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**LA THÈSE A ÉTÉ
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NEUROPHYSIOLOGICAL CORRELATES OF HUMAN PROBLEM SOLVING

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Thesis presented to the School of Graduate Studies
of the University of Ottawa
in partial fulfillment of the requirements
for the degree of Master of Arts.

Ottawa, Canada, 1979.

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CURPICULUM STUDIORUM

Normand Perrault was born in Amqui, Quebec, on January 4
1955. He received his Bachelor of Arts with specialization
in Psychology from the University of Ottawa in 1977.

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ABSTRACT

The evoked potential to attended task-relevant informative stimuli contains a late positive component, or P3 wave, with peak latency of around 300-500 ms. When the relation between stimuli is also important to the task a negative baseline shift, or CNV, also occurs. A problem solving paradigm was designed to investigate the nature and functional significance of these ERP components. On each trial subjects were presented with a sequence of four geometric visual stimuli. Each stimulus consisted of two concentric figures, each figure having one of two shapes (square or circle), one of two colours (red or yellow) and one of two types of line (thick or thin). Each set of four stimuli could be classified according to one dimension (shape, color or line) and the subject's task was to determine this classification criterion. The strategy involved the sequential comparison of each stimulus to the previous stimuli, and the elimination, as possible classification criteria, of those dimensions whereby stimuli differed. Large P3 components were recorded, their amplitude being related to the goal-relevance of the stimuli. Negative afterwaves occurred between stimuli, probably indexing updating of context and preparation for further stimuli. A large P2 component was

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found at the first stimulus of each sequence, presumably related to the memorization necessary for further comparisons. Finally, a CNV developed during the stimuli, becoming larger as the end of the task approached. It might relate to some supervisory process controlling the more elementary stimulus evaluation procedure, or to the expectancy for task-closure. These evoked potential components thus reflect several distinct processes taking place during problem solving.

INTRODUCTION

The development of digital averaging in the early sixties permitted the large scale application of signal averaging techniques to the investigation of cerebral electrical activity. Signal averaging facilitates the recording from the scalp of cerebral potentials temporally locked to external events by reducing noise unrelated to these events in the raw EEG. The advent of such a non-intrusive technique allowed a direct exploration of the brain's activity in normal people, thereby opening an important gateway to the physiological investigation of psychological processes.

In the evoked potential waveform there are many components that appear related in some way to the requirements of the task facing the subject. Among them the so-called "P3 wave", a positive deflection peaking at a latency of approximately 300-600 ms following stimulus onset, has been the object of much research in the past few years. Various experimental paradigms have been used and several hypotheses generated as to its nature and functional significance. It has been said to reflect the amount of information processed (Sutton, 1969; Campbell, et al. 1978; Picton, Campbell, Baribeau-Braun and Proulx, 1978), to index an activity of template fitting (Hillyard et al., 1971; Squires et al., 1973)

or to covary with the updating of the interpretational context (Squires et al., 1976; Duncan-Johnson and Donchin, 1977; Donchin 1978, 1979).

Many of the experimental tasks used in previous studies have required subjects to classify events into one of two exclusive categories. Although simple tasks facilitate the experimental design, they also allow the subject to use a variety of possible strategies. Furthermore, several important or characteristic aspects of human cognition may be left unexplored because they are not required to solve the problems given. The human brain is an adaptive system and, as Simon and Newell (1971, page 149) have pointed out:

to the extent a system is adaptive, its behavior is determined by the demands of [the] task environment rather than by its own internal characteristics. Only when the environment stresses its capacities along some dimension -- presses its performance to the limit -- do we discover what those capabilities and limits are, and are we able to measure some of their parameters.

Bearing this in mind, I decided to evaluate the human event-related potential during a demanding and complex problem solving task.

The task I designed involved finding the classification criterion underlying sets of four composite geometrical figures, each having four possible values for each of three separate dimensions (shape, colour and line). A trial consisted in the successive presentation of four figures and the criterion was defined as the dimension which did not vary across the trial. In order to find this criterion and

solve the problem, the subject had to store the first stimulus in memory for later comparison to the succeeding stimuli. Any differences that were then noted allowed the elimination of certain dimensions as possible classification criteria for that particular trial. The basic hypothesis was that clear reflections of this eliminative strategy would be found in the components of the evoked potential waveform. Furthermore, a second hypothesis was that the amplitude of the P3 component would vary as a direct function of the amount of information contained in the eliciting stimulus, this amount being quantitatively described for each stimulus simply by counting the number of dimensions (0, 1, 2) by which it differed from the initial stimulus.

In the following pages the literature concerned with the evoked potential correlates of cognition will be reviewed. The various hypotheses formulated to account for variations in the P3 component will be emphasized, since these are directly relevant to the present work. Following this the behavioural task will be described and the hypotheses more precisely stated. Then will follow the procedure and results. Principal component analyses have been performed on the amplitude data and repeated measures analyses of variance used on the component scores. Correlation techniques have also been used where predicted values or ranks could be related to the empirical data. More details as to the statistical procedures will be found in the methodology sec-

tion. Finally, the bearing of the results on the experimental and other current hypotheses is discussed, tentative conclusions are drawn and suggestions for further research proposed.

REVIEW OF THE LITERATURE

A typical evoked potential waveform contains several peaks in the 100 ms following the eliciting event. Broadly speaking, these deflections index activity in the primary sensory pathways, subcortical structures and primary sensory cortex (Picton and Hink, 1974). In the following review, our concern will be mainly with the later peaks of the waveform, which are supposed to originate in the associative areas of the cerebral cortex. The latter components can be classified as either "exogenous" or "endogenous" (Donchin, 1978). Exogenous components require the physical presence of an external stimulus for their elicitation, and their amplitude and latency can be represented as some function of the stimulus' characteristics (e.g. intensity, frequency, etc.). Endogenous components do not require the physical presence of a stimulus to be elicited. Their trigger is within the brain, although locking these trigger processes to external stimuli is usually advantageous for analysis purposes. Such endogenous components are influenced in their amplitude and latency by psychological processes occurring in the subject's mind. Other late components of the evoked waveform could be described as "mesogenous" in that they are related both to the physical aspects of the stimu-

lus and to the psychological interpretation. From the standpoint of cognitive psychology, only components which show some endogenous properties are of interest. Included in this class are N1, P2, N2, P3, P4, various slow waves and the contingent negative variation (CNV). Major aspects of the work that has been done on these components are reviewed in the following pages. Before turning to this section of the thesis, however, some definitions and clarifications are in order.

The terms "evoked potential" (EP) and "event-related potential" (ERP) will be used to refer to the brain's electrical response following a stimulus or to the averaged response to a series of equivalent stimuli. In those cases where the eliciting event is the absence of a stimulus, the resulting brain response will be called an "emitted potential". The letters "N" and "P" refer to the electrical sign of the deflection in the waveform. The attached number refers to the order in which these components appear in the waveform. For example N1 is the first negative deflection appearing in the late waveform (i.e. after approximately 100 ms). Similarly, P3 is the third positive peak occurring in the late waveform. In those cases where the description of a particular peak with one of those symbols could be misleading, an alternate nomenclature is used and the precise latency is given instead of the rank number. The terms "peak", "deflection" and "wave" will be used interchange-

ably. The term "component" however, will be used only where the process under consideration has been derived from a Principal Component Analysis (PCA). Therefore, peaks and deflections are electrical in nature, while components are statistical. The P3 component, for example, is the statistical component which correlates most highly with the P3 peak of the evoked waveform. More details on Principal Component Analysis can be found in the Data Analysis section.

The Vertex Potential

The N1 peak of the evoked potential

The N1 peak of the evoked potential has often been studied in the context of attentional manipulations. Several early studies had reported an enhancement of the evoked potential to attended stimuli as compared to unattended ones (Satterfield, 1965; Spong, Haider and Lindsley, 1965). In order to control for arousal differences these studies presented both the attended and unattended stimuli simultaneously in different channels. The stimuli they used were, however, regularly alternated. These results were criticized by Näätänen (1975) as leaving open the possibility of a phasic expectancy process. Since the stimuli occurred at regular intervals, the subjects could easily have managed to cycle their arousal in phase with the relevant stimuli (Karlin, 1970). Any enhancement of the waveform would then result from a difference in states of general arousal rather than from selective attention. Later studies controlled for

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this phasic expectancy process by presenting randomly the relevant and irrelevant stimuli. Using such a paradigm, some studies, found no difference between waveforms to attended versus unattended stimuli (Hartley, 1970; Nääätänen, 1967; Wilkinson and Ashby, 1974; Wilkinson and Lee, 1972) whereas others did (Eason, Harter and White, 1969; Picton, Hillyard, Galambos and Schiff, 1971). These latter studies however, still offered some basis for prediction of the relevant stimuli, since they used two independent sequences for the relevant and irrelevant events. Under such conditions the occurrence of relevant stimuli can be at least partially predicted and thus a "statistical" difference in general arousal might explain the EP enhancement (Nääätänen, 1975).

The first study to control adequately for the differential preparation artifact was that of Hillyard, Hink, Schwent and Picton (1973). Auditory stimuli were presented in rapid succession and the ear of delivery was completely unpredictable. Under these conditions, a selective enhancement of the baseline-to-N1-peak amplitude was noted for the attended stimuli. Further studies (Picton and Hillyard, 1974; Schwent, Hillyard and Galambos, 1976a, 1976b) replicated the effect and clarified the conditions necessary to obtain it. The stimulus rate must be high enough so as to render a wandering of attention between channels incompatible with successful task performance. Prior to the study by Hillyard, Hink, Schwent and Picton (1973), no experiment had fulfilled these conditions.

The N1 peak of the auditory EP is also enhanced by selective attention to any one of four channels differentiated by pitch and spatial location (Schwent and Hillyard, 1975). Each of the latter cues taken alone will also produce an effect, albeit a smaller one (Schwent, Snyder and Hillyard, 1975). Similar results concerning the enhancement of the N1 wave have also been obtained for the visual (Hillyard and Van Voorhis, 1977) and somatosensory (Desmedt and Robertson, 1977) modalities. The effect of selective attention on the EP can begin as early as 60 ms and has been interpreted as providing evidence for a "stimulus set" mode of attention as described by Broadbent (1971). Hillyard and Picton (1979) have reviewed evidence on this subject. Such a stimulus set mode of attention entails a preliminary selection of inputs on the basis of simple physical cues such as pitch or spatial location. Once a stimulus has been recognized as relevant, further processing can occur. The obvious advantage of such an early selection of inputs is to protect short-term memory from overload (Broadbent, 1971).

The P2 peak of the evoked potential

Often seen as the second limb of a biphasic process whose negative limb is N1, the P2 peak of the EP, peaking around 175 ms, is not usually considered to be an endogenous component. Indeed, its elicitation appears to require the physical presence of a stimulus, since it is not seen in the

brain's response to omitted stimuli in a train. (Klinke, Frusthorfer and Finkenzeller, 1968). It is also known to be much affected by the physical characteristics of the stimulus (Picton, Hillyard, Krausz and Galambos, 1974; N. Squires et al., 1975). Picton et al (1974) proposed that the P2 component might reflect the setting up of perceptual analysers necessary for stimulus processing. Chapman (1978) has recently reported on a statistical component that might be identified with P2 and whose amplitude could be used to predict recall. This work will be reviewed in greater details later.

The Parietocentral Late Positive Wave

Effects of stimulus probability or information content

Although a clear late positivity could be seen in the waveforms of Walter (1965), the first report on P3 as a separate entity came from Sutton, Braren, Zubin and John (1965). In this paper a late positive wave was observed in the response to stimuli confirming or disconfirming a previous guess about their nature. It was of greater amplitude when the subject was uncertain about the outcome of his guess, when the stimulus was improbable, and when it had disconfirmatory value. In a later study (Sutton, Tueting, Zubin and John, 1967), in which the subjects had to guess about the occurrence or non-occurrence of a stimulus, P3 oc-

curring 300 ms after the point in time where information was given to the subject about his guess whether or not the stimulus was actually present, (i.e. when the presence or absence of the "guessed about" stimulus was revealed). This showed that P3 was triggered by an internal event; it was proposed to coincide with the resolution of uncertainty. Two further studies (Tueting, Sutton and Zubin, 1971; Friedman, Hakerem, Sutton and Fleiss, 1973) showed "outcome probability", the combined probability of guess and stimulus occurrence, to explain a large proportion of P3's variance in amplitude. In these studies the difference between the response to confirming and disconfirming stimuli disappeared, leading to the proposal of "effective information content" as the major determinant of P3 amplitude.

Several other studies have investigated the P3 component to stimuli providing feedback (FB) about prior perceptual or motor performance. With increasing task difficulty, the P3 to FB stimuli denoting correct performance becomes larger in amplitude (Nielson, Teas and Idzidowski, 1970; Picton and Low, 1971; Benson and Teas, 1972). Studies by Squires, Hillyard and Lindsay (1973) and by Picton, Hillyard and Galambos (1976) found greater P3 amplitudes to disconfirming than confirming FB, again suggesting a possible effect of stimulus meaning. In these experiments however, disconfirming stimuli were less probable than confirming ones. In a series of experiments aimed at clarifying this issue Camp-

bell, Courchesne, Picton and Squires (1978) showed the P3 component evoked by FB stimuli to vary with the "contingent probability" of the stimulus, rather than with its meaning. Contingent probability is the probability of a stimulus (FB) given a particular response, in tasks where multiple choices of response exist. Other studies bearing on the effects of stimulus meaning on the P3 wave will be reviewed in a later section.

Information theory (Shannon and Weaver, 1949; Attneave 1959) has often been used to relate more precisely the information content of a stimulus to P3 amplitude. In terms of information theory, the less probable a stimulus, the more information it contains. The exact amount of information, in bits, can be obtained through the formula $-\log_2 p$, where "p" is the stimulus probability. Some studies have reported significant correlations between information content and P3 amplitude (Campbell, Courchesne, Picton and Squires, 1978; Picton, Campbell, Baribeau-Braun and Proulx, 1978). Campbell et al. (1978), for example, report a correlation of $-.83$ between P3 amplitude and task-relevant information. However, the relation between information and P3 amplitude seems to deteriorate after two bits, P3 reaching an asymptote. In general raw probabilities, untransformed into bits, give a better prediction.

Several experiments have been reported in which P3 amplitude varies independently of the stimulus information content or improbability. In signal detection paradigms, P3 amplitude will vary as a function of the subject's confidence in his decision rather than with the signal's probability of occurrence (Hillyard, Squires, Bauer and Lindsay, 1971; Squires, Squires and Hillyard, 1975). The ease of discriminability of a FB stimulus was found to influence P3 amplitude independently of its information content, difficulty being associated with lower P3 amplitudes. In order to reconcile such results with the information theoretical viewpoint, Ruchkin and Sutton (1978a) forwarded the concept of "equivocation", or the a posteriori uncertainty of having correctly perceived an event. When discrimination is made more difficult such equivocation occurs, reducing the effective information content of the stimulus. Equivocation could reduce P3 amplitude either directly or through increased latency variability in the decision process underlying the late positive wave. Such latency smearing might cause the P3 waves to partially cancel one another during the averaging process. Latency variability has also been invoked to explain the reduced effect of probabilities on "emitted" P3s, those resulting from the informative absence of a stimulus (Ruchkin, Sutton and Tueting, 1975). This effect has been confirmed in a study analysing P3s on a trial-by-trial basis. The corrected averages yielded a greater P3

than uncorrected ones, albeit still smaller than the P3 evoked by physical stimuli (Ruchkin and Sutton, 1978b). Campbell et al. (1978) have proposed that equivocation can also occur in relation to response selection. In a paired-associate learning paradigm (Peters, Billinger and Knott, 1977) the P3 wave to the initial stimulus became larger as the associations were learned. It might be that as learning proceeds, the equivocation in response selection becomes smaller. Thus, in the words of Picton et al. (1978, page 456), "...the parietocentral late positive component of the evoked potential seems in some way associated with the passage of unequivocal task-relevant information to its appropriate response in the context of the range of possible responses to that information".

Many studies have pointed out to the fact that P3 amplitude is determined more by the probability of a stimulus class (e.g. "targets" or "standards") than by the probability of individual stimuli (Courchesne, Hillyard and Courchesne, 1977; Kutas and Donchin, 1978; Friedman, Ritter and Simson, 1978). If several events are defined, globally, as non-signals, then the P3 amplitude to each of these events will depend on the global probability of a non-signal occurring rather than on the probability of occurrence of any given non-signal (Friedman et al. 1978). These authors have shown, however, that the P3 response to the non-signals was also a function of the type of processing they were sub-

jected to. Two tasks were used. In Task A the signal was the number "08" and the non-signals different numbers from "02" to "19". In Task B the signals were the repetition of any immediately preceding number and the non-signals similar to those in Task A. While P3 amplitude to signals in both tasks were equivalent, the non-signal response was much greater in Task B. This difference was interpreted as reflecting the greater processing demands of non-signals in Task B, where the subjects were required to remember each non-signal and then wait to see if the number recurred. The authors suggested that one should be able to manipulate P3 amplitude by changing the complexity of memory search or storage.

The P3 amplitude to an event also seems highly dependent on the particular sequence of stimuli that preceded it, inasmuch as this sequence induces changes in the subjective expectancy for the next event (Squires, Wickens, Squires and Donchin; 1976). These authors analysed the P3 response to signals of equal global probability as a function of the number of non-signals that had preceded it in a Bernoulli sequence. P3 amplitude was found to decrease with increasing number of like stimuli in the preceding sequence, and to increase with the number of unlike stimuli which had preceded it. Therefore, although the objective probability of a given stimulus always remained the same, its subjective probability varied with its position in the sequence and in-

fluenced P3 amplitude. A model was proposed in which P3 amplitude varied with the subject's expectancy for the eliciting event. Expectancy is defined as the interaction of three factors: the memory for event frequency within the prior stimulus sequence, the specific structure of the sequence (whether patterns of alternations are set up) and the global probability of the stimulus.

Language, meaning and incentive

Thatcher (1978) proposes that when looking at the effect of verbal stimuli on the evoked potentials, one should take care to differentiate between those effects due to the formal operations that have been performed on the material presented, versus the contents of these operations. Presumably, someone interested in studying how the brain encodes meaning should try to vary the content of his stimuli while always asking for the same formal operations from the cerebral processor. Conversely, somebody interested in finding in the evoked waveform correlates of the various forms of processing performed on the input information, should try to keep constant the content of his stimuli while varying the required formal operations. Examples of the first type of endeavour are manifold in the literature.

John et al., (1968), presenting their subjects with different geometrical figures equated for luminosity and area, found differences in the evoked waveforms indexing the dif-

ferent types of figures presented. Triangles, whether large or small, produced brain waves which were statistically different from those evoked by squares. Johnston and Chesney (1974) found different potentials evoked by an ambiguous symbol when it was presented to the subject in the context of a string of letters, as compared when the string was made of numbers. Their epoch of analysis was however too short (240 ms) to examine this effect of meaning on the later components. Begleiter and Porjesz (1978) presented words previously rated for their affective tone under two conditions: (a) letter identification, where the structural contents of the words was the important parameter, and (b) affective rating, where the connotative content of the words was the relevant aspect. Lateral parietal electrodes were used. A significant difference was found between conditions, for both electrodes, at the level of the N1-P2 amplitude. Within the affective rating condition, differences were found between the various types of words, the pattern of these differences being more consistent for the left parietal electrode. Chapman (1978) has recently published an experiment in which he used Osgood (1964)'s semantic differential technique to classify stimuli, and thereafter, waveforms. Osgood's technique structures connotative meaning along three major axes: (a) Evaluation (b) Potency, and (c) Activity. All scales are bipolar. the Evaluation dimension, for example, can be represented by a scale going

from "good" to "bad" or "nice" to "awful". The Potency dimension might be exemplified by a scale going from "powerless" to "powerful" or "little" to "big". Finally, the Activity dimension can be derived from continua going from "quiet" to "noisy" or "slow" to "fast". Chapman classified his stimuli (words) into six categories referring to both extremes of each semantic dimension (E+, E-; P+, P-; A+, A-). He submitted the evoked responses to these various categories to a Principal Component Analysis and used the resulting component scores to develop discriminant functions capable of classifying the waveforms according to the various categories of elicitors. Classification within each dimension taken separately averaged 97%, significantly better than chance (50%). When all six categories were considered at once, the success rate of discriminant functions was about 42%, again significantly better than chance (16.7%). In a second experiment reported in the same paper, Chapman investigated the effects of semantic expectancy on the evoked brain response. The subjects were now asked to rate the words according to specific scales of the semantic differential corresponding to the three major dimensions, and the evoked potentials were recorded following stimulus presentation. The same statistical procedure was followed as in the previous experiment and again the resulting discriminant functions could discriminate better than chance between the various dimensions which were used by the subject to rate

stimuli at the time of recording. The success rate was much lower, however, than for discrimination between different stimulus classes (overall rate 47.4%; chance = 33.3%).

In a signal detection paradigm using human sounds and real speech words Friedman, Simson, Ritter and Rapin (1975a) found P3s to all stimuli, even in a condition where the subject had no task to perform. They suggested that the use of human sounds might engage the P3 system independently of the functional value of the stimuli. In another experiment using real words arranged in sentences (1975b), they reported P3s to all the words in the sequence although some of them were entirely predictable. The hypothesis forwarded in the previous study was therefore supported. Furthermore, the last word in the sentence always elicited the greatest P3, independently of its information content. This led the authors to postulate an effect of "syntactic closure" indexed by the P3 component. In their own words (1975, p.260):

Presumably the brain processes sentences in terms of their meaning and syntactic structure simultaneously. These are independent matters, in that syntactic structure need not have meaning, and humans are able to determine if words sequences have syntactic structures whether or not they have meaning. When a syntactic structure, such as the sentence, ends, the brain presumably recognizes it as a language unit. The enhancement of the P300 to the last word of the sentence regardless of meaning and the point of task-related information delivery within the sentence, suggests that this enhancement of P300 is a correlate of 'syntactic closure'.

Hömberg, Grönewald and Grönewald-Zuberbier (in press) manipulated subjective relevance in an experiment where the subjects (children) were presented with trains of stimuli consisting of four numbers (0, 2, 10, 50). In a no-task condition, each number represented the amount of money (german pennies) that would be given to the subject simply for paying attention to the stimuli. The amounts were cumulative and given to the subject at the end of the experiment. A large positive wave at the parietal electrode, corresponding to the P3 wave of adults, was found to be influenced by the amount of money represented in the stimuli. In a second experiment designed to control for interindividual differences in the subjective relevance of stimuli, pictures were presented that had previously been rated by the subject as to their interest value. The amplitude of the late positive component was found to follow precisely the interest value of the stimuli. The authors interpreted these findings as providing support for the hypothesis that the late positive wave reflects processes of relevance-evaluation. Several authors have already noticed the fact that P3 amplitude is higher to events that have been made relevant through manipulation of task instructions, than when the same events are irrelevant (Courchesne, 1977; Picton and Hillyard, 1976; Ford et al., 1976). The importance attached to event categories can therefore influence by itself the amplitude of the P3 component.

Another way to manipulate meaning is to take stimuli which are inherently neutral and make them important to the subject through some experimental manipulation. Sutton (1978) has studied this "saliency" aspect of meaning in a guessing paradigm by varying the amount of money won or lost following a bet. The amplitude of the P3 peak varied as a function of the amount of money bet by the subject, whether it was won or lost. When the bet was made by the computer the same results were obtained but the differences were much smaller. This was interpreted as indicating an effect of subject involvement.

The issue of multiple P3s

Late positive waves have also been found in situations where the stimuli were not attended by the subject (Ritter, Vaughan and Costa, 1968; Roth and Koppel, 1973) and have been associated with a central component of the orienting response. A study by Squires, Squires and Hillyard (1975) however, led to the conclusion that this type of wave was different in scalp distribution and latency from the usual P3 found in the signal detection and FB paradigms, being earlier and more frontal. This "P3a", as they called it, was postulated to index a basic sensory mechanism registering any change in background stimulation, perhaps by means of mismatching a specific neuronal model (Sokolov, 1963) established by repetition of the background. The parietal

"P3b" (the usual one), in contrast, varied with the probability of the same stimuli when they were counted.

Another study by Courchesne, Hillyard and Galambos (1975) further complicated the issue of multiple P3s. Visual stimuli (letters) were used where the subject had to count the occurrence of an occasional different letter (target). Interspersed within the main sequence were two types of unpredictable stimuli: the "simples" (easily recognizable drawings or words) and the "novels" (quasi-random colour patterns unrecognizable by the subject). Posteriorly distributed P3s were elicited by the targets and by the simples, whereas the novels elicited large frontocentral P3s. Although the P3 elicited by the novels was postulated to index some cognitive component of the orienting response, matters of amplitude and latency led the authors to consider it as fundamentally different from the P3a of Squires et al. (1975). The novel P3s were more than twice as big in amplitude, and much later in latency. On the basis of these results the hypothesis was proposed that the difference between frontally and posteriorly located P3 waves to irrelevant stimuli was related to ease of recognition. A later study confirmed this interpretation (Courchesne and Hillyard, 1978). On the basis of these data the authors differentiated three different types of P3 waves, triggered by different types of stimuli and requiring different types of processing: (a) Frontal P3 waves elicited by non-target

unrecognizable stimuli; (b) Posterior P3 waves elicited by non-target easily recognizable stimuli, and; (c) Posterior P3 waves elicited by any target stimuli.

Another study by Courchesne (1978) using the Courchesne et al. (1978) paradigm, investigated the effects of stimulus repetition on the various kinds of P3 waves. When analyzed by successive small groups, the novel P3s appeared to shift from a frontal to a parietal scalp distribution. However, evidence for at least two distinct neural generators underlying this phenomenon comes from the fact that over the first eight trials (novels) there was decreasing activity at Fz but increasing at Pz. Over the last eight trials, however, activity at Fz continued to decrease while activity at Pz returned to the levels found for the first four trials. Since the parietal P3 amplitude increased in trials 5-8 compared to 1-4, considerable doubt is cast upon the generality of findings linking amplitude to the subjective probability of events; undoubtedly the subjects came to expect more and more the presentation of novel events. The interpretation proposed in the previous study (Courchesne and Hillyard, 1978) was thus partially disconfirmed since even novel unrecognizable events could elicit parietal P3 waves. These results could be reconciled however, by viewing the parietal shift as representing the evolution of categorization rules. In Courchesne's own words (1978, p. 762):

"The evolution of categorization rules can be considered to be concept formation, that is, the ab-

straction of invariant event attributes and of the rules defining the relationship between such attributes [...] Thus, one could speak equally well in terms of different P3 distributions representing differences in the extent to which available concepts are applicable to the eliciting event: frontal P3 waves would then occur whenever new concepts were required and parietal P3 waves would occur whenever existent concepts were appropriate."

As to the parietal P3 amplitude, Courchesne proposes that it might reflect the importance or interest of an event category to the subject.

Response relationships

Several investigators have seen in the occurrence of the P3 wave a reflection of some decision-making process. (Hillyard, 1969; Smith, Donchin, Cohen and Starr, 1970; Shelburne, 1972, 1973). The exact content of the decision would involve, at least in target detection tasks, a comparison of stimulus input against representations in memory (templates) (Tueting, 1978). Klinker et al. (1968) spoke of an interaction between external and stored information, while Weinberg (1970) alluded to the probable role of memory search in P3 elicitation. Similarly, Thatcher (1977) proposed "representational matching" as an underlying construct for P3 elicitation. Representational matching might occur with hypotheses, task-related expectancies and task strategies, as well as with simpler memory elements, and might be invoked at different levels of serial cognitive information processing. Most of the evidence for and against the deci-

sion-making interpretation of P3 comes from studies correlating P3 latency with reaction-time. The basic idea is that response time should be closely linked to decision time, for example in tasks where the subject must respond to detected targets. Several studies have reported a good correlation between P3 latency and reaction time (RT) (e.g. $-.81$ for Friedman, Vaughan and Erlennmeyer-Kimling, 1978) while others have reported very low correlations (e.g. $-.10$ for Roth, Pfefferbaum, Horvath and Koppel, in press). The major piece of evidence against an interpretation of P3 as reflecting decision-making comes from studies reporting P3 latency to be longer than reaction time (Ritter, Simson and Vaughan, 1972; Harter and Previc, 1978; Picton and Hillyard, 1974).

An alternate explanation of P3 occurrence is that it might index something occurring after the decision, something to which response time need not be precisely time-locked. Such is the "response set" hypothesis of Hillyard and Picton (Hillyard, Hink, Schwent and Picton, 1973; Picton and Hillyard, 1974; Hillyard and Picton, 1977), derived from Broadbent's theory of selective attention (Broadbent, 1971). In this model, P3 would reflect "...the percepto-motor sequelae of the decision that a certain stimulus has occurred. Such sequelae could involve the registration of pertinent sensory information in memory, the resetting of perceptual analysers or an appropriate behavioral response". (Picton

and Hillyard, 1974, page 97). Such an interpretation leaves the door open to parallel processing following the decision, releasing the constraint of a definite time relation between P3 and RT. By parallel processing is meant the simultaneous execution of processing routines which can lead to different results. Memory storage, goal resettings or response selection and initiation are examples of such results. The processes indexed by the P3 wave do not necessarily have to be precisely time-locked to response initiation.

Donchin and colleagues also proposed a model in which P3 latency is related to stimulus evaluation time, but is largely independent of response selection time. In this model, P3 would reflect the "updating of context" that follows the intake of new information. Since this updating affects responses on future trials only, P3 latency need not be time-locked to response time on any given trial (Donchin, Pitter and McCallum, 1978; Duncan-Johnson and Donchin, 1977; Squires, Wickens, Squires and Donchin, 1976). Such a point of view implies that the relation between P3 latency and RT is a function of the subject's strategy. Kutas, McCarthy and Donchin (1977) verified this assumption by emphasizing either speed or accuracy of response in a detection task in which processing complexity was varied. In their Condition 1 the target was the word "Nancy" presented 20% of the time, among repeated occurrences of the word "David" at the complementary probability. In their Condition 2 female names

occurred 20% of the time in a series otherwise comprising male names. In a third condition, targets were synonyms of the word "prod" presented among other unrelated words. For all conditions, the correlation between P3 latency and RT was lower when emphasis was put on speed rather than accuracy (.257 and .617 respectively). Such results can be explained easily if we consider that under the speeded condition, response could be initiated before stimulus evaluation was fully completed. If P3 occurs only after stimulus evaluation is completed, then the P3-RT correlation should indeed be very low. On the other hand, accuracy of response entails a more complete evaluation of the stimulus, therefore diminishing the possible variability of P3 latency with respect to response. A higher correlation should thus be expected. Another study by McCarthy, Kutas and Donchin (in preparation; reported in Donchin, 1979) should be mentioned. Subjects were asked to classify events of a series comprising 20% male names and 80% female names, under both speed and accuracy conditions. In the speed condition, 40% of the rare items were misclassified, i.e., they were responded to as if they were frequent. By examining the waveforms on a trial-by-trial basis, it was found that RT was shorter than P3 latency in all cases of misclassification. In Donchin (1979)'s own words:

Whenever the subject acted before "thinking", he tended to err. Whenever "thought" preceded action (as it presumably does whenever P300 latency is shorter than reaction time), the subject tended to be correct.

It has also been suggested that P3 might be related in some way to conscious awareness (Posner, 1975; Simson, Vaughan and Ritter, 1976; Ritter, 1978). There is a point in time, during its journey to and through the cortex, where the event-related pattern of neuronal firing is consciously interpreted by the subject as referring to the triggering event. Since P3 occurs late enough but not too late, it might represent the conscious realisation that something has occurred. Consciousness is needed, in the analysis of an event, when no automatic processing routines are available to analyse the event and respond appropriately (Bassine, 1973). This type of conscious processing might be the one underlying P3 generation. If so, progressive automatization of the processing routine should cause P3 to disappear.

The inference of a relation between P3 and the vaguely defined introspectively based concept of consciousness is impeded by results coming from experiments using the target detection paradigm. In such tasks, the non-target stimuli do not usually provoke the appearance of P3 in the waveform. Certainly, however, the subject is conscious of these standard stimuli as well.

The previous phenomenon can be interpreted in at least two ways. First, it might be that even standard stimuli evoke P3 components but that the latter are too weak to be averaged out of the noise in typical experiments. Second,

this phenomenon might point out to consciousness being somewhat different from the unitary construct it is often equated with. If consciousness exists it must have a structure and for this structure to be functionally adaptive it must not be rigid. Pather, it must depend on the momentary requirements of the processing situation. In this case a consciousness-related P3 is likely to be influenced by a wealth of factors, depending on specific situations, and it does. Within such a framework, the idea of consciousness as a form without content must be abandoned. Then only might P3 be useful in studying the structural and functional aspects of conscious processes.

Other Late Peaks of the Evoked Potential

The N2 peak is a negative deflection of the waveform occurring at about 200 ms from stimulus onset. It is best seen in the response to stimulus omissions since in this case the stimulus-related P2 is absent and overlap is avoided (Klinke et al. 1968; Picton, Hillyard and Galambos, 1974). Donchin (1978) describes N2 as endogenous and modality specific. The amplitude of the N2 component, like P3's, is inversely related to the probability of the eliciting event (Squires, Squires, Donchin and McCarthy, 1977); contrary to P3 however, the stimuli eliciting an N2 response need not be task-relevant. Its short latency renders it liable to reflect many of the processes previously mentioned

for P3, such as target detection or information processing (Ritter, 1979).

Squires, Squires and Hillyard (1975) reported a positive deflection occurring about 240 ms following unpredictable shifts in pitch, whether or not the subject was attending. They labelled this wave P3a. It could be differentiated from the usual P3 in terms of its shorter latency and more frontal scalp distribution. The P3 peak varied in amplitude as a function of the rarity of the shifts, and seemed to occur whenever mismatches happened. Roth (1973) had reported a similar wave and suggested that it might index some component of the orienting response. However, he thought the wave to be an early manifestation of P3.

Goodin, Squires, Henderson and Starr (1978) recently identified another positive deflection, termed P165 because of its latency, which was associated with rare attended tones in a signal detection paradigm. This peak, however, could only be observed after subtracting the waveform to unattended tones from that to attended ones. Presumably, this might explain its late discovery. Although occurring approximately at the same latency as the currently reported P2, P165 could be differentiated from it by manipulating electrode locations. When using lateral electrodes referenced to the tip of the nose P165 was found to be constantly positive at all leads, in contrast to P2 which inverted in polarity across the supratemporal plane.

Chapman, McCrary and Chapman (1978; Chapman, 1979) reported a "latent" component of the evoked potential, positive and peaking at approximately 250 ms, apparently related to the storage of information in short-term memory. This is a latent component because it derives from a Principal Component Analysis and could not be detected by mere visual inspection of the raw waveform. The task was as follows. Two letters and two numbers were presented individually in random order at intervals of 750 ms, preceded and followed by a blank flash. The subject's task was to compare either the letters or numbers forming a pair, depending on the particular run. Three different luminous intensities were used for all runs, in different conditions. The "storage component" as Chapman has it, was recorded maximally to the first stimulus of each pair, the one which had to be kept in memory for later comparisons to the other members of the pair. The correlation between the component scores and probed recall for the various stimuli was $-.77$, quite high as Chapman points out, in view of the fact that other factors such as retrieval are not taken into account. Chapman hypothesized that it might reflect the reading of information out of a sensory register into short-term memory, its latency occurring about at the time the visual icon fades out (Sperling, 1974).

In a study of concept formation using visual stimuli, Stuss and Picton (1978) reported on a positive deflection

peaking around 650 ms in the evoked response to auditory tones given as feedback on the subject's performance. This "P4" peak, as it was called, was maximally recorded at the vertex and over the parieto-occipital regions. It increased in amplitude during periods where the subject was making continual errors. Except for this particularity it was quite similar to the feedback P3 in its variation with experimental manipulations, being also related to the amount of task-relevant information present in the FB stimuli. The authors suggested that the P4 component might reflect the utilization of FB information to modify visual perceptual processes. They proposed, however, that P4 might not be specific to the visual modality but rather would reflect general perceptual adjustments occurring in the parietal association cortex. In a further study (Stuss and Picton, in press) the P4 was observed in response to visual FB stimuli providing information about performance during an auditory concept formation task. In this latter study, however, the P4 was observed in only about half the subjects. A P4 wave had also been noted by Jenness (1972), in the response to discriminative stimuli in a perceptual discrimination learning task.

Slow Waves

Näätänen and Michie (in press) have reviewed evidence for the existence of a "processing negativity" which might start

rising as early as 60 ms following stimulus onset and could last for several hundreds of milliseconds, depending on stimulus rate, duration and difficulty of discrimination. In attentional studies where the rate of stimulus delivery is high the onset of this shift might overlap with the N1 peak, thus explaining in a different way the previously reviewed "N1 effect". Näätänen and Michie have proposed that this negativity reflects the orienting to and further processing of inputs found relevant in preliminary sensory analysis. Such an interpretation differs from the previous suggestion by Hillyard and colleagues (Hillyard et al. 1973; Hillyard and Picton, 1977; Picton and Hillyard, 1974) about the N1 wave. These authors, it will be recalled, suggested that the variations in amplitude of the N1 peak under attentional manipulations indexed the contingencies of a stimulus set mode of attention (Broadbent, 1971).

Another type of slow wave has been described (Squires, Squires and Hillyard, 1975; Squires, Squires, Donchin and McCarthy, 1977), which is positive going parietally and negative going frontally. It covaried with the same variables as did P3. The scalp distribution of this slow wave probably interacts strongly with that of P3 and might therefore explain the lower P3 amplitude usually found at frontal electrodes.

Rohrbaugh and colleagues recently reported a negative afterwave elicited by unpaired stimuli under various tasks manipulating the subject's involvement (Rohrbaugh, Sydulko and Lindsley, 1978; 1979). This negativity changed its scalp distribution with latency from a frontal to a parietal maximum and peaked within the first second. It lasted for a minimum of 1.5 seconds. A Principal Component Analysis delineated two factors corresponding to the negative afterwave. The first factor accounted for the early negative peak of the slow wave at frontal sites and sometimes also included the P3 component. The second factor represents the late portion of the negative wave and is widely distributed on the scalp. The negative afterwave was of greater amplitude for auditory than for visual stimuli. The appearance of the negativity for visual stimuli seemed to require more stringent task requirements. The authors proposed that this negativity might represent non-specific activation processes, and correspond to the early part of the CNV usually observed between pairs of stimuli.

Contingent Negative Variation and Bereitschaftspotential

The Contingent Negative Variation, was first reported by Walter, Cooper, Aldridge, McCallum and Winter (1964). It was recorded as a negative shift, maximal over the frontal areas of the cortex, occurring in the interval separating a "warning" from an "imperative" stimulus to which the subject had to respond. In situations where the imperative stimulus

was consistently omitted, the CNV receded gradually over about 30 trials. Walter et al. suggested that the CNV might be "...the electrical sign of cortical 'priming' whereby responses to associated stimuli are economically accelerated and synchronized" (page 383). Hillyard (1973) has offered a fourfold classification of CNV-generator paradigms: 1) holding a motor response in readiness; 2) preparing for a perceptual judgment; 3) anticipation of a reinforcer, positive or negative; 4) preparing for a cognitive decision. More generally, it might be said to occur whenever the relation between two successive stimuli is important to the task. Several investigators have proposed attention as a possible underlying process for the CNV (Walter et al., 1964; McCallum, Low and Hillyard, 1969; Hillyard and Galambos, 1967; Tecce and Scheff, 1969; Tecce, 1970).

Tecce (1972) has reviewed most of the literature dealing with the CNV prior to 1970. It is maximally recorded at frontal sites, with antero-posterior and lateral gradients of diminution. Its early part seems related to arousal processes, while the late CNV is readily linked to facilitation of attention to S2 in the classical paradigm. The late CNV combines with the motor readiness (or Bereitschaft) potential, in paradigms asking for a response from the subject.

Because both the CNV and Bereitschaftspotential (BP) are widespread in distribution and confounded in several tasks, the existence of a "true" CNV has often been questioned. Loveless and Sanford (1974) distinguished between an early "O" wave presumed to be a component of the orienting response, and a later "E" wave rising in anticipation of the imperative stimulus and closely resembling the BP preceding a voluntary movement. Several studies had found a difference in scalp distribution between the two phenomena, especially a higher bilateral asymmetry and more frontal distribution the CNV (Deecke, Grozinger and Kornhuber, 1976; McCallum, 1976; Deecke and Kornhuber, 1977) Kutas and Donchin, 1974, Using a pattern recognition technique, Weinberg and Cooper (1972) had found a rather poor correlation between the frontal and vertex recordings of the CNV. These results were confirmed by Papakostopoulos and Fenelon (1975), who were led to propose that these two aspects of the CNV indexed fundamentally different functional processes. Interesting in this respect are the findings of Rohrbaugh et al. (1978, 1979) whose factor I seems to correspond to the early CNV. These results were obtained in a task using unpaired stimuli, thus strengthening an orienting response interpretation of this early process.

The preceding results, however, can be interpreted in a different way to propose that the currently recorded BP is the result of both motor preparation processes and some true CNV (Näätänen, in press). The BP is greater in amplitude at

Cz than over the contralateral hand areas, and the amplitude over the ipsilateral hand area is substantial (Syndulko and Lindsley, 1978). Also speaking in favor of the existence of a true CNV is the fact that many experiments recorded it in situations free of motor response requirements (Järvillehto and Frushtorfer, 1973; Irwin, Knott, McAdam and Rebert, 1960; Low, Borda, Frost and Kellaway, 1966).

Several experiments reported the CNV to vary in amplitude with the manipulation of variables which have little to do with motor preparation. An increase in CNV amplitude related to the subjective expectancy for the imperative stimulus was reported by Järvillehto and Mäntysalo (1976). Roth, Koppel, Tinklenberg, Darley, Sikora and Vesecky (1975), using a typical Sternberg paradigm found that the amplitude of the CNV and the speed of its resolution following the probe varied as a function of target size. CNV amplitude was greatest when the set size was one. Thus, there seems to be plenty of evidence for the existence of a true CNV, independent of the BP.

The relationship of CNV to performance has been the object of much controversy. The assumption of this negative shift indexing attention or "cortical priming" should imply a positive correlation with RT. Tecce (1973) reviewed about 20 experiments on the subject and concluded to the independence of the two variables. McCarthy and Donchin (in press) have proposed the "terrain hypothesis", aimed at explaining

the poor relation between CNV and RT. More precisely they proposed that the CNV might constitute the manifestation of a control system that mobilizes organismic resources to a varying degree to keep constant some behavioural output. From this viewpoint the "aim" of CNV amplitude is to maintain a fixed behavioural output in the front of varied conditions. No constant relation should therefore be expected between the CNV and response time.

In a somewhat different line of thought Cooper, McCallum and Papakostopoulos (1978) proposed a bimodal slow potential theory of cerebral processing, in which two modes of cerebral functioning can occur. The categoric mode refers to states in which actions or decisions are executed automatically and mechanically according to some predetermined and pre-established response procedures. The scopeutic mode refers to a ". . . selective state of involvement with a particular set of circumstances which have taken over the central processor for a given period of time and which require at their end point some action or decision". These two modes can interact or occur simultaneously, and are affected by the processing load imposed on them. In this formulation, the CNV would reflect the scopeutic mode of functioning in which emphasis is put on the the organization of information. Similarly, Picton et al. (1978) have proposed that the frontal component of the CNV might be related to a activity in the frontal regions that programs, directs and energizes the mechanisms of attention, therefore linking it

directly with the organization of selective information processing and behaviour.

CNV-P3 relationship

The coincidence in time of P3 and CNV resolution in several paradigms (Donchin and Smith, 1970) has led to the proposal that P3 might be determined by generalized preparatory activity preceding the eliciting stimulus rather than by processes invoked by the stimulus itself (Näätänen, 1967, 1970). Karlin (1970) suggested that the P3 component was essentially a "reactive change" to the development of the CNV. Several studies however have reported manipulations of P3 amplitude in situations precluding the artifact of differential preparation (Donchin and Cohen, 1967; Eason, Harter and White, 1969; Tueting, Sutton and Zubin, 1970; Harter and Salmon, 1972; Friedman, Hakerem, Sutton and Fleiss, 1973; Hillyard, Hink, Schwent and Picton, 1973). Furthermore, the scalp distribution of P3 is maximal over the parietal areas, which is not the case for the CNV. Donchin, Tueting, Ritter, Kutas and Heffley (1975) demonstrated, through Principal Component Analysis, the coexistence of two orthogonal components corresponding to P3 and to the pre-stimulus negativity. As Tueting and Sutton (197) point out however, the possibility remains open that the CNV and P3 interact in several situations. Particular care should therefore be taken to disentangle these effects.

METHOD

The task involved the discovery of the classification criterion underlying a set of four complex geometrical figures, each of which could vary along three dimensions -- shape, colour and line. All stimuli consisted of two concentric shapes (square or circle), each shape having its own colour (red or yellow) and its own line width (thick or thin). A pool of 64 different figures (4 shapes x 4 colours x 4 lines) permitted the construction of 108 different sets of four stimuli. Each of these sets fell into one of six different categories defined by the location of dimensions variation within the set and by the amount of dimensions varied at each location. The sets of four stimuli were constructed according to the following rules:

1. The first slide of each sequence was chosen at random among the 64 instances of the original pool.
2. Individual slides in the second, third or fourth position of each train could vary 0, 1 or 2 dimensions with respect to the first one. (In this way, the amount of processing required from the subject could be graded).

3. A maximum of 2 dimensions could be varied in any sequence. This is a logical constraint, since the total number of dimensions was three.
4. Once a dimension had been varied, it remained the same throughout the rest of the sequence. This permitted the construction of reversible sequences, the use of which diminished by one half the number of slides needed.
5. Any change in a given dimension, whether it affected one or both of the concentric figures, would be considered as a "complete" variation and be sufficient for the subject to eliminate this dimension as a possible classification criterion.
6. All permutations of location by number of variations would be exploited, inasmuch as rule four was respected.
7. All three dimensions would be used an equal number of times as classification criterion.

Each set of four stimuli was seen four times by the subject during the experiment, twice forward and twice backward, adding up to 432 trials. Thus, there were 72 trials for each type of sequence. The complexity of the figure sets, as well as their relatively high number, prevented completely the subject from knowing in advance the nature of the upcoming sequence. Each trial was preclassified

according to the conjunctive occurrence of two attributes within one dimension, and the subject's task was to determine this classification criterion. For example, the conjunction "square inside circle" might occur in all four stimuli on a given trial. The nature, complexity and time pressure of the task allowed only one successful problem-solving strategy. The subject fixed the first stimulus in memory for comparison to succeeding stimuli. Any differences that were then perceived allowed the elimination of particular criteria as possible solutions to the problem. The final answer occurred when only one possible criterion remained, i.e. when two dimensions had varied. The subject was also required to indicate the slide number at which the solution had occurred. This diminished the possibility for the subject of solving the problem only at the end of the trial by a retrospective processing of the stimuli. The subjects were explicitly asked not to rely on such retrospective processing. Close monitoring of the subject's strategy, through verbal reports during the extensive practice periods indicated a satisfactory "online" elimination of possible criteria in proportion as the stimuli were delivered.

The different possible elimination steps occurring prior to problem-solution provided the basis for a division of trials into six different "sequences". In the first type of sequence two possible criteria could be eliminated on the second slide; in the second type, one criterion was

eliminated on each of the second and third slides; in the third type, both dimensions were varied on the third slide; in the fourth type one dimension was varied on each of the third and fourth slides; in the fifth type, one dimension was varied on the second slide, and one on the fourth; in the sixth type both dimensions were varied on the fourth slide. Table I depicts the various types of sequence according to the number of dimensions varied. The first stimulus in each sequence is simply labelled "S", because its functional significance is qualitatively different from that of the other stimuli. It provides the original template from which further comparisons are made. Figure 1 gives an

Table I
Variation of dimensions within sequences

		STIMULI				
		I	S	2	0	0
S E Q U E N C E	T Y P E S	II	S	1	1	0
		III	S	0	2	0
		IV	S	0	1	1
		V	S	1	0	1
		VI	S	0	0	2

example of each of the six types of sequence.

The experimental hypotheses which were being checked in this experiment are the following:

1. There are independent components of the evoked potential waveform elicited by the stimuli in the problem-solving task, and these components reflect different cognitive processes occurring during the solving of the problem.
2. The P3 component of the evoked potential is related to the amount of information in the stimuli which is relevant to the eliminative strategy. This amount is indexed by the number of dimensions varied, at each stimulus, from the preceding one. (See Table I)

Subjects

Ten volunteer subjects, 9 males and one female, participated in the experiment. All were colleagues of the experimenter. All of them had university education. One male subject was excluded from the analyses because of incorrect electrode placement. All subjects were right handed and had normal vision, with or without refractive correction.

Apparatus

Electroencephalographic (EEG) activity was recorded using Beckman Biopotential Ag/AgCl electrodes affixed to the scalp

with gauze and collodion. The skin was scratched under each electrode (except the ones used for electro-oculogram) so as to diminish skin-potential artifacts (Picton and Hillyard, 1972). Electrodes were placed at Fz, Cz, P3, P4 and Oz, according to the international 10-20 system (Jasper, 1958). These electrodes were referenced to linked mastoids. Electro-ocular activity was simultaneously recorded from the medial supraorbital ridge and the inferior outer canthus of the right eye, so as to monitor both vertical and horizontal eye movements. The EEG activity was amplified using Beckman R611 polygraph amplifiers modified to have an eight second time-constant and with high pass filters set at 30 cps. The amplified activity was monitored online (Tektronix D10 Oscilloscope) and recorded on FM tape at 3 3/4 inches per second (Vetter Model A Tape Recording System).

Stimulation

The visual stimuli were slides projected from behind a small translucent screen through a mirror system. Two Kodak Carousel projectors were used for this purpose. The first one (800) was used to project the sequences of slides which consisted of geometric figures drawn on a yellow background. The second one (750H) continually projected a yellow slide used as a background between stimuli. These two projectors were equipped with shutters independent of the slide changing mechanisms (Lafayette 42011). The shutters were synchronized (lab-made device¹) so that whenever one was open,

the other was closed. The simultaneous "closing-opening" of the shutters was through within 10 to 15 ms. For someone looking at the screen, the subjective impression was that of a coloured figure "appearing" on a yellow background at regular intervals. The subject's initiation of a trial by pressing a button caused a pulse (initiation pulse) to activate a stimulator (Grass S48) which then produced a train of four equally spaced pulses. These were fed into Grason-Stadler timers and the output of these timers was used to drive the first (800) slide projector, backward or forward, for four consecutive slide changes. The train of pulses from the Grass stimulator was also used, after a delay, to activate the shutters. The delay provided the time necessary for slide changes between shutter openings within a train. The first pulse generated by the Grass apparatus, coincident upon the subject's button press, produced a click in the subject's earphones (Telephonics TDH-49) which served as a warning that the visual stimuli would come soon. It also told the subject that his button press had been effective.

Coding and decoding of sequence types and criteria

The 800 projector, which was used for the sequence slides, was equipped with an array of photocells arranged so as to face one side of the slide's frame. Holes were drilled into some of the slides, their number and -----

¹All "lab-made devices" were designed and constructed by Gilles Hamel, B.Sc.

arrangement corresponding to specific sequence types. The last slide in each train of four provided the code appropriate for the next train. These codes were read by the photocells and related apparatus (Lehigh Valley Electronics) and fed into a set of six and-gates. These and-gates were interconnected so that only one of them fired when a code corresponding to a specific sequence was input in conjunction with the initiation pulse. In other words the subject's initiation pulse was only allowed to pass through the particular and-gate corresponding to the sequence type of the slide train being projected. Hereafter, the outputs from these and-gates will be called "sequence pulses". These sequence pulses were fed into three different flip-flops depending on the particular sequence they represented. A first flip-flop was activated by the output from the and-gate corresponding to sequence I, where the solution occurred at the second slide. A second flip-flop was activated by the output of the and-gates corresponding to sequences II and III, where the solution occurred at the third slide. A third flip-flop was activated by the outputs from the and-gates corresponding to sequences IV, V and VI, where the solution occurred on the fourth slide. Hereafter, these will be called "location flip-flops".

The code for the correct criterion within a given trial was set manually by the experimenter. This consisted in activating a duo of flip-flops arranged to function as a

counter (criterion flip-flops). The code for the colour, line and shape criteria were set by activating one, the other or both flip-flops respectively. The subject's response as to the criterion also activated these flip-flops. They were so arranged that whenever the subject's response corresponded to the code set by the experimenter (i.e. when he or she was right), no flip-flops were left open. In other words a correct response from the subject canceled the experimenter's code. Similarly the subject's location response de-activated (when right) the location flip-flop currently "on". If any of the criterion or location flip-flops were still activated at the end of the subject's response, a pulse indicating a wrong answer was generated (error pulse). The sequence and error pulses were fed into an eight-channel frequency coder-decoder (lab-made device), along with the pulse resulting from the subject last button press (location response). Each of these eight pulses was then attributed a different frequency code. All these codes were stored on one channel of the FM tape.

Playback

The tapes were played back at 15 ips. The frequency codes were decoded by the same device that had coded them. A code corresponding to a particular sequence type, for example, caused a pulse to be output from a specific channel of the coder-decoder. The same was true for the error and response codes.

The EEG waveforms were digitized and averaged on a Tracor Northern 1500 digital signal analyser. The pulses generated by the sequence codes were used to start the averager's period of analysis. This permitted separate averaging of the EEG activity corresponding to each sequence type. Following reception of a sequence pulse the computer went on digitizing for a period of 2.17s (8.75 real time). Then it stopped automatically, to be restarted only by the response trigger corresponding to the trial under consideration. Since this trigger coincided with the end of the subject's response, it had a constant time relation to the FB stimulus. Following this trigger the averager went on again for .4 s (1.6 s real-time) to digitize the FB evoked potential.

All EEG epochs contaminated by EOG artifact were rejected by the TN 1500's artifact rejection (AR) system. Along with the EOG, the error pulses were also passed through the AF system, permitting the rejection of all trials where the subject's response was wrong. Furthermore, all trials where the subject had responded too early (i.e. less than one second after the onset of the last slide) were prevented from reaching the digitizing stage. Three counters were set up which monitored the number of sequence pulses emitted by the coder-decoder (check on decoding accuracy), the number of trials with responses coming too early, and the number of trial with wrong responses.

Since the number of trials successfully averaged varied for each sequence type, the resulting waveforms were normalized. This permitted a direct comparison of the various sequence types within subjects, controlling for the number of averaged trials. The resulting waveforms were then graphed on paper, for each subject and sequence type, (Hewlett-Packard 7044-A X-Y Recorder). The same waveforms were also stored on cassette to be later used in the computation of grand averages over subjects (TN 1003 Tape Cassette Unit).



Procedure

Each subject gained mastery of the task during several practice periods which were continued until a consistent performance level of 85% correct was achieved. This required between one and eight hours. The evoked potential session occurred within a few days of the last practice period and began with a few practice trials, in order to refresh the subjects' skills.

The subjects sat comfortably in a reclining chair and looked at a fixation cross drawn on a 90 cm² translucent screen located 150 cm from their eyes (a visual angle of approximately 4 degrees). The subjects wore earphones (TDH 49) in which white noise of 80 dB SPL occurred continuously in order to mask the equipment sounds. The subjects initi-

ated each trial by pressing a button with their left thumb when they were ready. This caused a click stimulus (250 μ s, 280 mV) to be heard over the masking noise. One second after the click, the visual stimuli began. The duration and interstimulus intervals for these four stimuli were 100 and 2200 ms respectively. The subjects were instructed to wait for at least one second before responding with their solution to the problem and the slide location at which it had occurred. This was done through a system of four microswitches. The criterion response was made by pressing a microswitch with the right index once, twice or three times for shape, line, and colour respectively. Three other microswitches on the response box could be activated with the remaining fingers of the same hand in order to indicate the location at which the solution had occurred. From left to right the second button corresponded to slide number two, the third to slide number three and the fourth to slide number four. A 1500 cps 200 ms 90 dB nHL feedback tone was delivered through the earphones one second after a correct response, the absence of such a tone indicating a wrong answer.

Data Analysis

Baselines determination and raw measurements

The EP responses for each experimental trial were averaged, for each subject separately, across all trials belonging to

a particular sequence type. There was therefore 6 different average responses for each subject, one per sequence type. Each sequence comprises 4 stimuli. The responses particular to these stimuli were averaged simultaneously and were based on the same number of individual trials.

An individual baseline was traced for each stimulus in the sequence, on the basis of the average amplitude of the waveform in the 200 ms preceding the stimulus. The use of measurements taken from individual baselines does not allow the evaluation of processes taking place across the whole sequence. A general baseline was therefore traced on the basis of the mean amplitude in the 400 ms preceding the first visual stimulus in the train. Measurements were taken, at each stimulus, of the difference between this general baseline (B) and each individual baseline (b). The resulting value (B-b) was entered along with other dependent measures in the data matrix, in order to identify the presence of a possible general CNV.

For all separate stimuli the amplitude measurements were taken within windows whose limits were determined by prior visual inspection of the grand average waveforms (over subjects). The major peaks of a waveform could therefore be measured and averaged together, in spite of their latency variability between subjects and conditions. The following latency ranges (from stimulus onset) were used to identify

and measure the separate peaks: N1 -- 80-220 ms, P2 -- 200-325 ms, N2 -- 250-380 ms, P3 -- 270-700 ms. The average amplitude of the waveform was also measured inside windows whose limits were: 350-650 ms, 650-1030 ms, 1030-1340 ms, 1340-1650 ms, 1650-1970 ms and 1970-2200 ms. Owing to the limits of the averaging epoch, the last four window measurements were not available for stimuli occurring at location four. Figure 2 illustrates the various windows used in measuring amplitude.

Principal component analysis

Visual inspection of the plotted waveforms revealed several peaks and pointed to possible differences between experimental treatments. The peaks in the raw waveform, however, can be partially correlated. The amplitude of the P2 peak, for example, might have an influence on the amplitude of the succeeding N2 peak. I was looking for traces of the eliminative strategy and wished to assess independent underlying cognitive processes. Although different peaks can be assumed to index different cognitive processes, the electrical interactions between these peaks do not necessarily reflect cognitive interactions. Since I was looking for independent sources of variation in the waveform, Principal Component Analysis seemed an adequate technique. PCA has been used previously several times in the field of evoked

potentials. The relevance of this technique for the interpretation of EP data has been examined by several authors (Donchin and Heffley, 1978; Picton and Stuss, in press; Puchkin and Glaser, 1976). The following overview of relevant aspects draws on these sources as well as on more general ones (Ferguson, 1971; Kim, 1975; Laforge, 1976; Morrison, 1976).

Principal Component Analysis looks for independent sources of variation in the data matrix. It determines their location and extent across the set of dependent variables. They are called components, or derived factors, and do not covary. This orthogonality of the derived factors makes them more easily compared to theoretically independent cognitive processes. This is why PCA was performed on the data: in order that the theoretical interpretation of the results be made easier. By reducing variance sources (dependent variables) to progressively smaller and independent basic sources of variation, we decrease considerably the complexity of the data set. In a sense, this compensates for the complexity of the task.

In order to interpret these components, reference to the previous literature will be necessary. It is therefore desirable that the components derived correspond to phenomena usually seen in the raw waveform. Previous research on these phenomena can then be brought to bear upon the derived

components. Hypotheses formulated to account for variations in these phenomena can be checked against variations in the derived components across experimental treatments.

The PCA was performed using the P4M program of the BMDP package (Dixon and Brown, 1977). To keep closer to the real data, so that the components retain more physiological meaning, a covariance matrix was used as representing the associations between variables. The advantage of using a covariance matrix is that, the data being only centered and not normalized, each of the original variables will contribute its real amount of variation to the derived components. Consequently those dependent measures exhibiting the greatest amount of variation will account for more in the PCA solution. Since I was especially interested in those peaks which vary the most with experimental manipulations, this is an appropriate state of affairs.

The matrix of amplitude data used as input to the PCA was organized as follows. The columns corresponded to the dependent variables and the rows to the cases. A case was the averaged EP response of a given subject to a specific stimulus. Each subject therefore generated 24 cases (6 sequence types X 4 stimuli). From the 9 subjects, 216 cases were available with 7 dependent variables. The last four dependent variables (windows) could not be entered in this matrix, because they were not available at the fourth stimulus of

the sequences. These four windows span the area of the waveform which is referred to as the negative afterwave. The possibility of a component corresponding to this negativity was examined in a second PCA where only the responses from the first three stimuli of each sequence type were used. This gave a matrix of 11 dependent variables by 162 cases (9 subjects X 6 sequences X 3 stimuli).

The set of dependent variables on which measurements were taken can be represented geometrically as a set of axes along which the collected data points scatter. If the variables covary these axes will not be orthogonal, i.e. they will not intersect at right angle. PCA will reduce the number of axes needed to represent the data in this space, and have them intersect at right angle. The new axes are the components of PCA. For each newly derived component, PCA will provide a set of loadings which represent the correlation between this component and every original input variable. The loadings can be used to determine how much of the variance in the original variables is accounted for by the new component or, inversely, what is the contribution of each variable to the new component. The pattern of loadings for each derived component is used to name it after the original variable contributing most to its formation.

The maximum number of components extracted by PCA is equal to the number of input variables. Since the goal of

the analysis is to achieve greater simplicity, however, we must determine a priori a fixed number of components to be derived. Several methods are available to limit the number of components. In this study, the minimum amount of variance to be explained by a component was manipulated. Because the task is complex it is legitimate to expect a fair amount of separate processes going on during its execution. Furthermore some of these processes might occur only under specific experimental treatments and therefore, although important from the interpretational point of view, might account for only a small proportion of the total variance in the data matrix. Following these considerations it was decided that a lower cutoff point of 5 percent of the total variance would be adequate.

Varimax rotation. Because the PCA components tend to covary across the waveforms from which they were derived, and also because the dependent variables often covary, the PCA will produce loadings for each component across the entire waveform. The interpretation would be easier if each component had maximized activity within a restricted region of the waveform, and minimized activity elsewhere. This can be achieved through the use of Varimax rotation. This technique has the effect of maximizing high loadings and minimizing low ones while maintaining orthogonality. Consequently the derived components will relate highly to a lesser number of variables and their interpretation will be made easier.

The plots presented in figures 3-A and 4-A are based on the Varimax rotated factor loadings.

The component scores. Once the derived components have been identified and labelled according to the major peak or region of the waveform they represent, the pattern of their variations following specific experimental treatments can be investigated. For this purpose the component scores are used.

The component scores reflect the activity of the derived components under the various experimental conditions, the same as do the amplitude measurements from which they are computed. These scores are obtained from a linear equation where the terms are the raw amplitude values of the dependent variables, weighted according to their respective loading on the component under consideration. For each derived component, therefore, there will be as many scores as there were cases in the original matrix. Because of the use of a covariance matrix to derive the components, the means of the scores for each component is zero. Thus a component score of zero represents the mean activity level of the corresponding component across the whole set of data. Positive values are above the mean and negative values under it.

Analyses of variance

The analyses performed on the data up to now can be considered as transformations of the raw values into scores which better represent the activity of the "real" components in the waveform. Plotting the means of these scores for each stimulus within each sequence therefore provides an idea of the activity of the derived factors under the various experimental treatments. Still, as in the case of interpreting raw data, the differences between means can be due to error variance. In order to verify the effect of experimental treatments on the derived factors and reach decisions which have a high probability of being right, the component scores must be subjected to analysis of variance. Since the component scores represent activity in orthogonal factors, there is no loss of information from the use of univariate rather than multivariate ANOVAS, and so the component scores corresponding to each component were analyzed separately.

A two-way repeated measures analysis of variance was used to assess treatment effects (Dixon and Brown, 1977 - BMDP Program 2V). One treatment is the stimulus location, and has four levels. The other treatment is the sequence type, and has six levels. Within each of the 24 cells of this design are the scores for each of the 9 subjects on a given derived factor.

The two dimensions along which the results are aligned in this design are not completely independent, since the sequence type is definable only in terms of the content of a given slide at a given location. Because of this, treatment effects lose somewhat their clear cut meaning. The main interest, however, was not in comparing treatments, but in assessing the specific aspects of their interaction. The interaction, in this design, is really between slide content and location, or in other words, between information content and time of delivery. The different sequence types used are globally equivalent and differ only in their interaction with slide location. Any overall sequence effect would then result from its interaction with slide location.

The slide location treatment also interacts with sequence type (inasmuch as slide one always has the same content while slide two, three and four vary it), but it also has an independent existence from being scaled on a continuous time dimension. Two interpretations of a slide location effect are therefore available. Either it is a real effect due to the scaling of events on the time dimension, or it represents a significant difference between slide one and the other slides in the sequence. Both interpretations could be warranted at the same time. Comparisons among means can be used to reject one interpretation or the other.

Comparisons among means.

Because of the interdependence between treatments in this design, the interaction effect will probably be overestimated by the ANOVA. The correct interpretation of an interaction effect in this design is that it is a positively biased overall test of the difference between component means at different slides. In order to counterbalance this bias, two-tailed post-hoc tests with alpha set at .01 were used, instead of the legitimate a priori one-tailed tests with alpha set at .05. The risk of type I error was therefore reduced by at least a factor of ten. Because all tests involved comparisons between groups of means, Scheffe's "F" was used (Kirk, 1968), based on the interaction error term.

Assessment of correlations

To further help the interpretation of the results, Spearman's rank-order correlation coefficient (Ferguson, 1971) was used to assess the fit between the derived component scores and theoretical predictions that could be made on the basis of existing hypotheses.

RESULTS

Only results from the Cz electrode are presented in this paper. The grand average waveforms evoked by the sequence and FB stimuli are given in figure 3. A gradual shift of the whole epoch toward negativity can be observed for all types of sequence. Large positive waves occur after all the stimuli. At times, particularly at the first slide of each sequence, this wave divides into two easily recognizable P2 and P3 waves, but at other times these seem almost confounded into a single large wave. One can also discern a N1 peak to most slides and sometimes also a N2. The waveforms are also characterized by a negative going ramp developing between stimuli. The FB responses consist of a negative-positive deflection comprising the N1 and P3 peaks.

First PCA and Related ANOVAS

The first PCA delineated four factors. Plots of the loadings and factor scores are given in figure 4. Summarized results from the ANOVAS will be found in table II.

Table II

Summary of ANOVAS for First PCA

	#	FACTOR I	FACTOR II	FACTOR III	FACTOR IV
	#	F	F	F	F

SLIDE	#	0.56	31.74 **	18.77.**	1.99

SEQUENCE	#	4.53 *	0.69	0.98	0.69

INTERACTION	#	14.32 **	1.38	1.36	1.81

* = P<.01

** = P<.001

Factor I explains 43.3% of the variance in the raw data and loads mainly on the measurement corresponding to the P3 peak of the EP, of which it accounts for 84% of the explained variance. Its loadings distribution is widespread however, and the proportion of shared variance between this factor and the P2, N2 and LP measurements are 14.5%, 17.6% and 90.4% respectively. The second factor loads mainly on the P2 peak measurement (83% of the variance accounted for) although it also has a rather widespread time distribution across the epoch. The percentages of variance accounted for in the N2 and P3 peaks by this second factor are 48% and 8.4% respectively. When the whole set of measurements is considered, it explains 24.8% of the total variance. There

is a fair amount of overlap between the first and second factor. The third factor can be seen to explain almost exclusively the amplitude variance of the difference between general and individual baselines (B-b). This "CNV" factor accounts for 97% of the explained variance in the B-b measurement. Its influence can be seen to increase steadily throughout the whole epoch, of which it explains 16.4% of the total variance. The fourth factor corresponds to the N2 measurement of the raw waveform. It accounts for 11% of the total variance. Since this factor, as shown by the subsequent ANOVAS, is not related to the experimental treatments in any appreciable way, it will not be discussed here.

An examination of the factor score plots reveals factor I (hereafter called "P3 factor") to be most active at those slides where criteria can be eliminated following a variation in content. Notice the second slide of sequence I, the second and third slides of sequence II, the third slide of sequence III, and so on. A sharp drop can be seen at those stimuli following problem-solution (in the first three sequences). Interestingly the important late positive wave to the first slide of each sequence, which can be seen clearly in the raw waveform, is only weakly represented in the scores of the P3 factor. The analysis of variance for these factor scores show a sequence effect and a more important interaction effect. The sequence effect makes no sense, experimentally, and must therefore derive from the interaction of slide and sequence effects. It probably stems from the

particular arrangement of experimental treatments in our statistical design. There is, for example, a gradual increase in latency of information delivery from sequence I to sequence VI. This is only due, however, to the arbitrary way the data were placed into the design. Scheffe's F (Kirk 1968), reveals a significant difference between slides contributing to the elimination of criteria, and those which do not ($F=0.42$, $p<.01$). The difference is still significant even when only slides varying one and zero dimension are compared ($F=0.46$, $p<.01$). There is no significant difference between slides varying one and two dimensions ($F=0.65$, $p>.10$). These comparisons excluded the first slide of all sequences which, on logical grounds, must be considered different from all the others in the train. This first slide cannot be said to really contribute to the problem solving process, but neither can it be qualified as uninformative. Rather, it might be described as permitting the creation of the original template against which all the other stimuli are compared.

The analysis of variance performed on the scores of the P2 factor reveal only an effect of slide. Examination of the plots in figure 4-B shows this effect to be mainly due to the difference between the first slide of each sequence and the following ones ($F=0.48$, $p<.01$). This component therefore appears to account for most of the variance of the large late positivity found at the first slide of each sequence, which was left unexplained by the P3 factor. The

ANOVA for the scores of Factor 3 (CNV factor), also show only an effect of slide. There is a trend toward a gradual increase in negativity of the factor scores across each sequence.

Second PCA and Related ANOVAS

Factor loadings and factor scores for this second PCA are depicted in figure 5. The summarized ANOVAS can be found in table II. This analysis, it will be remembered, included all measurements taken from the responses to the first three slides of each sequence only. Five factors were delineated. The fifth factor corresponds to the N2 peak and will not be

Table III

Summary of ANOVAS for Second PCA

	FACTOR I F	FACTOR II F	FACTOR III F	FACTOR IV F
SLIDE	0.80	1.42	31.94 **	13.16 **
SEQUENCE	3.84 *	1.49	0.86	0.97
INTERACTION	9.57 **	2.68 *	1.57	1.08

* = P<.01

** = P<.001

discussed here, for the same reasons as before.

Factor I still corresponds maximally to the P3 peak measurement and can be seen to decrease regularly in prominence thereafter. It now explains 41% of the variance in the enlarged waveform. Factors 3 and 4 (P2 and CNV) also present basically the same pattern, both in terms of loadings and factor scores, as that which was revealed by the first PCA, although the proportion of total variance they explain is expectedly lower (18% and 10% respectively). The new piece of information comes from the appearance of Factor 2, which now corresponds to the later portion of the stimulus evoked waveform, i.e. the interstimulus negative ramp (Negative Afterwave). The presence of this factor, conjointly with the CNV factor suggests the existence of two distinct slow processes, one riding over the whole sequence (CNV), the other following each stimulus within the sequence (Negative Afterwave). The proportion of variance accounted for by Factor 2 in the new waveform is 19%.

The results of the ANOVAS performed on the factor scores of the second PCA differ slightly from those of the first PCA. The P3 factor shows the same effects. The plots of factor scores also show basically the same pattern with a slight exception at the second slide of sequence V, where the amplitude should be higher. Again a significant difference is found between slides that vary dimensions and those that do not ($F=0.45$, $p<.01$). The difference between one and two dimensions still does not reach significance ($F=0.65$,

$p > .10$). Factor 3 (P2), like previously, shows only an effect of slide. It is highest again at the first slide and much smaller at the other two ($F=0.48$, $p < .01$). Factor 4 (CNV) again shows its previous slide effect. The new Factor 2 (Negative Afterwave) shows an effect of interaction on analysis of variance. If we except the third slide of sequence VI, the corresponding factor scores can be seen, roughly, to decrease proportionately to the amount of dimensions varied. The activity of this factor decrease whenever no new information is brought to the subject. The overall difference between slides varying dimensions and those which do not is, however, nonsignificant ($F=1.02$, $p > .10$).

Correlations with theoretical values

The Spearman rank-order correlation coefficients between the number of dimensions varied and the mean scores of the P3 and Negative Afterwave factors are +0.64 and -0.71 respectively.

ANOVAS on the measurements from the responses to feedback stimuli

The one-way ANOVAS performed on the feedback-related measurements showed no significant effects. The feedback responses following each type of sequence can therefore be considered identical. These results will not be discussed further.

DISCUSSION

The principal component analyses delineated five factors (P3, P2, Negative Afterwave, CNV, N2) among which four are influenced by experimental treatments. The P3 factor is influenced differentially by slides varying dimensions and those that do not. The same is true of the negative afterwave factor, although the differences are less clear cut. The P2 factor is active mostly at the first stimulus of each sequence. The CNV factor increased gradually through the epoch. It seems that the evoked waveform comprises several independent components that might relate to different aspects of the task. Thus, so far, the general starting hypothesis is supported. The precise relationship of these components to cognitive processes occurring during the task needs, however, further discussion.

The major portion of the variance in the average evoked responses is accounted for by the P3 component. This component is highest at slides which contribute to the eliminative strategy, although it does not reflect the precise amount of change from one stimulus to the next. A possible cause for this lack of precision might be latency variability of the P3 peak. If the P3 peak varies its latency of occurrence from one event to the next within the set of such events that were averaged together, some averaging of

non-correspondent time points will occur and this might contribute to diminish P3 amplitude. If the P3 wave is related to stimulus evaluation, then it is a plausible assumption that the more complex the stimulus, the more variable the latency of P3. Such latency variability should however, while reducing P3 amplitude, also increase the width of the peak. Visual inspection of the raw waveforms shows the P3 peak to be no wider for slides varying two dimensions than for those varying only one. If latency variability shows no discernible effect on P3 width, its effects on P3 amplitude must not be very important. Therefore either both simple (one dimension varied) and complex (two dimensions varied) stimuli are equally affected, or the explanation of the lack of difference between the responses to these two types of stimuli in terms of latency variability is not warranted. Since the first possibility is unlikely, it is concluded that the lack of difference under discussion is real.

Among the hypotheses which have been reviewed in chapter I, several can be eliminated as explanations of the present P3 findings. Stimulus uncertainty (Sutton et al., 1965; Friedman et al., 1967, 1968) and probability or information (Campbell et al., 1978; Picton et al., 1978) do not explain the results, since low probability stimuli such as the first one in each sequence elicit smaller amplitude P3's than more probable stimuli like the fourth of condition VI or the third of condition III. Although information might have

played a role, it is certainly not the major determinant of P3 amplitude in this task. In fact, it might very well be that when task-execution requires deep processing of the physical features of stimuli for what they mean, probability recedes in the background. To illustrate with an example from daily life, one can say trite things with rare words, or say meaningful things with words of frequent usage. When understanding is the goal, word probability becomes a factor of minor importance. Something similar most probably occurred in the present task, and this might explain the lack of correspondance between the amplitude of the P3 factor and information.

The hypothesis of Donchin and colleagues (Donchin et al., 1978; Duncan-Johnson and Donchin, 1977) that P3 indexes an activity of context updating is also partially disconfirmed by the present results, if the amount of updating is taken into account. Stimuli varying one and two dimensions, which lead theoretically to different amounts of updating, elicit same size P3s.

Friedman and colleagues had found P3 correlates of syntactic closure. Because syntactic closure relates essentially to the formal structure of the stimulus train being presented to the subject, it was deemed possible for traces of "problem closure" to appear in the responses to the sequences of the present task. In such a case the responses

to stimuli closing the problem, or bringing its solution, should have evoked greater amplitude P3s than other which deliver the same amount of information but do not close the problem (cf. II-1 versus II-2, or IV-3 versus IV-4). Such is not the case. It might therefore be that the closure phenomenon is specific to linguistic processing. There were some indications, in the raw waveforms, of a "task-closure" effect, reflecting the end of the task as a whole, occurring at the fourth stimulus of each sequence (see figure 3). However, the slight increment in P3 amplitude at this location was not reflected in the corresponding factor scores. This might indicate that the increment was due to an interaction between P3 and a fall-off of the CNV at the end of the task. The use of PCA, which delineated two separate factors for P3 and CNV probably subtracted such influence from the P3 factor scores.

The template mismatching hypothesis of Hillyard and colleagues runs into the same type of problem as Donchin's updating of context, when trying to explain the results at P3. The amount of mismatch, which was clearly defined in this task did not covary with P3 amplitude or with the corresponding factor scores. It might be argued that the present task did not really elicit template fitting in the Sokolovian fashion, since there was little or no repetition of a background and since changes were always somewhat expected. However, the task required the comparison of the current

stimulus against an internal memory representation of the previous one, and template mismatching might have been a plausible explanation of P3 findings.

The last hypothesis to be discussed from previous literature, is that which relates P3 amplitude to the subjective evaluation of the stimulus task-relevance (Courchesne, 1978; Hömberg et al. in press; Picton et al., 1976). The task-relevance of a stimulus is determined by its relation to the task goal. In a simple task such as target detection, the determination of task-relevance is straightforward. This is not so, however, when dealing with complex tasks. The more complex the task, the more organized the problem-solving strategy must be. The problem is solved in several steps. Information processing during a "step" is oriented by the goal specific to that step. The "global" goal of a task can therefore be split into several subgoals which can then be organized by the problem solver (with or without external help or constraints) into a problem solving strategy. A strategy therefore has a structure which can be, for example, serial or hierarchical, depending on the functional relations between the subgoals that orient processing within it. The task-relevance of a stimulus can thus be determined by its relation to more than one goal, or to a subgoal embedded within a more global goal.

The concept of "goal-relevance" might provide the best explanation of P3 variations in this task. Three major possibilities arise:

1. The stimulus provides a starting point for the global strategy that will lead to goal attainment, but does not permit any elimination of possible criteria. Processing is oriented by the goal of memorizing properly. Included in this category are all stimuli coming first in the sequence.
2. The stimulus permits the elimination of criteria and therefore provides information as to problem solution. Processing is oriented by the goal of eliminating possible criteria. Included in this category are all stimuli that vary dimensions.
3. The stimulus is neither a starting point nor does it provide information as to problem solution. Processing is oriented by the need to eliminate possible criteria. Included in this category are all stimuli which do not vary dimensions.

The second and third categories are opposites in terms of goal-relevance. Between these, a significant difference was found. The first category is not evaluated by the subject entirely along the same lines, since it has an altogether different function in the global strategy. It is

plausible, however, that its relevance to the global goal is intermediate between that of categories 2 and 3. The amplitude of the corresponding factor scores would support such an interpretation. It is therefore proposed that the P3 factor reflects the subjective evaluation of goal relevance, with the qualification that there can be more than one goal, and if so, that the goals can interact in determining the subjective importance of stimuli.

The P2 factor seems to reflect some process occurring mainly at the first stimulus of each sequence, and little elsewhere. It should be pointed out that although the peak to which it corresponds has been labeled "P2", it occurs in fact much later than the P2 peak usually recorded in simpler experiments.

Three hypotheses are available in the previous literature, that might fit the present results. It is possible that the P2 factor corresponds to what Squires and colleagues (1975) have labelled P3a. They interpreted this peak as reflecting some aspect of the orienting response. In the present task, the probability of occurrence of any specific stimulus occurring at the first position within the train is quite low (1/64). These stimuli therefore fill the rareness condition of the orienting response. However, other factors militate against such an interpretation. Although the precise content of the stimulus is unknown to the

subject before its occurrence, the time of its occurrence and its functional meaning within the task are entirely known to the subject. The P3a of Squires et al. was elicited by stimuli which were unpredictable in time and, furthermore, unrelated to the subject's task. The correspondence between P3a and the present P2 is therefore not straightforward. A more powerful test of the identity of these two peaks will await analysis of the scalp distribution data.

Picton and colleagues (1974) have proposed that the P2 peak of the evoked potential might index the set up of perceptual analysers that is necessary to process stimuli. Given a train of stimuli, such a set up might occur only at the onset, being kept as long as needed. The major problem with this hypothesis is that it was originally applied to a P2 peak occurring much earlier in latency than the present one. It might be, however, that because of the great complexity of the stimuli in the present experiment, the building up of perceptual expectancies occurs later. Again, scalp distribution will be useful in determining the appropriateness of this hypothesis for the present results.

A third explanation stems from Chapman and colleagues' discovery (1978; in press) of a latent component related to short-term memory storage in a letter comparison task. Although Chapman's task was much simpler than the present one, it compares favourably in terms of the need for memorization

of a "template" stimulus to be used for later comparisons. Chapman's latent component was positive, maximum at the first stimulus within the pair, and peaked around 250 ms. This is only 20 ms earlier than the mean latency of the present P2, and stimulus complexity must be taken into account. Careful memorization of the first stimulus was very important in the present experiment, and this fact was particularly emphasized during the practice periods. This emphasis on memorization, as well as the difficulty of it, might have turned Chapman's "latent" component into a peak readily visible in the raw waveform. Therefore, it is suggested that memory storage provides the best interpretation of the present results at the P2 factor.

The negative going ramp of electrical activity between stimuli is represented in the PCA results by the negative afterwave factor. One interpretation of the negative afterwaves is that of local CNVs occurring between the stimuli in the train. Loveless and Sanford (1974) have proposed that the CNV was composed of two separate slow waves, one occurring early in the interstimulus interval and representing a cognitive component of the orienting response, the other occurring more toward the second stimulus and related to the expectancy of it. The two subcomponents can only be differentiated when the ISI is long enough. Rohrbaugh and colleagues (1978, 1979), have found negative afterwaves to unpaired stimuli and have proposed that it corresponded to the

early part of the CNV. The negative afterwave of Rohrbaugh et al. is strikingly similar, morphologically speaking, to the one found in the present experiment. These authors found two factors underlying the negative afterwave, whereas the present results indicate only one. This is probably due, however, to the fact that their PCA was performed on a matrix including data from all electrodes. Since the scalp distribution of the early and late parts of the afterwave differed, two independent factors have turned out. It is possible that, due to the coarse resolution of the measuring windows used in the present task, PCA just did not succeed in separating the two factors. Finally, it might also be that the putative underlying factors were strongly correlated at the Cz electrode and so were represented at the scalp as a unique process. Whatever the reason is for the wholeness of the negative afterwave at the Cz electrode in this task, a rational analysis indicates that more than one cognitive process might have taken place during this period between stimuli.

The negative afterwave factor comprises the end portion of the response to individual stimuli. Its activity starts shortly after the P3 peak and goes on increasing till the occurrence of the next stimulus. The pattern of its factor scores somewhat parallels that of the P3 factor, an increase in negativity of the former being generally matched by an increase in positivity of the latter. Such a covariation

between P3 and a succeeding negative slow wave was also noted by Rorhbaugh and colleagues (1978, 1979). The timing of this process as well as its relation to the eliminative strategy make possible its interpretation in terms of updating of context and of the preparation which bases itself on it. Following the elimination of possible classification criteria, some form of updating must occur which will orient the preparation necessary to process the upcoming stimuli more effectively. The preparation process can be considered as an alloy of two subcomponents. It is proposed that the level of preparation toward the next stimulus is determined jointly by the predictability of the upcoming stimulus and by the expected difficulty of processing it. The necessary preparation level can be intuitively computed by the subject during the task, on the basis of current stimulus content and location. Through the use of such information, the subject can prepare a more selective processing of the event to come next, therefore effectively economizing effort.

Owing to the B-b measurement which was entered in the PCA along with the other dependent measures, an additional factor could be derived whose activity covers each sequence in its entirety. This factor is not affected by the contents of specific stimuli, but rather only by their location in the sequence. Its activity goes on increasing across each train, irrespective of the specific work executed on individual stimuli. The direct relation of this factor to the

general slant affecting the whole waveform warrants its labeling as a "CNV factor". Cooper et al., (1978) have proposed that the CNV might index a "scopeptic" mode of action, in which the subject is selectively involved with a particular set of circumstances which require at their end point some decision or action. During the course of this process a continuous interaction with the environment is possible so that modification of the final response can occur at any time. Similarly, Picton et al., (1978) have proposed that the CNV might manifest the general organization of perceptual information that leads to appropriate behavioural response. In a preliminary presentation of the present results we have proposed (Perrault and Picton, in press) that the CNV might reflect some supervisory process controlling the more elementary stimulus evaluation procedures. It is intuitively appealing to think of the CNV in this task as a "binding" factor. Several studies using a paired associate learning paradigm have pointed out to the CNV reflecting in its amplitude the association strength between stimuli (Walter et al, 1964; Peters et al, 1977; Proulx and Picton, in press). In the present experiment the CNV factor might therefore reflect the exertion of mental effort (Cf. Kahneman, 1973; Pribram and McGuinness, 1975) necessary to link the stimuli together, or in other words, to keep them simultaneously in the focus of consciousness so that the work of pairwise comparisons upon which the whole task is based can

take place. Another explanation of the CNV factor in terms of expectancy for task-closure cannot however, be ruled out on the basis of the present results.

Concluding statement

This experiment was designed to evaluate the evoked potential during a task which would tax appreciably the subjects' cognitive abilities, while reducing to a minimum the option for alternate strategies. This was successful and interpretable results were obtained. Evoked potential components related to memorization, evaluation of goal-relevance and preparation were proposed. The characterization of the amount of processing occurring is not clearcut, particularly for the last two processes. Further delineation of the type of processing indexed by the P3 component may come through better time-locking of the molecular processes comprising stimulus analysis. This goal could be approached by reducing the internal complexity of the stimuli, i.e. eliminating the conjunctive aspect of the stimuli dimensions. This would effectively reduce the difficulty level without affecting the formal complexity of the task. Some means would have to be found to control the variability of perceptual strategy in simple tasks.

On the basis of the present results the occurrence of several interrelated cognitive processes has been hypothesized. This provides a basis for theoretical guidance of

further research. The ability of the P3 component to characterize hierarchical levels within a problem-solving strategy, and the hypothesized interaction of factors underlying the negative afterwave must be further investigated. Similarly, the nature and functional significance of the "P2" component must be ascertained. As with many experiments, this one poses more questions than it answers. Sometimes, however, unsolved problems are more important than answered questions.

FIGURE LEGENDS

Figure 1. Examples of Sequence Types. Each row consists of four figures which were presented successively during the experiment. Roman numerals refer to the six different types of sequence. The solution to each problem as well as the location (slide number) at which this solution could be found are given on the right-hand side of the figure. Dotted and plain areas were red and yellow, respectively, in the experiment. If we take, for example, sequence number II, we see that the first slide has its dimensions characterized as follows: circle inside square (shape), yellow inside red (colour) and thin inside thick (line). The second slide brings changes to the colour dimension (red inside yellow), thereby permitting the elimination of this dimension as a possible classification criterion. Similarly, the third slide changes the shape dimension (square inside circle). At this point only line has remained unchanged, which is necessarily the classification criterion. The fourth slide will bring no further change. The correct answer to that trial is "Line at slide no. 3". In sequences II, IV and V, two steps are required before reaching solution, whereas in sequences I, III and VI, one step only is needed (two dimensions varying at the same location).

scale used for all factors is arbitrary with positive up; the baseline corresponds to the mean (0) of the factor scores. An examination of graph no. II, for example, reveals the P3 factor to be most active at slides 2 and 3, which is where information was delivered. Factor 2 (P2) is highest at the first slide, and quite low at the other slides. Factor 3 (B-b or CNV) decreases regularly from slide 1 to 4. Owing to the way measurements were taken (the results of the subtraction being always negative), this is indicative of a gradual increase in negativity of the waveform across the trial. Comparing these graphs with the corresponding exemplar sequences of figure 2 will provide a clearer understanding of the results.

Figure 5. Factor Loadings and Scores for Second PCA.

(A) This analysis was based on the responses to the first three stimuli only. The mean amplitude measurements corresponding to the negative afterwave have been added (B through E), and an additional factor turned out (Factor 2).

(B) This new factor is represented by a "dash-dot" line in the plots of part B. The interpretation is otherwise similar to that of figure 4.

Figure 3. Grand Averages. Evoked waveforms recorded at the Cz electrode and averaged over 10 subjects. Negativity is indicated by an upward deflection. Roman numerals indicate the type of sequence which elicited the waveform. Only the general baselines have been traced. The bottom line describes the temporal relationships between events. A self-initiated warning click (WC) was followed one second later by a train of four slides (S1, S2, S3, S4) coming every 2.2 seconds. The subject's response, occurring one second or more after the last slide, was followed 500 ms later by a feedback tone if it was correct. Feedback potentials are given on the right-hand side of the figure.

Figure 4. Factor Loadings and Scores for First PCA. (A) Factor loadings derived from the first PCA are graphed across the various dependent measures taken on the waveform. Latencies at which the amplitudes were taken are given in the text. Discrete horizontal lines indicate that the measurement was of the mean amplitude within the corresponding latency bracket. B-b was also computed from mean amplitudes. Otherwise, peak amplitudes were used. The scale is arbitrary with positive up. Percent of total variance explained by each factor is given on the right. (B) Factor scores at each slide location for all six types of sequence (I-VI). Type of line differentiates between Factor 1 (plain line), Factor 2 (dashed line), and Factor 3 (dotted line). Stimulus number is indicated below the baseline. The common

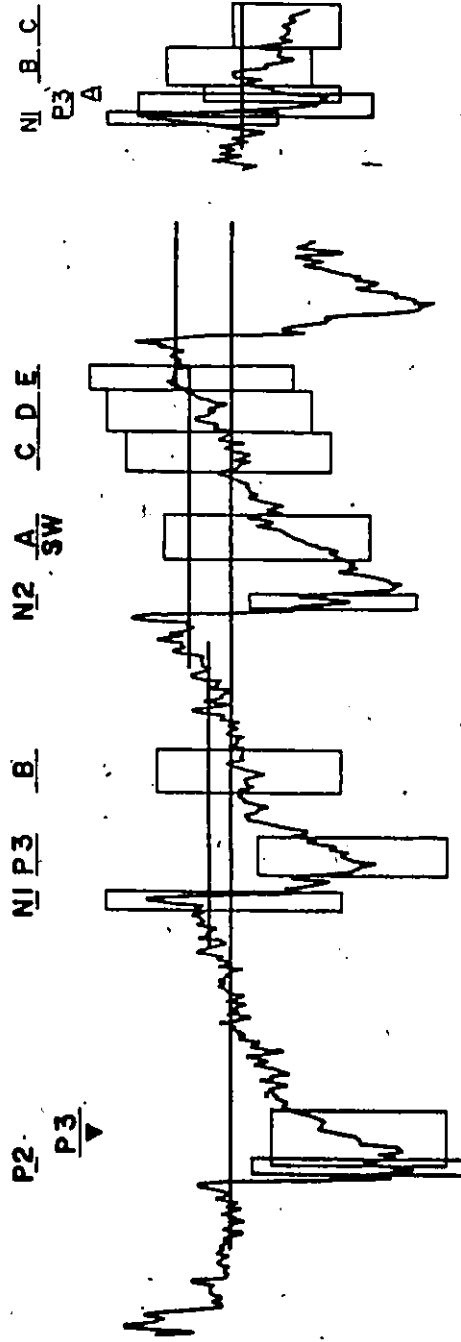
Figure 2. Dependent Measures. The various windows within which peak or mean amplitude was measured are illustrated here. Limit latencies are given in the text. Height is arbitrary. For visual clarity, the windows have been spread over four stimuli. In reality, all windows were used at each of the first three stimuli, yielding 11 dependent measures (10 windows plus the B-b difference). The fourth stimulus yielded only 7 dependent measures (6 windows plus the B-b difference). Notice the increasing difference between general and individual baselines across the sequence. Above each window is the label for what was measured. The first P3 window (arrow) was used in locating and measuring the P3 peak. The second one was used in determining the mean amplitude of the waveform at this location. The labels "SW" and "A" correspond to the same measurement. The first was used in PCA-I and the second in PCA-II. On the right, the windows used for the feedback evoked responses are illustrated. The bottom line indicates the timing of events from the warning click (WC) to stimulus 4 (S4). Then comes the feedback tone. The precise latencies of occurrence of these events are given in the legend of figure 3, as well as in the text. The waveform used for this figure is from subject G.P., at the Cz electrode. It corresponds to sequence no. IV, and is the average of 62 individual responses.

PROBLEM

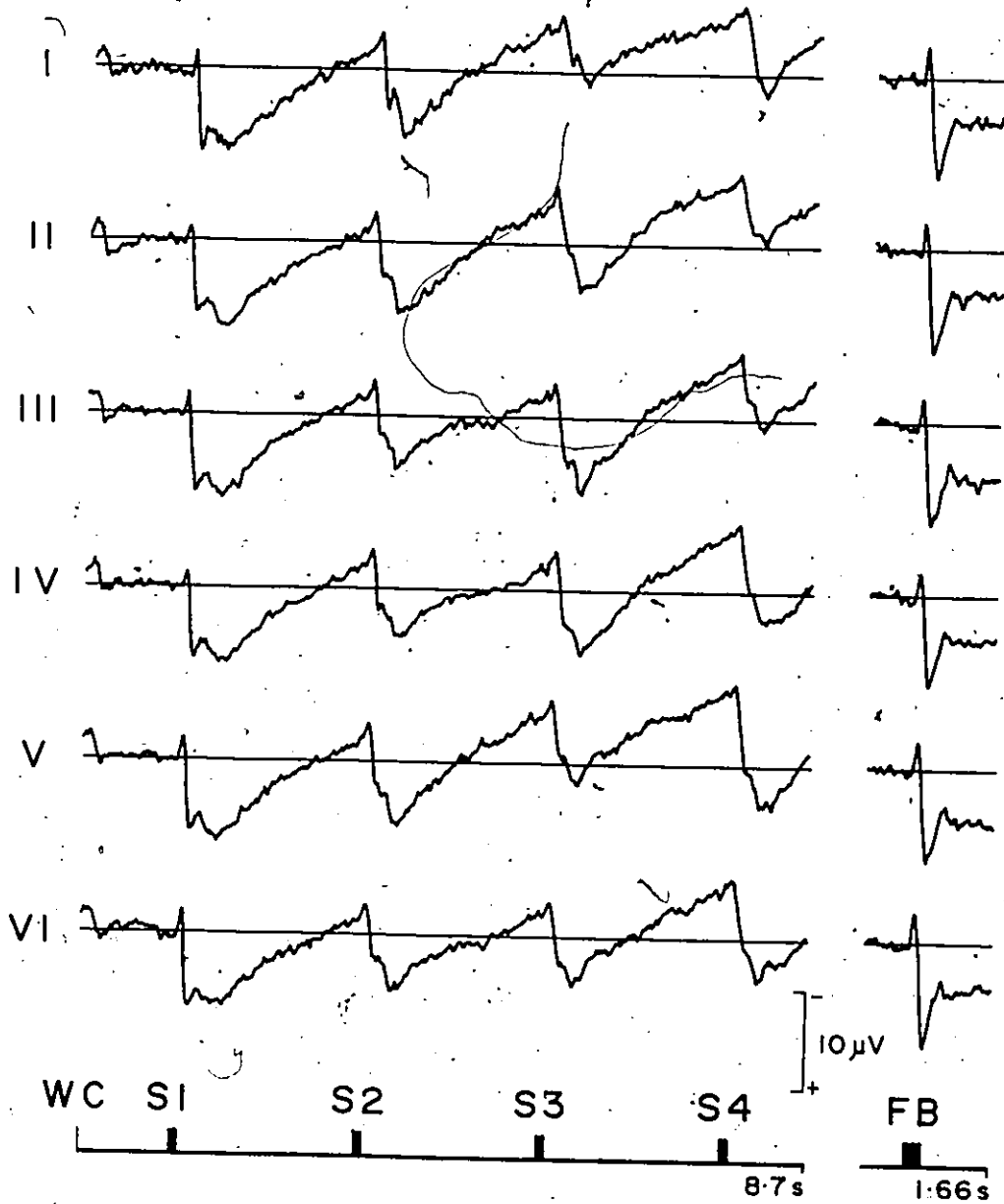
SOLUTION

I					SHAPE-2 square inside square
II					LINE-3 thin inside thin
III					COLOR-3 red inside red
IV					SHAPE-4 square inside circle
V					COLOR-4 yellow inside red
VI					LINE-4 thin inside thick

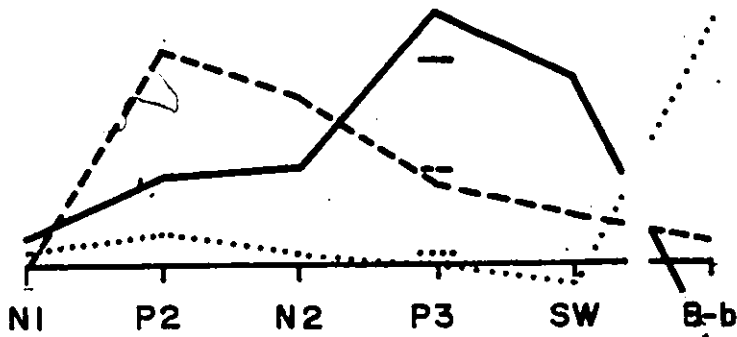
DEPENDENT MEASURES



GRAND AVERAGES (Cz-10 subjects)

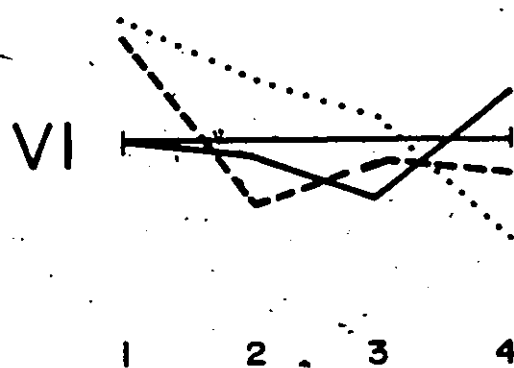
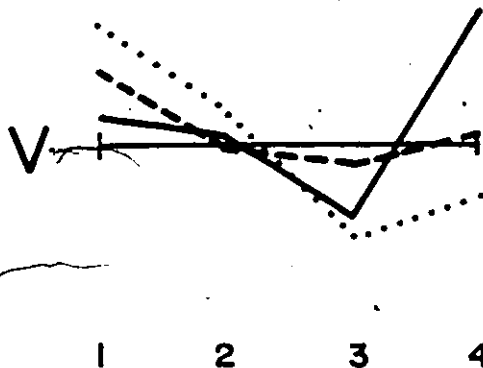
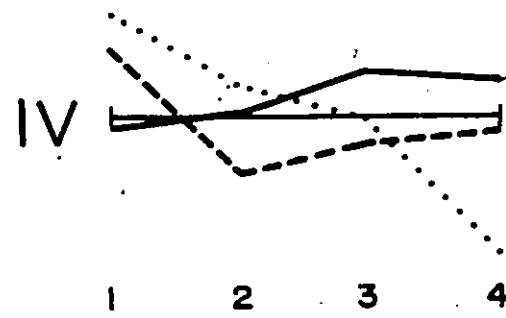
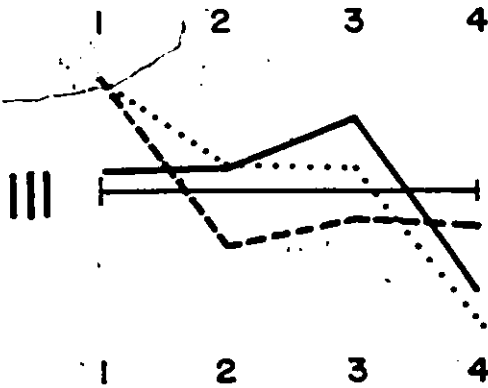
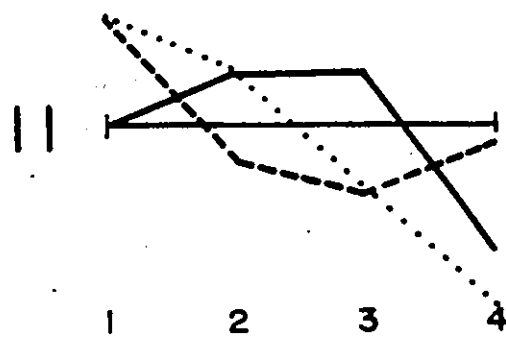
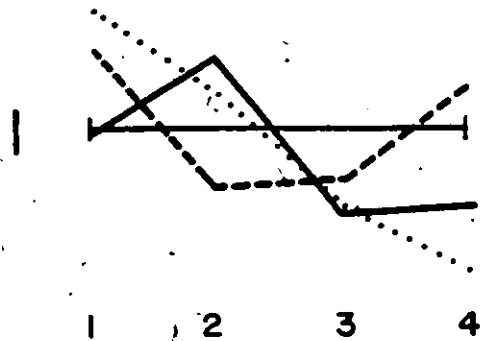


A - FACTOR LOADINGS

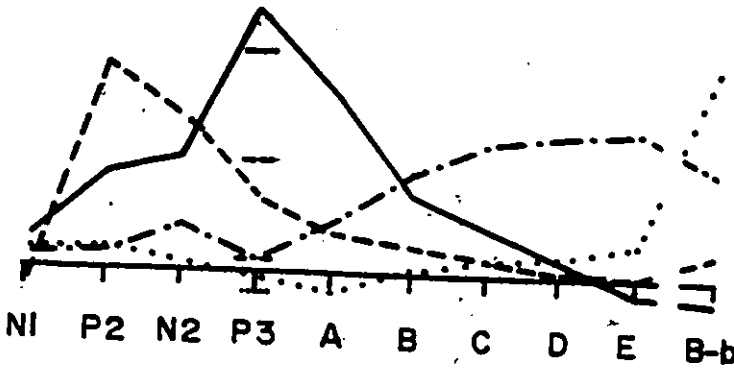


FACTOR	% VAR
— 1	43.4
- - - 2	24.9
..... 3	16.4

B - FACTOR SCORES

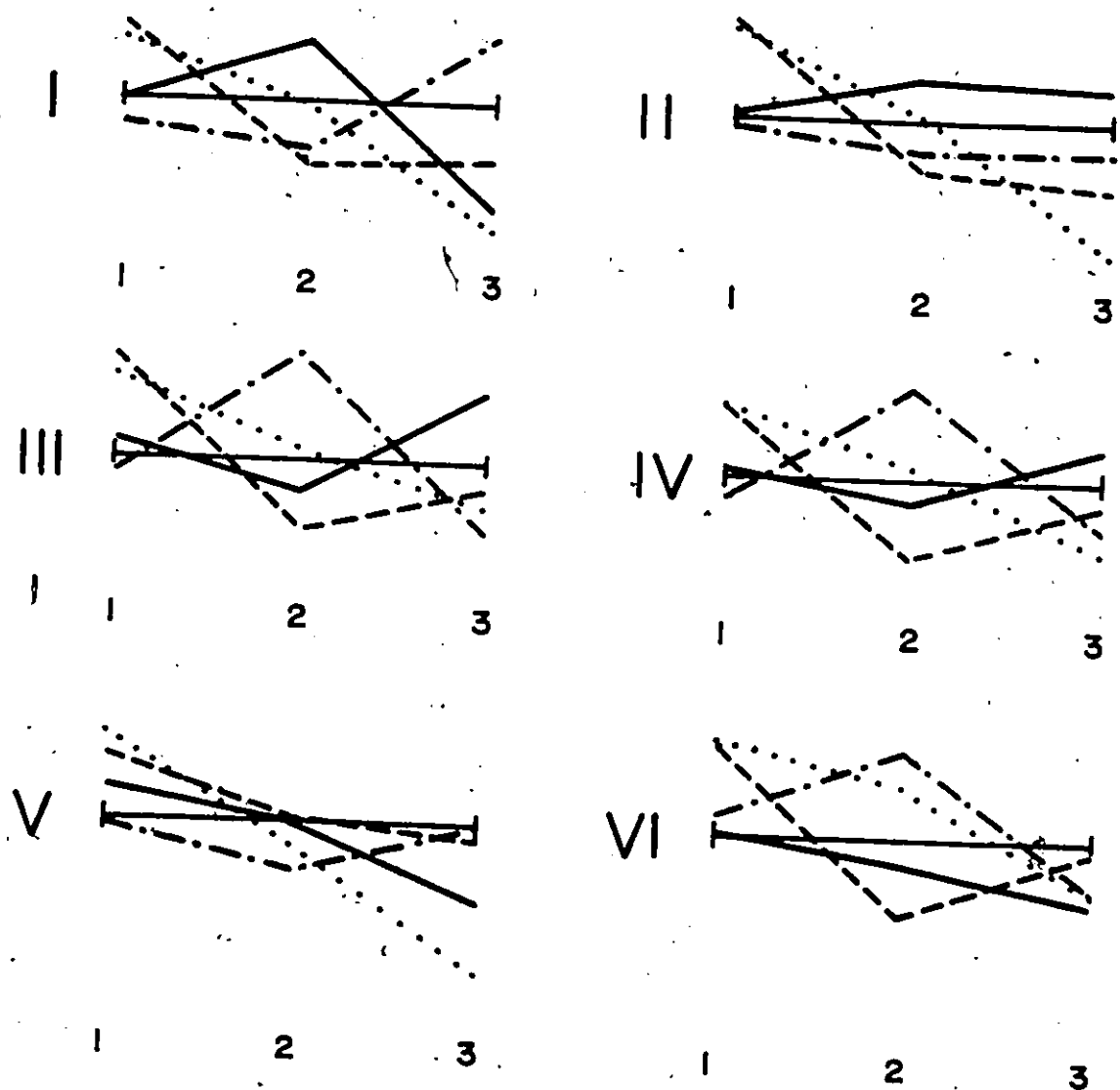


A - FACTOR LOADINGS



FACTOR	% VAR
—	40.6
- - -	19.1
- · - ·	17.8
·····	10.4

B - FACTOR SCORES



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