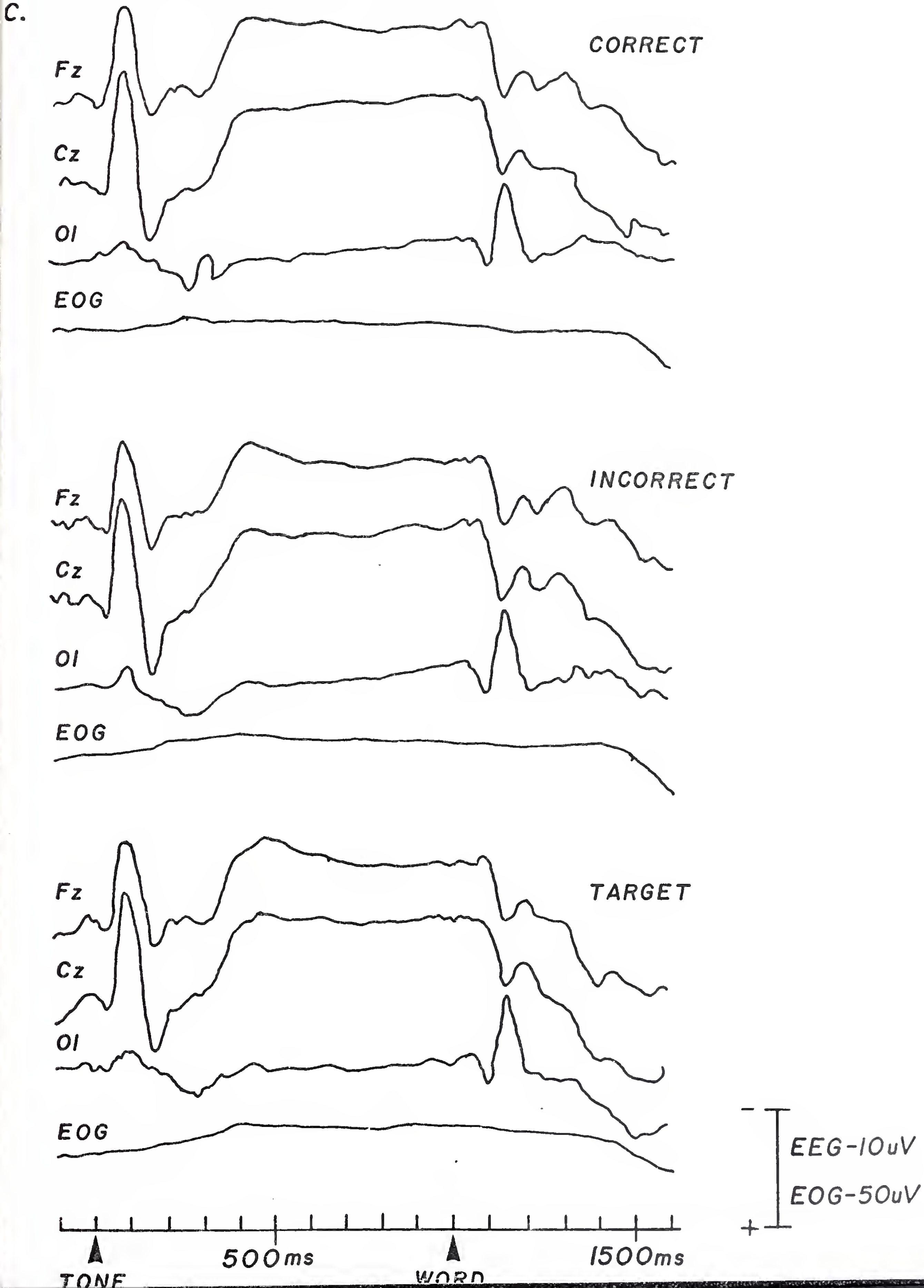


Figure 2

C. Grand average curves for all 16 subjects. Three channels of EEG plus EOG for each of the 3 conditions. Peaks are smaller and less sharp than for individual curves due to variability in latency across subjects.



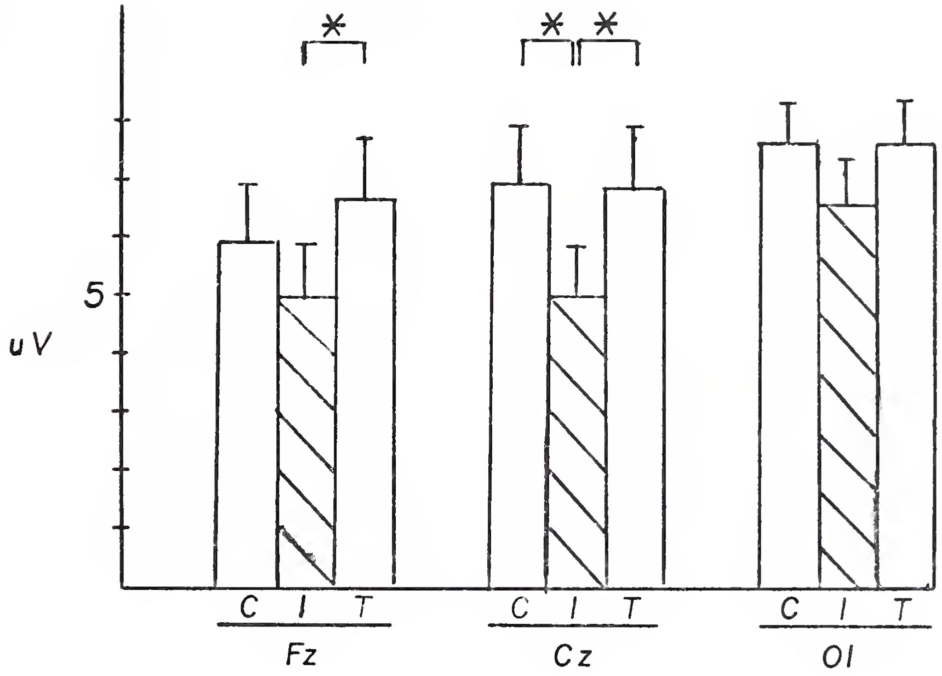
components were consistently identified in the evoked potential to the warning tone: a prominent negative peak at approximately 100 ms (N1), a positive peak with a latency of approximately 200 ms (P2), another negative wave occurring at about 250 ms (N2), followed by a late positivity just beyond 300 ms (P3). N1 and P2 were well defined in all subjects thus permitting the use of a simple computer algorithm for peak measurement which identified N1 latency as the maximum negativity in the range of 70 to 130 ms and P2 as the maximum positivity between this value and 280 ms. N2 and P3 were not as consistent across subjects and, in fact, could not be identified at all in the curves of 3 subjects. For the other 13, the experimenter selected the maximum negative peak following P2 in the range of 200-325 ms as N2 and the largest positive peak in the range N2 to 380 ms as P3 by positioning cursors on the curves as displayed on the computer CRT screen. The amplitude and latency of the peaks so identified were then calculated by the machine. All latencies were determined relative to the onset of the tone. Amplitudes were measured with respect to a 100 ms baseline just preceding tone onset in units of microvolts of equivalent input at the scalp. In addition, a peak to peak measure, N2-P3, was computed. These data are presented in Table 2 and Figure 3. N1 and P2 amplitudes and latencies were nearly identical for the three types of averages as were N2 and P3 latencies. N2 and P3 amplitudes also yielded nonsignificant differences across conditions, but the peak to peak measure was reliably greater in the C as compared to the I average at lead Cz ($t=3.78$, $df=12$, $p<.01$) and in the T vs. I average as well at both Fz and Cz (Fz: $t=3.20$, $df=12$, $p<.01$; Cz: $t=2.62$, $df=12$, $p<.05$).

TABLE 2

Evoked potential to warning tone. Mean (standard deviation)

Component	Lead	Latency (ms)			Amplitude (uv)		
		C	I	T	C	I	T
N1	Fz	104 (13)	107 (14)	106 (15)	- 9.4 (4.9)	- 9.1 (4.1)	- 9.5 (6.3)
	Cz	102 (10)	104 (12)	103 (12)	-11.2 (5.3)	-10.8 (4.5)	-10.8 (6.0)
	01	108 (14)	106 (16)	106 (17)	- 2.8 (1.8)	- 3.0 (2.7)	- 3.0 (2.3)
P2	Fz	211 (43)	204 (37)	211 (42)	4.4 (5.0)	5.1 (3.5)	4.4 (6.2)
	Cz	208 (44)	189 (28)	202 (38)	7.9 (6.3)	9.0 (5.1)	7.6 (6.8)
	01	181 (35)	192 (39)	180 (59)	2.5 (2.9)	2.9 (2.6)	2.8 (2.6)
N2	Fz	251 (31)	255 (34)	244 (36)	- 4.6 (3.7)	- 3.9 (3.6)	- 3.7 (4.1)
	Cz	252 (40)	254 (38)	250 (38)	- 3.7 (4.8)	- 3.0 (4.7)	- 4.1 (6.1)
	01	220 (28)	221 (25)	223 (29)	1.7 (2.9)	1.0 (2.3)	1.9 (2.0)
P3	Fz	321 (31)	321 (30)	320 (29)	1.3 (2.4)	1.0 (2.1)	2.9 (2.9)
	Cz	318 (28)	318 (36)	317 (28)	3.1 (5.3)	2.0 (5.0)	2.6 (5.7)
	01	308 (36)	294 (40)	302 (44)	5.9 (3.9)	5.5 (3.6)	5.8 (2.5)
N2-P3	Fz				5.9 (3.1)	4.9 (3.2)	6.6 (3.7)
	Cz				6.8 (4.0)	5.0 (3.3)	6.7 (4.2)
	01				7.6 (2.6)	6.5 (3.0)	7.6 (2.3)

Figure 3. Mean P3 amplitude and standard error of the mean for the evoked potential to warning tone. Asterisk indicates significant difference computed by t-test.



The visual evoked potential to the presentation of the word has the same major components in leads Cz and Fz as the EP to the tone; however, in the occipital lead (O1) a positive wave at approximately 100 ms (P1), a negative wave with a latency of about 150 ms (N1) and another positivity occurring around 250 ms (P2) are the only reliable features seen. The waveform components in lead O1 were prominent in all subjects, again allowing latency and amplitude measurement to be made with simple computer algorithms. P1 was selected as the maximum positivity in the range 80 to 130 ms, N1 as the greatest negativity in the range of the latency of P1 to 180 ms, and P2 as the maximal positive wave between the latency of N1 and 330 ms. The results of this analysis are presented in Table 3. There were no significant

TABLE 3

Evoked potential to word at lead O1. Mean (standard deviation)

Component	Latency (ms) C	Latency (ms) I	Latency (ms) T	Amplitude (uv) C	Amplitude (uv) I	Amplitude (uv) T
N1	153(15)	153(13)	153(15)	-7.2(4.3)	-7.7(4.1)	-8.1(4.3)
P2	248(42)	255(41)	267(50)	4.3(3.2)	4.2(3.0)	5.5(4.3)

differences across conditions for any of these measures. The analysis of the visual evoked potential in leads Fz and Cz was rendered more complex by the fact that CNV resolution was occurring simultaneously with the generation of the EP. The peaks N1, P2, N2, and P3 were identified manually by use of the cursor described above. No waves clearly corresponding to N2 and P3 could be found in the records of 2 subjects; consequently, data from only 14 subjects were used for the statistical tests of these measures. The mean peak latencies and amplitudes are presented in Table 4 and Figures 4-5. N1 and P2 showed no significant differences across conditions. N2 latency at lead Fz in both the C and I averages was greater than in the T average (C vs. T: t=2.54, df=13, $p < .05$; I vs. T: t=2.51, df=13, $p < .05$). The amplitude of N2 in the C and T conditions was smaller than in the I condition at both leads (Fz--C vs. I: t=3.20, df=13, $p < .01$; T vs. I: t=3.06, df=13, $p < .01$; Cz--C vs. I: t=3.02, $p < .02$; T vs. I: t=3.52, $p < .01$). At lead Fz, P3 latency in the I curves was greater than in the C curves (t=2.59, df=13, $p < .05$). In addition, the amplitude of P3 was greater in the T condition than for C or I (T vs. C: t=4.31, df=13,

TABLE 4

Evoked potential to word at Fz and Cz. Mean (standard deviation)

Component	Lead	Latency (ms) C	Latency (ms) I	Latency (ms) T	Amplitude (uv) C	Amplitude (uv) I	Amplitude (uv) T
N1	Fz	93 (11)	95 (11)	91 (12)	- .3 (1.7)	- .8 (1.1)	- .3 (2.1)
	Cz	92 (10)	94 (10)	95 (14)	- .3 (1.5)	- 1.1 (1.6)	- .4 (2.5)
P2	Fz	153 (13)	156 (16)	155 (12)	5.2 (2.8)	4.9 (3.1)	4.1 (2.1)
	Cz	155 (14)	156 (14)	156 (16)	9.0 (3.6)	8.5 (4.9)	8.2 (3.9)
N2	Fz	268 (41)	271 (50)	250 (32)	.9 (4.1)	- .7 (3.6)	1.4 (5.7)
	Cz	258 (65)	259 (62)	254 (60)	1.7 (3.8)	.1 (4.4)	2.4 (4.7)
P3	Fz	394 (27)	406 (36)	393 (24)	9.9 (3.4)	8.2 (3.4)	14.0 (6.32)
	Cz	419 (61)	422 (44)	408 (40)	14.1 (8.4)	12.6 (8.0)	17.1 (8.3)
N2-P3	Fz				9.0 (2.2)	8.9 (3.7)	12.6 (3.3)
	Cz				12.5 (7.4)	12.5 (7.1)	14.7 (7.5)

Figure 4. Mean N2 amplitude and standard error of the mean for the evoked potential to the word. Asterisk indicates significant difference computed by t-test.

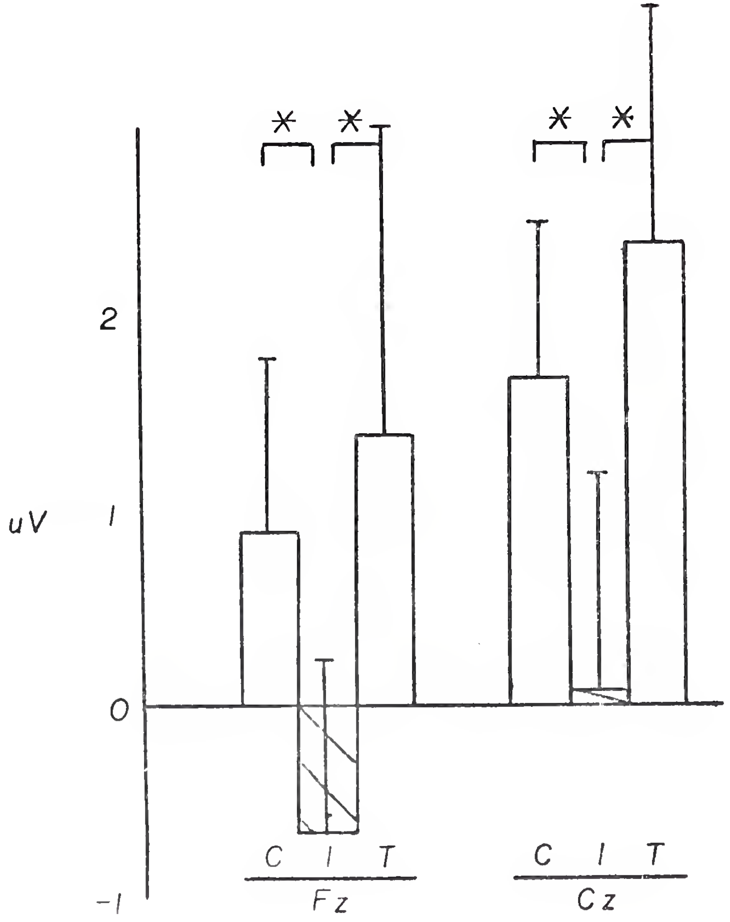
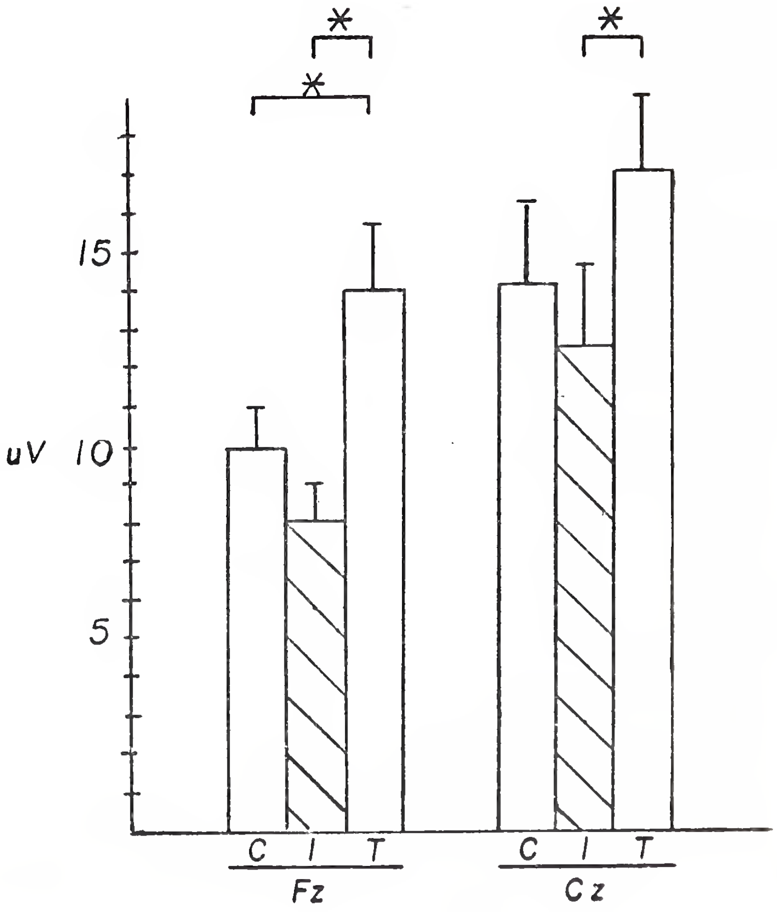


Figure 5. Mean P3 amplitude and standard error of the mean for the evoked potential to the word. Asterisk indicates significant difference computed by t-test.



$p<.01$; T vs. I: $t=4.17$, $df=13$, $p<.001$). At lead Cz, P3 amplitude in the target curves was greater than in the incorrect curves ($t=3.49$, $df=11$, $p<.05$), but there was no significant difference between the target and correct conditions. The N2-P3 measure yielded results identical to those for P3 amplitude.

The height of the CNV was determined as the mean voltage of the 100 ms immediately prior to the presentation of the word (S2) relative to the 100 ms baseline preceding the tone (S1). This data appears in Table 5 and Figure 6. The CNV was greater in the C curves than in the I curves at Cz ($t=2.55$, $df=15$, $p<.025$).

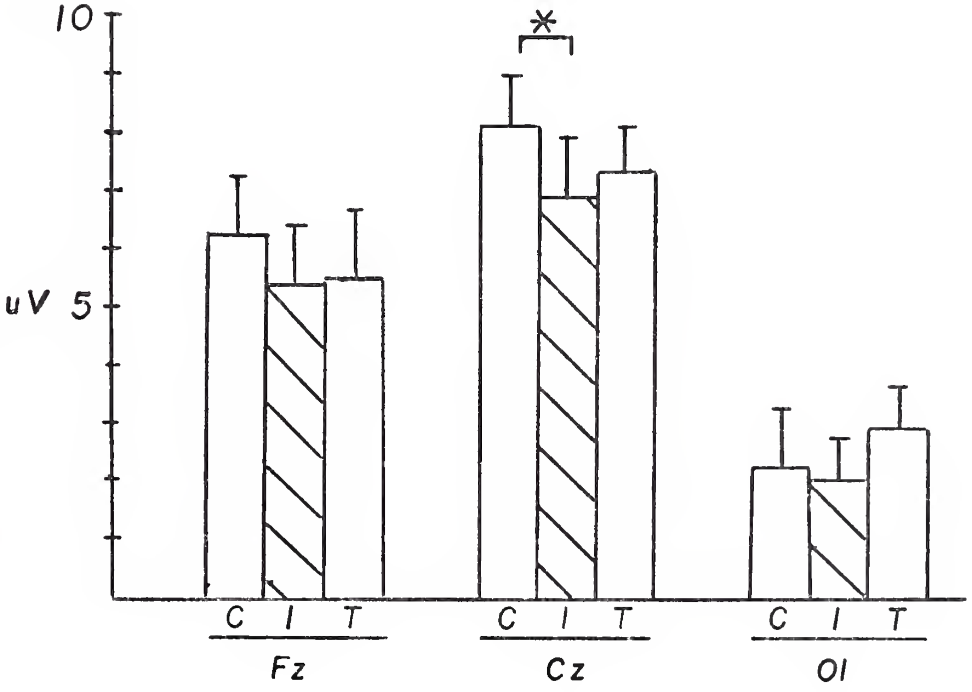
TABLE 5

CNV amplitude. Mean (standard deviation)

	Amplitude (uv)		
Lead	C	I	T
Fz	-6.3(3.8)	-5.4(3.9)	-5.5(5.0)
Cz	-8.1(3.7)	-6.9(3.8)	-7.3(5.3)
O1	-2.2(3.6)	-2.0(3.0)	-0.5(2.9)

The serial position curves demonstrated disproportionate sampling from the initial 20 items of the presentation list, which were relatively over-represented in the C averages and under-represented in the I averages. If the CNVs during the early trials tended to be greater than those on later trials, this would account for the CNV difference observed, but it would reflect merely a non-specific temporal effect and bear no relationship whatsoever to memory processes.

Figure 6. Mean CNV amplitude and standard error of the mean. Asterisk indicates significant difference computed by t-test.



In fact, Walter (1966) has reported increasing, not decreasing, CNVs over the initial few trials of an experiment. An attempt was made to eliminate this effect in the current study by providing a total of 40 practice trials before presenting the experimental list. Beyond that, an analysis for possible order effects was performed by generating a set of 5 curves per subject. Successive blocks of 20 consecutive trials contributed to each of the curves. Target items were excluded from averaging, as they do not enter into either the C or I curves. Mean CNV amplitudes for these curves are reported in Table 6. A one-way analysis of variance with repeated measures performed on this data yielded a non-significant result (f [1,15] = 0.29) suggesting that no serial position effect was present for CNV amplitude.

TABLE 6

CNV amplitude at lead Cz from successive blocks of 20 non-target trials. Mean (standard deviation)

Trials	Amplitude (uv)
1-20	-7.9 (4.5)
21-40	-7.5 (5.1)
41-60	-8.0 (4.7)
61-80	-7.3 (5.0)
81-100	-7.0 (5.7)

To summarize, the principal findings of this experiment concerned CNV and P3 amplitude. The CNV was significantly greater prior to words destined to be recognized than to words that were not to be remembered. The N2-P3 measurement of the evoked potential to the warning tone was larger in the target as well as the correct averages when either was compared with the incorrect curves. Finally, analysis of the P3 component in the visual EP to word onset revealed greater amplitude in the target relative to the correct or incorrect averages.

In addition, significant differences were observed for the N2 component of the EP to the word, specifically, shorter latency in the target curves when tested against the correct or incorrect curves, and greater magnitude in the incorrect averages in comparison with either of the other two.

IV. DISCUSSION

A. Incidental Memory

Incidental learning paradigms are particularly appropriate for the electrophysiological investigation of memory, as they permit the experimenter to exert control over the cognitive activity of the subject during presentation of stimuli. Under conditions of intentional learning, each subject employs an unknown coding strategy whereas in an incidental learning experiment the subject must process the materials in a way compatible with or determined by the orienting task. A second important, perhaps crucial, feature of these paradigms is the elimination of rehearsal during inter-stimulus intervals. ERPs as currently recorded are restricted to a relatively narrow time period just prior and subsequent to physical stimuli. In any experiment in which one seeks to demonstrate ERP differences related to disparate behavioral outcomes, the probability of a successful result will be maximized if the phenomena which contribute to behavioral variability are concentrated in the critical period around the stimulus. Rehearsal processes take place in the interval between stimuli and are therefore likely to be insensitive to ERP measures. As a consequence, if rehearsal determines the probability of recall, demonstration of associated changes in ERP components is unlikely. However, elimination of rehearsal may permit cognitive processes and states (for instance, level of attention), occurring in temporal proximity to items which are to be learned, to assume the principal role in determining probability of subsequent recall during memory tasks. Such processes are most likely to be

indexed by ERP components.

Averaging of single trial EEG activity based upon dichotomous response alternatives has been a useful technique in ERP research. It has permitted the demonstration of moment to moment changes in psychological states, an accomplishment which is beyond the reach of simple behavioral measures. The CNV indexes auditory and visual perceptual sensitivity (Hillyard, 1969; Cohen, 1973; Donald and Goff, 1973). Auditory sensitivity is monitored by P3 as well (Hillyard et al., 1971). The present study extends the use of this design by investigating ERPs as indices of information storage processes.

The primacy effect occurs in many types of list learning experiments (Kintsch, 1970). It has generally been explained on the basis of increased rehearsal of the initial few items leading to improved registration in memory (Atkinson and Schiffrin, 1968). Marshall and Werder (1972) tested this hypothesis by examining serial position curves from an incidental memory task, in which rehearsal is assumed to be eliminated, and found that the primacy effect was eliminated as well. They concluded that their data were consistent with the rehearsal hypothesis. However, in the current experiment, a primacy effect was clearly demonstrated for the non-target items. This finding calls into question any rehearsal-based explanation of enhanced recall for the first portion of a list. The absence of this effect in the aforementioned study is probably due to the low absolute level of recall (10%) provided by the task that was used, i.e., a floor effect. A related explanation can be proposed for the failure to observe a primacy effect in the serial position recall curve for

the target items in the present experiment. The very high levels of recognition (>90%) probably imposed a ceiling effect thereby preventing the development of differential recognition by position.

Accuracy of recognition of target items was much greater than non-targets (93% vs. 67%). Enhanced memory for items belonging to a target class relative to distractors has been previously established in incidental learning paradigms employing semantic orienting tasks (Hyde and Jenkins, 1973; Schulman, 1971). An additional factor accounting for the high target recognition was that virtually all common four letter animal names were required to form the set of 20 used in the presentation list leaving very few to serve as distractors in the recognition task. Under these conditions, adopting a strategy of responding positively to all but the most unfamiliar animal names would result in excellent recognition performance.

B. <u>N2 Elicited by Word Presentation</u>

N2 (or N200) is a negative wave occurring with a latency of approximately 200-250 ms, most clearly seen in the EP occasioned by an omitted stimulus. In auditory or visual EPs, N2 is often obscured by the preceding P2 wave. Studies by Simpson, Vaughan, and Ritter (1976, 1977) suggest that N200 reflects target detection, the registration of either omitted or task-relevant stimuli. They have proposed that N2 may be elicited in any situation in which P3 occurs and in fact may initiate processes which lead to P3 generation.

In the present study a small N2 component can be appreciated in the EPs elicited by word presentations in the records of 14 of the

16 subjects. The distorting influence introduced by the positive shift of CNV resolution is evident. As a result of this slow potential, mean baseline-to-peak amplitude of N2 is positive in two of the three conditions, even though this is nominally a negative wave. The frontal distribution of N2 observed here is at odds with previously published reports of scalp topography (Simpson et al., 1977). Furthermore, the pattern of results at N2 is the mirror image of those for CNV amplitude: while the I curves manifest less negativity immediately prior to word onset, they demonstrate a larger negative component in the EP to the word. These findings suggest that the resolution of the CNV, rather than any changes in the N2 component, is producing the significant differences in the baseline-to-peak measurement. Since N1 and P2 precede appreciable CNV resolution, a similar effect was not seen for these components. Amplitude differences may have been introduced at P3 secondary to resolution of the CNV, but these small differences would have been overshadowed by the large effect on P3 amplitude of responding to the target stimuli.

In summary, the effect observed for the N2 component of the word EPs appears to be artifactual in the sense that it relates to resolution of preceding CNVs of different magnitude rather than to processes directly associated with N2 itself.

C. P3 Elicited by Warning Tone

Analysis of the amplitude of the P3 component of the evoked potential associated with the warning tone is complicated by the presence of a developing CNV. Latency to appreciable CNV magnitude

relative to the onset of S1 has been reported to range from 200 ms (Walter, 1965a) to 300 ms (Donchin and Smith, 1970). Since the mean P3 latency in this experiment is approximately 320 ms, significant overlap and summation with CNV would be expected resulting in a reduction of apparent P3 amplitude when measured with respect to a pre-stimulus baseline. Use of a peak to peak instead of the more traditional baseline to peak measure, specifically N2-P3, tends to minimize the distorting effects of a superimposed slow negative ramp potential. Unfortunately, this technique introduces uncertainty as to whether the pattern of results observed represents an N2 effect, a P3 effect, or a combination of the two. The fact that the baseline to peak measurement of N2 yielded no significant differences among the conditions, coupled with the expectation that the developing CNV would have a greater effect on the longer latency P3 than on the N2 component, suggest that the differences found for N2-P3 amplitude probably primarily reflect variability contributed by P3.

The presence of a warning stimulus in a reaction time paradigm significantly reduces response time (Loveless, 1973). Since the subjects in the present study were instructed to maximize their speed of responding, the warning tone served as a task-relevant stimulus. Successive tones were infrequent events, as the mean interval between them was eight seconds. The warning tone, therefore, satisfied the criteria for stimuli expected to elicit a P3 component. In fact, the P3 baseline to peak amplitude was quite small, being approximately 20-50% of the values usually reported for infrequent relevant stimuli (Donald and Goff, 1973; Picton and Hillyard, 1974; Ford, Roth, and Kopell, 1976).

As suggested above, this reduced P3 is at least partially accounted for by cancellation secondary to CNV superimposition. Analysis of scalp topography supports this explanation; P3 amplitude in the EP to the warning tone was greatest in the occipital lead, progressively diminishing at more anterior scalp recording sites. Such a distribution is decidedly unusual for P3, but not at all unexpected if a CNV is partially suppressing P3 at Fz and Cz. P3 amplitude at 01 should be unaffected by CNV since P3 is 70% transmitted to lateral occipital leads relative to Cz amplitude (Picton and Hillyard, 1974), while CNV is virtually absent at posterior scalp leads (Tecce, 1972).

In terms of the subject's experience, the underlying trials contributing to the C, I, and T averages could not be differentiated at the time of warning tone presentation. Since the target stimuli occurred at random during list presentation, the EP in the T averages represents a random sampling of EEG activity elicited by the tone. There was no significant difference at N2-P3 between this curve and the C curve in which trials were selected for averaging if the word subsequent to the warning tone was recognized with high confidence; consequently, there was no P3 enhancement in the C averages. However, in the I average, composed of trials in which recall of the word following the tone was unsuccessful, there was a significant diminution of N2-P3 relative to the other two conditions.

The magnitude of this peak to peak measure of the late EP components appears to monitor a cognitive state of at least one second duration that determines the extent to which information concerning an event will be stored in memory. The usual factors known to affect

P3 amplitude are held constant throughout this experiment; as far as the subject is concerned, at the time of tone occurrence, each trial is identical to every other trial. Differences observed in the tone EP must reflect moment to moment fluctuations in the psychological state of the subject occurring throughout list presentation. This cognitive variability affects both the magnitude of the late component and the probability of forming a memory trace of sufficient strength to allow for subsequent retrieval. Specifically, a diminished N2-P3 component is associated with less than optimal memory storage processes, manifested in turn by impaired recognition performance. This hypothesis is, of course, a *post hoc* formulation based upon associations between the outcome of a memory task and reconstructed averaged EEG waveforms. A critical test would involve segregating items on the basis of warning tone P3 amplitude for individual trials and subsequently assessing recognition. Performance should be directly related to the size of P3. Unfortunately, inasmuch as P3 waves were not identifiable in the raw EEG, this analysis could not be performed.

In this study the warning tone functions not only as a task-relevant stimulus, but as a probe of the cognitive state of the subject. Similar uses of sensory probes have been reported. Hink and Hillyard (1976) used simple phonemes to assess attention to complex messages during dichotic listening. Donchin (in press) investigated P3 amplitude in a series of auditory stimuli presented throughout the course of a visual tracking task. The auditory P3 reflected cognitive demands of the visual task. It may be that the N2-P3 measure indexes efficiency of stimulus processing. Similar concepts have been previously proposed

on the basis of associations between P3 amplitude and accuracy during signal detection and visual perception (Hillyard et al., 1971; Cohen, 1973). It is both exciting and surprising that a fluctuating psychological state affecting memory processes can be assessed, at least on a statistical basis, fully one second before the presentation of the stimulus which actually activates informational storage processes.

As discussed previously, P3 latency appears to reflect the duration of cognitive processing in many experimental situations. The proposed concept of perceptual efficiency cannot be applied in a temporal sense to suggest that enhanced efficiency would result in more rapid stimulus evaluation, since P3 latency was constant across conditions.

Decreases in P3 amplitude have commonly been attributed to one of two mechanisms: 1) presumed decrease in the amplitude of the P3 component in the underlying trials; or 2) increased variability of P3 latency producing time jitter during the averaging process and thus diminished amplitude in the averaged waveform only. In the absence of independent behavioral data monitoring cognitive processing of the tone, it is impossible to delineate which of these mechanisms accounts for the differences observed.

D. P3 Elicited by Word Presentation

Again, as was the case for the warning tone, analysis of P3 amplitude in the visual EP elicited by word presentation is rendered more complex by the superimposition of a contemporaneous slow wave process--in this instance, the resolution of the CNV. This positive

baseline shift begins well before P3. Walter et al. (1964) have reported a latency of 140 ms in a simple constant foreperiod reaction time task; in paradigms requiring more complex decisions, values of approximately 200 ms have been obtained (Donald and Goff, 1973; Roth et al., 1975). Summation of the positive CNV resolution and P3 would tend to produce artifactually large P3 amplitudes when measured relative to a pre-stimulus baseline. Variability in the rate of CNV resolution could well contribute to the differences observed in P3 amplitude across experimental conditions. The P3 component in the word EP was of greater magnitude in the target averages as compared to either of the non-target curves. As discussed in the introduction, enhancement of P3 amplitude for task-relevant stimuli in simple reaction time paradigms has repeatedly and reliably been demonstrated. An identical effect has been reported during more complex tasks including phoneme identification (Galambos et al., 1975), selection of rhymes, synonyms, and male proper names (Kutus and Donchin, in press in Hillyard, in press), and item recognition from short term memory (Gomer, Spicuzza, and O'Donnell, 1976). The results of the present experiment extend the demonstration of P3 enhancement for target stimuli to a semantic categorization task.

E. Contingent Negative Variation

With the failure of theories that depend upon one or two psychological constructs to account for the great diversity of reported CNV findings, questions have been raised as to whether the CNV can be regarded as a unitary phenomenon (e.g., Hillyard, 1973). This trend has been abetted by experiments which claim to demonstrate subcomponents

of the CNV (Rohrbaugh, Syndulko, and Lindsley, 1976; Jarvilehto and Fruhstorfer, 1970). These authors, using relatively long inter-stimulus intervals between S1 and S2, recorded an early negative, frontally distributed component related to the warning stimulus and a later negative slow potential, whose characteristics were similar to those of the readiness potential. This line of inquiry may eventually lead to significant advances in CNV research; however, it has also led to the haphazard invocation of multiple hypothetical components and processes in situations where they are not experimentally demonstrable. It may be preferable to appeal to parsimony and continue to seek unifying explanations.

The ideas that have been proposed to describe the relationship between mental phenomena and CNV do cluster around a single sphere of psychological function. They all appeal to the notion that the CNV is related to processes activated by the individual to facilitate behavioral interactions with the environment. A large body of evidence suggests that, at least under certain conditions, CNV indexes the quality of a preparatory state. This has been true for simple reaction time (Rebert and Tecce, 1973), auditory signal detection (Hillyard, 1969; Hillyard et al., 1971), accuracy of visual perception (McAdam and Rubin, 1971; Cohen, 1973) and auditory discrimination (Donald and Goff, 1973). In addition, interference with focused preparation by distracting stimuli or divided attention tasks results in decreased CNV amplitude (Tecce and Scheff, 1969). A potentially valuable direction for research is to attempt to further delineate the characteristics of this preparatory state indexed by the CNV.

In the current study, CNV amplitude was greater prior to words that were ultimately recognized with high confidence than before items that were to be forgotten. Reasoning conversely, this indicates that when CNV was large, storage of information concerning S2 (the word) was facilitated and the probability of subsequent recognition was enhanced. Smaller CNVs were associated with a diminished chance for accurate recognition. CNV amplitude for the target curves was intermediate between the C and I curves, although it did not differ significantly from either. As previously discussed, the underlying trials contributing to the target averages essentially represent a random sample of all trials, and thus, CNV magnitude would be expected to fall somewhere between that of the other two conditions.

The amplitude differences observed for the N2-P3 component of the EP to the warning tone and the CNV are similar in that the C averages showed greater magnitude than the I averages in both cases. Moreover, similar theoretical constructs have been advanced here to account for these findings. At times a debate has raged in the literature concerning the relationship of P3 and the CNV. While these ERPs may overlap in complex and confusing ways (Roth et al., 1976), P3 and CNV are generally accepted as separate components with distinct psychological referents (e.g., Donchin, in press). Furthermore, questions concerning the interdependence of the two components usually center upon the superimposition of CNV resolution and the P3 elicited by S2. In the current study, it was P3 in the EP to the warning tone that behaved similarly to the CNV; P3 to S2 (the word) manifested a different pattern of results consistent with an explanation based upon task

relevancy. Although there was probably overlap of the initial portion of the CNV and P3 to the tone, the resulting effects on P3 magnitude at its peak latency would have been extremely small and, in any case, would have tended to produce an effect opposite to the significant differences actually seen in the N2-P3 measurement. Therefore, it appears from the present data that CNV and P3 serve as independent indices of ongoing cognitive activities. Their amplitudes correlate with moment to moment fluctuations in hypothesized preparatory attentional processes which in turn determine the efficiency of information storage.

V. SUMMARY

Sixteen subjects semantically categorized each of a list of tachistoscopically presented words while their EEGs and EOGs, for individual trials, were recorded and stored. Subsequently, a recognition test was administered to assess incidental learning of the list items during the orienting task. Three types of computer-averaged curves were generated for each subject: one was composed of the electrical activity recorded around the presentation of non-target words that were recognized with high confidence; a second consisted of the activity associated with non-targets that were not remembered; and the third comprised target items from the semantic task.

The P3 wave elicited by the target items was larger in amplitude than those generated in response to either of the two other categories of items. This finding lends support to the concept that increased P3 magnitude reflects cognitive matching of a stimulus with its representation stored in memory.

The amplitudes of both the P3 wave associated with the warning tone, and the CNV, were significantly greater for the correct average compared to the incorrect curve. These results suggest that the efficiency of information storage processes is at least partially determined by fluctuations in the functional state of the brain, fluctuations which can be assessed by analysis of ERP components.

REFERENCES

1. Atkinson RC and Shiffrin RM. Human memory: a proposed system and its control processes. In KW Spence and JT Spence (Eds.), The Psychology of Learning and Motivation: Advances in Research and Theory, Vol. II. N.Y., Academic Press, 1968, pp. 89-195.

2. Berger H. Uber das elektrenkephalogramm des Menschon. Journal fur Psychologie und Neurologie, Leipzig, 40: 160-79 (1930).

3. Broadbent DE. Stimulus set and response set: two kinds of selective attention. In DI Mostofsky (Ed.), Attention: Contemporary Theory and Analysis. New York, Appleton-Century-Crofts, 1970.

4. Butter MJ. Differential recall of paired associates as a function of arousal and concreteness imagery levels. J. of Exp. Psychol., 84(2): 252-56 (1970).

5. Cant BR and Bickford RG. The effect of motivation on the contingent negative variation. Electroenceph. and Clin. Neurophys., 23: 594 (1967).

6. Cohen J. The contingent negative variation and visual recognition. Electroenceph. and Clin. Neurophys., Suppl. 33: 201-4 (1973).

7. Corby JC and Kopell BS. Differential contribution of blinks and vertical eye movements as artifacts in EEG recording. Psychophysiology, 9: 640-44 (1972).

8. Corby JC and Kopell BS. The effect of predictability on evoked response enhancement in intramodal selective attention. Psychophysiology, 10: 335-46 (1973).

9. Corby JC, Roth WT, and Kopell BS. Prevalence and methods of control of the cephalic skin potential EEG artifact. Psychophysiology, 11(3): 350-60 (1974).

10. Corteen RS. Skin conductance changes and word recall. Br. J. Psychol., 60(1): 81-4 (1969).

11. Courchesne E, Hillyard SA, Galambos R. Stimulation novelty, task relevance and the VEP in man. Electroenceph. and Clin. Neurophys., 39: 131-43 (1975).

12. Delse F, Marsh G, and Thompson L. The contingent negative variation as a pre-motor potential. Paper presented at the meeting of the Society for Psychophysiological Research, Monterey, CA, October 1969, as quoted in Tecce JJ, 1972.

13. Donald MW. Direct-current potentials in the human brain evoked during timed cognitive performance. Nature, 227: 1057-58 (1970).

14. Donald MW and Goff WR. Attention-related increases in cortical responsivity dissociated from the contingent negative variation. Science, 172: 1162-66 (1971).

15. Donald MW and Goff WR. Contingent negative variation and sensory evoked responses: their interaction and relationship to auditory discrimination. Electroenceph. and Clin. Neurophys., Suppl. 33: 109-17 (1973).

16. Donchin E and Cohen MD. Averaged evoked potentials and intramodality selective attention. Electroenceph. and Clin. Neurophys., 22: 537-46 (1967).

17. Donchin E, Ritter W, and McCallum WC. Cognitive psychophysiology: the endogenous components of the ERP. In press.

18. Donchin E and Smith DBD. The contingent negative variation and the late positive wave of the averaged evoked potential. Electroenceph. and Clin. Neurophys., 29: 201-3 (1970).

19. Donchin E, Tueting P, Ritter W, Kutas M, Heffley E. On the independence of the contingent negative variation and P3 components of the human averaged evoked potential. Electroenceph. and Clin. Neurophys., 38: 449-61 (1975).

20. Duncan-Johnson C, Squires NK, Squires KC, and Donchin E. The effect of stimulus sequence on the bi-sensory event-related potential. Manuscript in preparation.

21. Ford JM, Roth WT, Dirks SJ, and Kopell BS. Evoked potential correlates of signal recognition between and within modalities. Science, 181: 465-66 (1973).

22. Ford JM, Roth WT, and Kopell BS. Attention effects on AEPs to infrequent events. Biol. Psychol., 4: 65-77 (1976).

23. Freedman NL, Hafer BM, and Daniel RS. EEG arousal decrement during paired-associate learning. Journal of Comparative and Physiological Psychology, 61(1): 15-19 (1966).

24. Galambos R, Benson P, Smith TS, Schulman-Galambos C, and Osier H. On hemispheric differences in evoked potentials to speech stimuli. Electroenceph. and Clin. Neurophys., 39: 279-83 (1975).

25. Gale A, Dylan MJ, Smallbone A. Short term memory and the EEG. Nature, 248: 439-40 (1974).

26. Giannitrapani D. Scanning mechanisms and the EEG. Electroenceph. and Clin. Neurophys., 30: 139-46 (1971).

27. Gomer FE, Spicuzza RJ, and O'Donnell RD. Evoked potential correlates of visual item recognition during memory-scanning tasks. Physiological Psychol., 4(1): 61-5 (1976).

28. Gullickson GR. The contingent negative variation in the preschool child. Dissertation Abstracts, 31, 3022B (1970).

29. Hillyard SA. The contingent negative variation and the vertex evoked potential during signal detection: a preliminary report. In E Donchin and DB Lindsley (Eds.), Average Evoked Potentials. NASA Document No. SP-191, 1969.

30. Hillyard SA. The contingent negative variation and human behavior. Electroenceph. and Clin. Neurophys., Suppl. 33: 161-71 (1973).

31. Hillyard SA. Electrophysiological assessment of attentional processes in man. In press.

32. Hillyard SA, Courchesne E, Krausz HI, and Picton TW. Scalp topography of the "P3" wave in different auditory tasks. In WC McCallum and JR Knott (Eds.), The Responsive Brain. Bristol: J Wright and Sons Ltd., 1976.

33. Hillyard SA and Galambos R. Effects of stimulus and response contingencies on a surface negative slow potential shift in man. Electroenceph. and Clin. Neurophys., 22: 297-304 (1967).

34. Hillyard SA, Hink RF, Schwent JL, and Picton TW. Electric signs of selective attention in the human brain. Science, 182(108): 177-80 (1973).

35. Hillyard SA, Squires KC, Bauer JW, and Lindsay PH. Evoked potential correlates of auditory signal detection. Science, 172: 1357-61 (1971).

36. Hink RF and Hillyard SA. Auditory evoked potentials during selective listening to dichotic speech messages. Percep. Psychophys., 20: 236-42 (1976).

37. Hyde TS and Jenkins JJ. Recall for words as a function of semantic, graphic, and syntactic orienting tasks. J. of Verbal Learning and Verbal Behavior, 12: 471-80 (1973).

38. Irwin DA, Knott JR, McAdam DW, and Rebert CS. Motivational determinants of the contingent negative variation. Electroenceph. and Clin. Neurophys., 21: 538-43 (1966).

39. Jarvilehlo T and Fruhstorfer H. Differentiation between slow cortical potentials associated with motor and mental acts in man. Exp. Brain Res., 11: 309-17 (1970).

40. Jasper HH. Report of the committee on methods of clinical examination in electroencephalography. Electroenceph. and Clin. Neurophys., 10: 370-75 (1958).

41. Johnston JS and Chesney GL. Electrophysiological correlates of meaning. Science, 186(4167): 944-46 (1974).

42. Karlin L and Martz MJ. Response probability and sensory-evoked potentials. In S Kornblum (Ed.), Attention and Performance IV. New York, Academic Press, 1973, pp. 175-84.

43. Kintsch W. Learning, Memory, and Conceptual Processes. New York, Wiley, 1970.

44. Kleinsmith LJ and Kaplan S. Paired-associate learning as a function of arousal and interpolated interval. J. of Exp. Psychol., 65(2): 190-3 (1963).

45. Kleinsmith LJ and Kaplan S. Interaction of arousal and recall interval in nonsense syllable paired-associate learning. J. of Exp. Psychol., 67(2): 124-6 (1964).

46. Knott JR and Irwin DA. Anxiety, stress, and the contingent negative variation. Electroenceph. and Clin. Neurophys., 24: 286-7 (1968).

47. Kutas M and Donchin E. Variations in the latency of P300 as a function of variations in semantic categorizations. In D Otto (Ed.), New Perspectives in Event-Related Potential Research. U.S. Environmental Protection Agency, Washington, D.C., in press.

48. Loveless NE. The contingent negative variation related to preparatory set in a reaction time situation with variable foreperiod. Electroenceph. and Clin. Neurophys., 35: 369-74 (1973).

49. Low MD, Borda RP, Frost JD, and Kellaway P. Surface-negative slow-potential shift associated with conditioning in man. Neurology, 16: 771 (1966).

50. Luria AR and Homskaya ED. Frontal lobes and the regulation of arousal processes. In DI Mostofsky (Ed.), Attention: Contemporary Theory and Analysis. New York, Appleton-Century-Crofts, 1970, 303-30.

51. Macpherson L and Kopell BS. A systems approach to the measurement of slow evoked potential changes. Med. and Biol. Eng., 6: 673-5 (1968).

52. Maltzman I, Kantor W, and Langdon B. Immediate and delayed retention, arousal, and the orienting and defensive reflexes. Psychon. Sci., 6(10): 445-6 (1966).

53. Marshall PH and Werder PR. The effects of the elimination of rehearsal on primacy and recency. J. of Verbal Learning and Verbal Behavior, 11: 649-53 (1972).

54. Massaro DW. Perceptual processes in dichotic listening. JEP: Hum. Learn. and Mem., 2(3) 331-9 (1976).

55. McAdam DW, Irwin DA, Rebert CS and Knott JR. Conative control of the contingent negative variation. Electroenceph. and Clin. Neurophys., 21: 194-5 (1966).

56. McAdam DW, Knott JR, and Rebert CS. Cortical slow potential changes in man related to interstimulus interval and to pre-trial prediction of interstimulus interval. Psychophysiology, 5: 349-58 (1969).

57. McAdam DW and Rubin EH. Readiness potential, vertex positive wave, contingent negative variation and accuracy of perception. Electroenceph. and Clin. Neurophys., 30: 511-17 (1971).

58. McAdam DW and Seales DM. Bereitschaftspotential enhancement with increased level of motivation. Electroenceph. and Clin. Neurophys., 27: 73-5 (1969).

59. McAdam DW and Whitaker HA. Electrocortical localization of language production. Science, 174: 1360-1 (1971).

60. McCallum WC and Walter WG. The effects of attention and distraction on the contingent negative variation in normal and neurotic subjects. Electroenceph. and Clin. Neurophys., 25: 319-29 (1968).

61. Miller LH, Van Veen W, Sandman CA, and Knott JR. Intermodal and intramodal distraction and contingent negative variation. Electroenceph. and Clin. Neurophys., Suppl. 33: 209-11 (1973).

62. Papakostopoulos D. Contingent negative variation and autonomic function. Electroenceph. and Clin. Neurophys., Suppl. 33: 269-80 (1973).

63. Parker RE and Warren L. Partial category cueing: the accessibility of categories. J. of Exp. Psychol., 102: 1123-25 (1974).

64. Paul DD and Sutton S. Evoked potential correlates of response criteria in auditory signal detection. Science, 177: 362-4 (1972).

65. Picton TW and Hillyard SA. Human auditory evoked potentials. II Effects of attention. Electroenceph. and Clin. Neurophys., 36: 191-9 (1974).

66. Postman L and Phillips LW. Short-term temporal changes in free recall. Quarterly J. of Exp. Psychol., 17: 132-8 (1965).

67. Rebert CS, McAdam DW, Knott JR, and Irwin DA. Slow potential changes in human brain related to level of motivation. J. of Comparative and Physiological Psychology, 63: 20-23 (1967).

68. Rebert CS and Tecce JJ. A summary of contingent negative variation and reaction time. Electroenceph. and Clin. Neurophys., Suppl. 33: 173-78 (1973).

69. Regan D. Evoked Potentials in Psychology, Sensory Physiology and Clinical Medicine. New York, John Wiley and Sons, Inc., 1972.

70. Ritter W, Simson R, and Vaughan HG Jr. Association cortex potentials and reaction time in auditory discrimination. Electroenceph. and Clin. Neurophys., 33: 547-55 (1972).

71. Ritter W, Simson R, and Vaughan HG Jr. Topographical analysis of task related cerebral potentials. In JE Desmedt (Ed.), Cerebral Evoked Potentials in Man. Basel, Karger, 1977.

72. Ritter W and Vaughan HG Jr. Averaged evoked responses in vigilance and discrimination: a reassessment. Science, 164: 326-8 (1969).

73. Rohrbaugh JW, Syndulko K, and Lindsay DB. Brain wave components of the contingent negative variation in humans. Science, 191: 1055-57 (1976).

74. Roth WT, Ford JM, Lewis SJ, and Kopell BS. Effects of stimulus probability and task-relevance on event-related potentials. Psychophysiology, 13: 311-17 (1976).

75. Roth WT, Kopell BS, Tinklenberg JR, Darley CF, Sikora R, and Vesecky TB. The contingent negative variation during a memory retrieval task. Electroenceph. and Clin. Neurophys., 38: 171-74 (1975).

76. Roth WT, Rothbart RM and Kopell BS. The timing of contingent negative variation resolution in a memory retrieval task. Biological Psychology, in press.

77. Roth WT, Tinklenberg JR, Kopell BS. Ethanol and marihuana effects on event-related potentials in a memory retrieval paradigm. Electroenceph. and Clin. Neurophys., 42: 381-88 (1977).

78. Rubin EH and McAdam DW. Slow potential concomitants of the retrieval process. Electroenceph. and Clin. Neurophys., 32: 84-86 (1972).

79. Schulman AI. Recognition memory for targets from a scanned word list. Br. J. of Psychol., 62(3): 335-46 (1971).

80. Schwent JL, Hillyard SL, and Galambos R. Selective attention and the auditory vertex potential. I. Effects of stimulation delivery rates. Electroenceph. and Clin. Neurophys., 40: 604-14 (1976).

81. Schwent JL, Snyder E, and Hillyard SA. AEP's during multichannel selective listening: role of pitch and localization cues. JEP: Human Percept. and Perform., 2(3): 313-25 (1976).

82. Simson R, Vaughan HG Jr, and Ritter W. The scalp topography of potentials associated with missing visual or auditory stimuli. Electroenceph. and Clin. Neurophys., 40: 33-42 (1976).

83. Simson R, Vaughan HG Jr, and Ritter W. The scalp topography of potentials in auditory and visual discrimination tasks. Electroenceph. and Clin. Neurophys., 42: 528-35 (1977).

84. Squires KC, Wickens C, Squires NK, and Donchin E. The effect of stimulus sequence on the waveform of the cortical event-related potential. Science, 193: 1142-6 (1976).

85. Squires NK, Donchin E, Squires KC, and Grossberg S. Bisensory stimulation: inferring decision-related processes from the P300 component. JEP: Human Percept. and Perf., 3: 299-315 (1977).

86. Squires NK, Squires KC, and Hillyard SA. Two varieties of long-latency positive waves evoked by unpredictable auditory stimuli in man. Electroenceph. and Clin. Neurophys., 38: 387-401 (1975).

87. Sternberg S. High-speed scanning in human memory. Science, 153: 652-54 (1966).

88. Stigsby B, Risberg J, Ingvar DH. Electroencephalographic changes in the dominent hemisphere during memorizing and reasoning. Electroenceph. and Clin. Neurophys., 42(5): 665-75 (1977).

89. Surwillo WW. Frequency of the EEG during acquisition in short-term memory. Psychophysiology, 8(5): 588-93 (1971)a.

90. Surwillo WW. Interhemispheric EEG differences in relation to short-term memory. Cortex, 7(3): 246-53 (1971)b.

91. Sutton S, Braren M, Zubin J, and John ER. Evoked-potential correlates of stimulus uncertainty. Science, 150: 1187-88 (1965).

92. Tecce JJ. Contingent negative variation and psychological processes in man. Psych. Bull., 77(2): 73-108 (1972).

93. Tecce JJ and Hamilton BT. Contingent negative variation reduction by sustained cognitive activity (distraction). Electroenceph. and Clin. Neurophys., Suppl. 33: 229-37 (1973).

94. Tecce JJ, Savignano-Bowman J, and Meinbresse D. Contingent negative variation and the distraction-arousal hypothesis. Electroenceph. and Clin. Neurophys., 41: 277-86 (1976).

95. Tecce JJ and Scheff NM. Attention and DC potentials in the human brain. Paper presented to the meeting of the Society for Psychophysiological Research, Washington, D.C., October, 1968.

96. Tecce JJ and Scheff NM. Attention reduction and suppressed direct-current potentials in the human brain. Science, 164: 331-3 (1969).

97. Thompson LW and Obrist WD. EEG correlates of verbal learning and overlearning. Electroenceph. and Clin. Neurophys., 16: 332-42 (1964).

98. Thorndike EL and Lorge I. The Teacher's Word Book of 30,000 Words. Teacher's College, Columbia University Bureau of Publications, New York, 1944.

99. Vaughan HG and Ritter W. The sources of auditory evoked responses recorded from the human head. Electroenceph. and Clin. Neurophys., 28: 360-67 (1970).

100. Walker EL. Action decrement and its relation to learning. Psychol. Rev., 65: 129-42 (1958).

101. Walker EL and Tarte RD. Memory storage as a function of arousal and time with homogenous and heterogenous lists. J. of Verbal Learn. and Verbal Behav., 2: 113-19 (1963).

102. Walter WG. Effect on anterior brain responses of an expected association between stimuli. J. of Psychosomatic Res., 9: 45-49 (1965)a.

103. Walter WG. Brain responses to semantic stimuli. J. of Psychosomatic Res., 9: 51-61 (1965)b.

104. Walter WG. Electrophysiologic contributions to psychiatric therapy. In JH Masserman (Ed.), Current Psychiatric Therapies. New York, Grune and Stratton, 1966, Vol. VI: 13-25.

105. Walter WG. Slow potential changes in the human brain associated with expectancy, decision, and intention. In W Cobb and C. Morocutti (Eds.), The Evoked Potentials. Amsterdam, Elsevier, 1967.

106. Walter WG, Cooper R, Aldridge VJ, McCallum WC, and Winter AL. Contingent negative variation: an electric sign of sensorimotor association and expectancy in the human brain. Nature, 203: 380-84 (1964).

107. Warren LR and Harris LJ. Arousal and memory: phasic measures of arousal in a free recall task. Acta Psychologica, 39: 303-10 (1975).

108. Wickens C, Isreal J, and Donchin E. The event-related cortical potential as an index of task work load. Proceedings of the Annual Meeting, Human Factors Society, San Francisco, 1977, in press.

109. Wickens DD, Moody M, and Shearer PW. Lack of memory for non-attended items in dichotic listening. JEP: Hum. Learn. and Mem., 2(6): 712-19 (1976).