FUNCTIONAL LANDSCAPES OF THE BRAIN: AN ELECTROTOPOGRAPHIC PERSPECTIVE

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The title "Functional Landscapes of the Brain" was borrowed from a particularly elegant study of regional cerebral blood flow changes during cognitive performance by Ingvar and Risberg (1967). Ingvar and colleagues (Risberg and Ingvar, 1973; Ingvar and Schwartz, 1974; Ingvar et al, 1975a) used radioactive xenon to monitor the metabolic regulation of cerebral blood flow (rCBF) which was regionally specific and accompanied problem solving and abstract thinking (Ingvar and Risberg, 1967; Risberg and Ingvar, 1973), voluntary hand movements (Ingvar et al, 1975a), speech and reading (Ingvar and Schwartz, 1974), and electrical cutaneous stimulation (Ingvar et al, 1975b). This work represents the first comprehensive quantitative topographic analysis of regionally specific physiological changes accompanying higher mental activity.

However, a major drawback of blood flow methods is that temporal resolution is on the order of seconds. In contrast, the method of evoked potential (EP) analysis offers the possibility of studying topographic correlates of mental activity on the order of milliseconds. The advantage of finer time resolution lies in the fact that those vital processes intermediate between the presentation of information and the final motor output can be brought under closer scrutiny. As discussed elsewhere (Thatcher, 1976), this is one of the major advantages of electrophysiological tests in contrast to psychometric tests. That is, only electrophysiological measures allow for the dissection of the millisecond transformations of sensory information to higher levels of cascading cognitive processing which occur before motor output and are fundamental to correct and adaptive performance.

In the present paper, preliminary attempts to develop an

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"Electrotopographic Task Analysis" (ETA) will be presented. This approach involves applying multivariate statistics to evoked potentials obtained during the performance of cognitive tasks. The full spectrum of multivariate techniques have not, as yet, been applied. This must await further study. However, the novel use of the varimax factor analysis will be emphasized as a method to dissect early (0 to ≈ 250 msec) and late (≈250 to 700 msec) evoked potential components which are specific to various aspects of cognitive performance and show regional specificity.

THE NEUROCOGNITIVE TEST BATTERY

The present chapter addresses itself to the application of evoked potentials in active task challenges. The work presented in this chapter dates back to 1973 where the "Background Information Probe" (BIP) paradigm was first presented at a conference on "Behavior and Brain Electrical Activity" (Thatcher and John, 1975).

BIP is a general procedure designed to control for background excitability states that precede and follow information delivery (Thatcher, 1977a). The procedure, which is illustrated in Figure 1, involves the presentation of a variable number of random dot displays (controls), then an information stimulus (the standard,

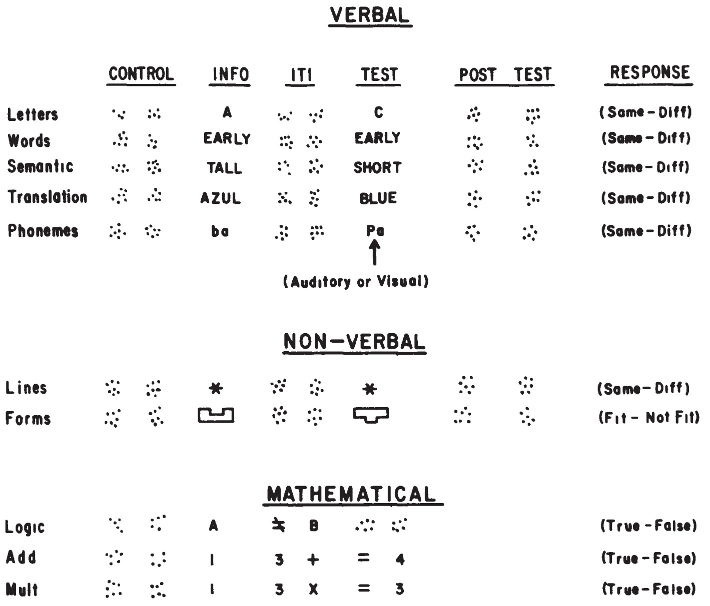

Fig. 1. Examples of items in the Neurocognitive Test Battery

e.g. a letter or word) followed by a second series of random dot displays (intertest interval or ITIs) followed by a second information stimulus (test stimulus) that matches or mismatches the standard. In some of the tasks a third series of random dot displays are presented following the test stimulus in order to further investigate excitability changes as well as to delay responses so as to avoid contamination by movement artifact. All of the displays within a task are equal in duration (20 msec), intensity, and in retinal area subtended (foveal). The interstimulus intervals are typically 1 second but can be varied. Intertrial intervals are usually 4 seconds during which subjects differentially respond to match (same), mismatch (different) and, in some tasks, an uncertain, no operation or neutral condition. A more detailed description of the procedure is presented elsewhere (Thatcher, 1976; 1977a).

It should be emphasized that this is only a prototype test battery. To date, subjects have been run on the letter and word matching tasks, the synonym and antonym task, the Spanish-to-English and English-to-Spanish task, the logic and mathematical tasks, and the form matching tasks. The complete battery has not, as yet, been standardized on a population of normals. Given the difficulty in obtaining government funding this test battery may never be applied in its entirety. It is presented here to illustrate and describe an hypothesized approach to neurocognitive assessment, namely, an evoked potential active task challenge that contains procedural invariants as controls that, theoretically, facilitate diagnostic and prognostic assessment. It can be seen in Figure 1 that all of the various tasks share the general cognitive challenge of delayed matching to sample. That is, a general demand on a subject's attention, the maintenance of the memory of the standard display and a subsequent comparison (sometimes at a concrete level and sometimes at more abstract levels) is required in all tasks. The aim of the test battery is to provide a series of tasks which are short in duration and thus not overly fatiguing and which challenge different aspects of cognitive function involving ascending or descending levels of complexity. Each of the tasks require a subject's continual attention since the subjects cannot predict exactly when the information display will occur. Examination of AEP variance to the random dot control stimuli may help in assessing attention fluctuations. Attention can also be assessed by separately averaging all the EPs elicited on correct trials in comparison to incorrect trials (this assumes that the subject's attention is needed for greater than chance correct performance).

The procedural invariants are an integral part of the test battery and are designed to maximize the following comparisons: 1) Within-Subject-Within-Task Differences; 2) Within-Subject-

Between-Task Differences; 3) Between-Subject-Within-Task Differences; 4) Between-Subject-Between-Task Differences. The first set of comparisons are between the AEPs elicited by succeeding random dot displays that precede information. This represents the control differences which yield information about within subject variance. As will be shown later (see fig. 2), stable and reproducable control AEPs facilitate the interpretation of the varimax factor analysis. Other Within-Subject-Within-Task differences are between AEPs elicited by identical random dot displays that precede and follow the standard stimulus (during the rehearsal period, see Thatcher, 1976; 1977a; 1977b), between AEPs elicited by the standard stimulus and physically identical test stimuli, and between AEPs elicited by test stimuli that match the standard stimulus in comparison to identical test stimuli that mismatch. These and other comparisons in the delayed letter matching task are shown in Table I.

The Within-Subject-Between-Task analyses involve differences within a subject for control, standard, ITI and test conditions across tasks. These comparisons can provide important information about changes in AEP component latencies and anatomical topography which occur as a function of the nature of the task (Thatcher, 1976).

The Between-Subject-Within-Task analyses involve first computing the Within-Subject-Within-Task differences and then comparing any individual subject with any other subject or any individual with the group mean (of the same age or a different age). Z transforms can be used, for instance, to compare the changes between control and the standard stimulus or between the standard and test stimuli, etc., for an individual with respect to the group mean. In this way, differences in "cognitive style" may be revealed as groups or clusters within the normal population (sometimes with membership = 1) as well as statistically significant deviance from normal in one or more scalp locations which may be related to a disability. Of course, large Ns and careful assessment of variance is necessary to adjust statistical thresholds so as to minimize false positives and false negatives.

The Between-Subject-Between-Task comparison is similar to the previous analysis but involves computing a difference across tasks for an individual with respect to any other individual or group. This analysis may eventually help in providing relevant neurophysiological information about a subject's strengths and weaknesses in cognitive function. Again, large Ns and replications of the discriminate functions are needed to establish the full diagnostic effectiveness of this approach.

It is believed that the meaningfulness of these various comparisons are maximized by the procedural details of the paradigm

Table I: AEP COMPARISONS THAT DISTINGUISH "CONTENT" vs "OPERATION" [a]

CONTROL ANALYSES	OPERATION IS CONSTANT WHILE INFORMATION VARIES	INFORMATION IS CONSTANT WHILE OPERATION VARIES
Control$_1$ AEP vs Control$_2$	"A" Standard AEP vs "B" Standard	"A" Match AEP vs "A" Mismatch
Control$_1$ AEP vs ITI$_{1-n}$	"B" Standard AEP vs "C" Standard	"B" Match AEP vs "B" Mismatch
Control$_1$ AEP vs Standard (A,B,C)	"C" Standard AEP vs "A" Standard	"C" Match AEP vs "C" Mismatch
Control$_1$ AEP vs Match (A,B,C)	"A" Test AEPs vs "B" Test AEPs	"A" Standard AEP vs "A" Test
Control$_1$ AEP vs Mismatch (A,B,C)	"B" Test AEPs vs "C" Test AEPs	"B" Standard AEP vs "B" Test
	"C" Test AEPs vs "A" Test AEPs	"C" Standard AEP vs "C" Test

itself, that is, the use of psychophysically controlled stimuli, unpredictable stimulus contents and the invariance of the operations of delayed matching invoked in different cognitive tasks. Also, the fact that the procedure requires attention,is interesting to subjects, and minimally fatiquing, helps reduce variance which, in turn, enhances meaningful comparisons.

Another important factor, unique to these procedures, is that stimuli are not presented repeatedly or redundantly. For instance, in the synonym-antonym task (Thatcher, 1977b), 48 different words are presented in a session and subjects are run on only two sessions. In the logic task the letters A, B, C and D are presented but in continually different logical contexts (Thatcher and Maisel, unpublished). Thus, habituation of the content of specific stimuli and redundancy in general is minimized.

Finally, the technique of embedding information within a series of meaningless stimuli should be discussed. The study of background excitability changes using non-contingent probes presented in the same or a different modality is a widely used technique in human and, particularly, animal research (Gershuni et al, 1960; Kitai et al, 1965; Morrell and Morrell, 1965; Khachaturian and Gluck, 1969; Ciganek, 1969; John et al, 1973a; Hudspeth and Jones, 1975). A number of studies (Gastau et al, 1957; John and Killam, 1960; Khachaturian and Gluck, 1969; Khachaturian et al, 1974) and, most recently, a particularly elegant study by Hudspeth and Jones (1975) report systematic changes in the coherence of anatomically distributed electrode sites during conditioning. These changes were complex, often involving regionally specific increases or decreases in coherence. As hypothesized more fully elsewhere (Thatcher, 1976; Thatcher and John, 1977) background neural excitability states represent the initial state from which trajectories of information flow originate. For this reason, it is believed that attempts to quantitize or measure EP waveforms to non-contingent probes is a necessary and vital adjunct to the understanding of the brain's response to information.

APPLICATION OF VARIMAX FACTOR ANALYSIS

The historical development of the field of human electrophysiology illustrates the frequent controversies that occur as a new science or scientific technique emerges. The application of orthonormal systems of equations (such as exponential, fourier, walsh analysis, etc.) and multivariate statistics to the analysis of EP data is one example of where controversy still exists. The methodological details and advantages of the application of these methods to EP data analysis, however, is beyond the scope of the present chapter. Several excellent reviews of this subject are available (Glaser and Ruchkin, 1976; John et al, 1977). Suffice it to say, that different procedures are suitable for different purposes and often involve different assumptions about the natural structure of the data. At this early stage of development it is our strategy to be open to any and all methods of analysis and not to purposely exclude any one or, conversely, to use only one method. However, in comparison to peak-to-peak or baseline-to-peak EP component analysis, there are several distinct advantages to the use of multivariate statistics. One, is that peak-to-peak or baseline-to-peak component analysis implicitly emphasize the independence of the EP components. In contrast, multivariate statistics (such as factor analysis and discriminant analysis) emphasize the covariance of the sequence of time points that comprise the EP. The multivariate approach assumes ignorance of the independence or dependence of the various EP components and asks, simply, which set of covarying time points are distinguishable from other sets of covarying time points. Another advantage of the use of multivariate statistics is that such methods provide for the analysis of large numbers of EPs in a maximally simplistic and parsimonious manner, a feature useful in large population studies.

One method used extensively by the present authors is the varimax rotation of the principal-component axes of the factor analysis (Kaiser, 1958; Harmon , 1967). The varimax rotation has the advantage of facilitating the physiological interpretation of the factors since an AEP tends to have a high coefficient for only one factor, and each factor has zero, or near zero, coefficients for at least some of the AEPs. This minimax constraint tends to produce a type of cluster analysis in which a set of AEPs, with shared waveform characteristics, load maximally on one factor and contribute minimally to any other factor (see John et al, 1973b Thatcher and John, 1975; Thatcher 1976; 1977a; 1977b).

The computer program that we use[1] provides the option of performing the factor analysis on a set of amplitude normalized AEPs. The normalization process, which involves setting the total variance of each AEP equal to unity,[2] constrains the factor analysis such that differential loadings on orthogonal factors <u>occur as a function of AEP waveshape, independent of amplitude</u>. Averaged EPs which differ only in amplitude may suggest a quantitative difference in function but not a qualitative difference. That is, increased amplitude represents either an increase in the number of generators (e.g. glial cells and/or neurons) or greater synchrony with equal population size (Thatcher and John, 1977). AEP waveform changes, on the other hand, reflect alterations in the spatiotemporal distribution of active generators which indicate a qualitative, and not simply, a quantitative difference in function.

An example of the results of varimax factor analysis of amplitude normalized AEPs from the delayed letter matching paradigm is shown in Figure 2. The top row of waves are AEPs from the various conditions of the letter-matching experiment (controls, standard, ITIs and test). The 4 waves in the column on the left are the orthogonal factors, which in this case accounted for 93% of the variance of all the AEPs. The first factor is called a control factor because it loads primarily on AEPs elicited by the random dot controls (the factor loadings on the AEPs are represented by scaling the amplitude of the factors by their weighting coefficients, see Thatcher and John, 1975 for details). The second factor is called a post-information factor because it loads undifferentially on all information bearing stimuli (Info, Diff. and Same). The third factor is called an information factor since it differentially loads on the first letter and the matching test test stimulus but not on the mismatching test stimulus. And

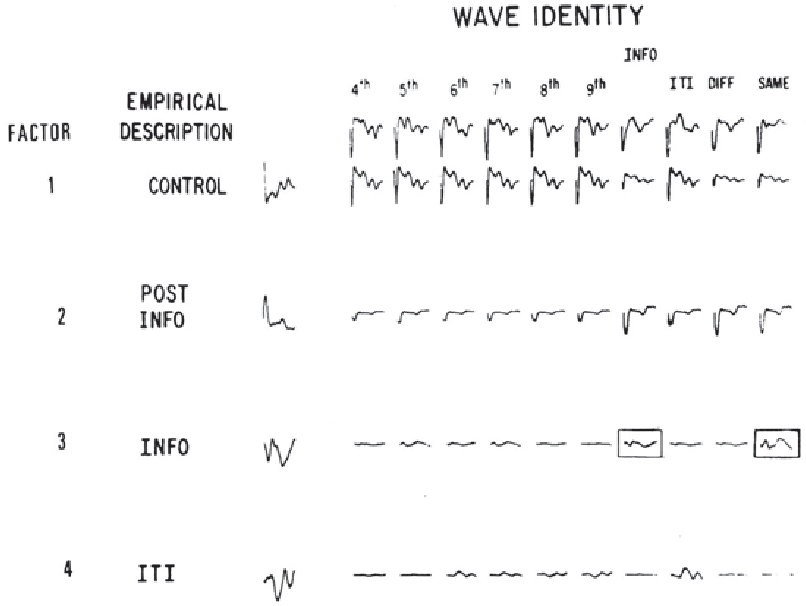

Fig. 2. The top are AEPs (N = 52 for all AEPs except same and different AEPs where N = 26) starting with the fourth control display and extending to the test. The four factors (accounting for 93% of the variance) are in the first column of waves on the left. The empirical description of factors was determined by the relative contribution of a factor to a specific variable of the experiment. Note that the information factor (factor 3) loads heaviest on the AEP produced by the information display and on the AEP elicited by the test stimulus that "matches" (same) the standard display but not on the AEP elicited by the "mismatch" (diff) stimulus. Factors are inverted because they are negatively correlated (from Thatcher and John, 1975).

finally, the fourth factor is called an ITI factor since it loads on the first ITI. Thus, orthogonally different factors loaded on AEPs which were determined by the critical variables of the experiment.[3]

The results of the varimax factor analysis in Figure 2 represents a "within derivation" analysis. That is, all of the AEPs were from one derivation (O_1) but were elicited by different stimulus conditions. Another method of analysis involves a "between derivation" factor analysis. That is, AEPs obtained simultaneously from all derivations but for only one stimulus condition at a time. The latter analysis is important since it provides topographic information. An example of such an analysis is shown in Figure 3. This analysis was performed on AEPs elicited in the logic task.

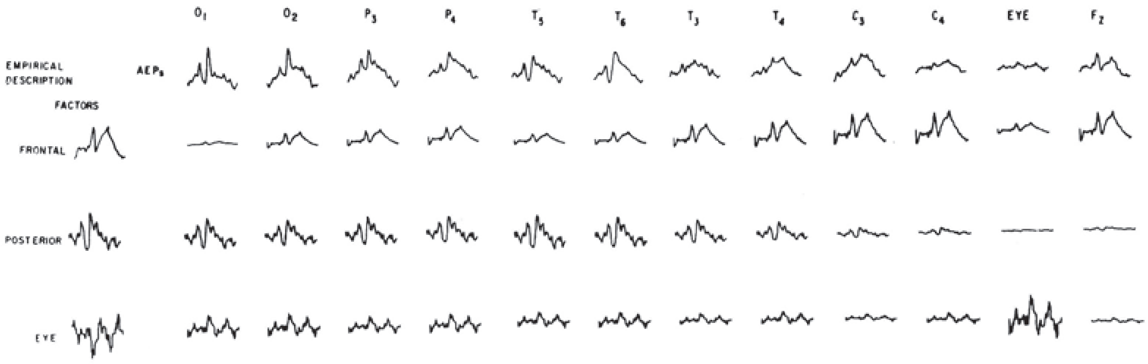

Fig. 3 Top row are AEPs (N=24; analysis epoch = 786 msec) from 12 different derivations elicited by random dot stimuli in the logic task. The three factors (column on left) account for 96% of the variance. Factor loadings are represented by amplitude scaling of the factor waveshapes. The first factor is called a "frontal factor" since it loads most heavily on frontal derivations (T_3,T_4,C_3,C_4,F_z); the second factor is called a "posterior factor" since it loads most heavily on posterior derivations (O_1,O_2,P_3,P_4, T_5,T_6); the third factor is called an "eye factor" since it loads most heavily on the eye lead.

The three factors in the column on the left account for 96% of the variance. It can be seen that factor one loads slightly on P_3 and P_4 but heavily on anterior derivations, particularly, T_3, T_4, and C_3, C_4. In contrast, factor 2 loads heavily on the posterior derivations, O_1, O_2, P_3, P_4, T_5 and T_6. Factor 3 is a unique factor loading primarily on the eye lead. In general the eye lead loads on an orthogonally different factor than do the scalp leads (Thatcher, 1977b). Differential factor loadings between match and mismatch AEPs and control and standard and ITI AEPs occur maximally in posterior derivations and are absent or attenuated in anterior derivations (see Figures 6 and 7). These consistent findings show that the various phenomena observed in these studies are not due to eye-movements. Another consistent finding revealed by the between derivation factor analysis (such as in figure 3 and table 2) is an anterior-posterior split or differential factor loadings in the anterior-posterior plane. That is, posterior derivations usually load on one factor while anterior derivations load on an orthogonally different factor (Thatcher, 1976). It has been shown that the anterior-posterior split can be altered, systematically, as a function of the various conditions of the BIP procedure (Thatcher, 1977a; 1977b).

Table 2 shows an example of changes in the anterior-posterior dimension, as well as between homologous derivations in the letter matching paradigm. The anterior-posterior split between factors 1 and 2 at T_3 is seen in the control condition. Note also that in the control condition there is an absence of interhemispheric asymmetries. That is, homologous electrode pairs load on the same factor. However, as seen in Table 2, a markedly different organization appears when information is presented to the subject. That is, interhemispheric asymmetries appear in which AEPs from the left and right hemisphere load on orthogonally different factors. Also, the anterior-posterior split disappears and is replaced by a uniform left side loading. That is, P_3, T_5, T_3 and F_7 all load on the same factor. This analysis suggests a functional organization. That is, there is a change in the topographic organization of AEP waveforms as a function of the presentation of information and this change involves an increased commonality of waveform across widely distributed, but lateralized, scalp regions. It is important to note that the interhemispheric asymmetries in table 2, which occur to the presentation of information, represent asymmetries in AEP waveform independent of amplitude. Thus, with this analysis the functional topography can be studied in terms of either amplitude changes or changes in AEP morphology.

LOGIC OF NEGATION AND EQUIVALENCE

There are many different logical systems. For example, there is the classical Aristotelian logic, single valued logical systems

TABLE 2
BETWEEN-CONDITION VARIMAX FACTOR ANALYSIS[a]

Derivations	O_1	O_2	P_3	P_4	T_5	T_6	T_3	T_4	F_7	F_8	EYE	F_z
Control Factors												
1	0.89	0.88	0.65	0.85	0.67	0.46	0.06	0.40	0.06	0.06	0.00	0.06
2	0.06	0.04	0.15	0.07	0.11	0.05	0.63	0.44	0.91	0.83	0.34	0.67
3	0.00	0.00	0.00	0.00	0.06	0.03	0.29	0.02	0.00	0.02	0.00	0.10
4	0.00	0.00	0.01	0.00	0.02	0.06	0.01	0.00	0.00	0.01	0.65	0.01
First Letter Factors												
1	0.90	0.96	0.42	0.57	0.22	0.17	0.02	0.08	0.01	0.01	0.00	0.11
2	0.04	0.00	0.35	0.10	0.54	0.18	0.95	0.35	0.90	0.04	0.00	0.28
3	0.01	0.02	0.00	0.07	0.06	0.10	0.00	0.42	0.04	0.95	0.08	0.17
4	0.00	0.00	0.15	0.16	0.07	0.52	0.00	0.06	0.00	0.00	0.14	0.32
5	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.77	0.00

[a] Varimax factor analysis on amplitude-normalized AEPs from 12 derivations for two different experimental conditions in subject D.D. Each row represents the loading of AEPs from different anatomical derivations on a single factor. Each column represents the factor structure for a given derivation. Results show that AEPs from anterior derivations (T_3 thru F_z) load on different factors than do AEPs from the posterior derivations (O_1 thru T_6)

(Lewis and Langford, 1932), doubled valued or probalistic systems (Reichenbach, 1949) and Whitehead and Russell's (1925) axiomatic system. All of these systems rely on the concepts of "sameness" and "difference" including Whitehead and Russell who proved that the foundations of axiomatic mathematics is based on logic. George Boole (1951) developed an algebra based entirely on binary classifications which involve the concepts of "sameness" and "difference". These concepts are unique for having played an important role in the history of psychology, mathematics and physics. Recently, G. Spencer Brown (1973) developed a logical notation which formalized in an elegant manner, the concepts of "sameness" and "difference". For instance, twenty-eight pages of complex notation from the "Principia Mathematica" (p. 98-126) was reduced to a single symbolic statement by the formal application of the concept of difference.

Recognition of the fundamental position of the concepts of sameness and difference led to the development of the test battery in Figure 1. That is, the general operation of representational matching is held constant while the content and complexity of tasks varies across items. Given the importance of logic in the development of cognition, a specific logic task was devised. The paradigm, which is represented in Table 3 (for letters A and B only), involves presenting a variable number of random dot control displays followed by a letter (A, B, C or D), followed by an operation sign (= or ≠ or a no operation ⅃), followed by a second letter (A, B, C or D). The number of illuminated dots is the same for all displays. The displays are 20 msec in duration and

Table 3. True, False, and No Operation (NOP) Statements

Function	First Letter	Operation	Second Letter
True	A	=	A
True	B	=	B
True	B	≠	A
True	A	≠	B
False	B	=	A
False	A	=	B
False	A	≠	A
False	B	≠	B
NOP	A	⅃	A
NOP	B	⅃	B
NOP	A	⅃	B
NOP	B	⅃	A

are presented at a repetition frequency of .66/sec. The subjects are instructed to move a lever to the left if the syllogistic statement is true (e.g. $A = A$; $A \neq B$, etc.), to the right if it is false (e.g., $A \neq A$, $A = B$, etc.) and both left and right in the no operation condition (e.g., A ■ B, A ■ A, etc.). All conditions are counterbalanced, there are 48 trials per session and each subject is run on at least two sessions. In this experiment concordance or disconcordance between letters occurs equally probably. Thus, the letter or perceptual aspect of the match-mismatch procedure is the same as in test item one (see figure 1). The difference in this experiment is that the operator determines whether the second letter matches a logic truth function or not. If matching of internal representational systems contributes to late EP positivity, then one might expect that matching of sensory representations with logic representations would also contribute to late positivity. The no operation condition (NOP) should provide valuable information about logic operations since letter AEPs in this condition can be contrasted with the logic conditions. The subjects were not asked to match letters, although the letters were presented successively as in the delayed letter matching experiment. Seven subjects (5 males, 2 females ranging in age from 23 to 35) have been run thus far. Figure 4 shows AEPs from one subject to second letters in the three conditions (truth, falsity, no operation). It can be seen that the EPs elicited by second letters in the truth condition exhibit greater late positivity than EPs elicited by the same letters in the false and no operation conditions ('t' tests are shown at the bottom of the figure).

An example of AEPs from the various conditions is shown in Figure 5. At the bottom of the figure are AEPs elicited by the random dot controls which can be compared to the AEP elicited by the first letter. The latency and shape of the late components of the AEPs elicited by the operator signs (=,≠ & ■) are different depending on the operation, while second letter AEPs are different depending on the logical condition.

Topographic analyses using the varimax factor analysis reveal different factor structures from different derivations depending on the different aspects of the task. A 3-dimensional representation of these findings is shown in Figures 6 and 7. The vertical axis represents the factor coefficients beginning at .25. The factors are on the left and the various experimental conditions are on the right. These analyses are from the grand averages computed by summing AEPs from all seven subjects. In the occipital derivations (Fig. 6) factor 1, with a pronounced early component, accounts for the variance due to the control AEPs. Factor 2, with a pronounced late component, accounts for the variance due to the letters and operator symbols. Very little variance is accounted

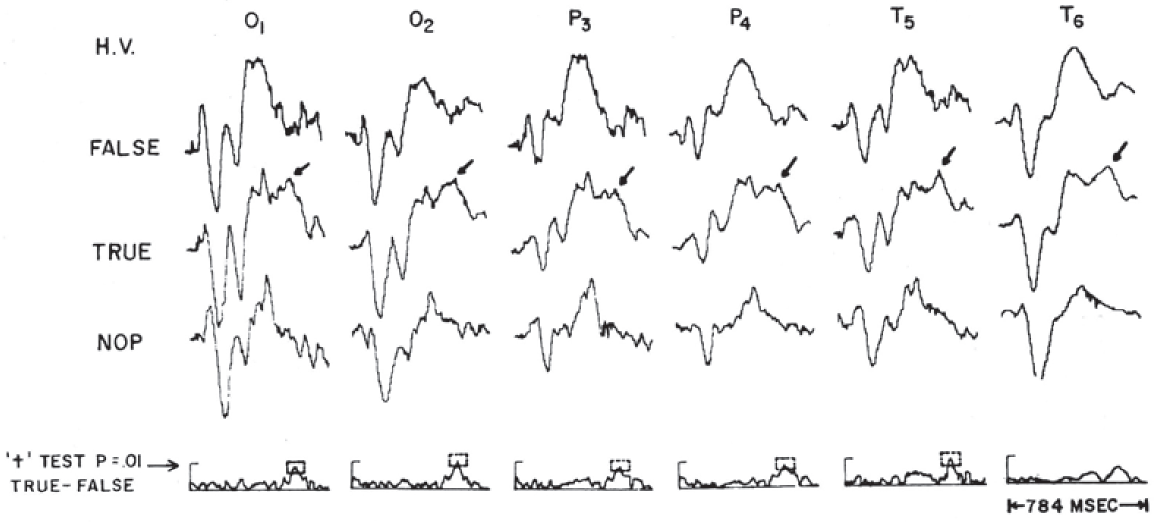

Fig. 4. AEPs (N = 24) from 1 subject elicited by the second letter of a logic statement (truth e.g., A = A; false e.g., B = A; and no operation A ▟ A). t-tests between true and false conditions are shown at bottom. Arrows point to enhanced late positivity. (Horizontal line represents p = 0.01, two-tailed).

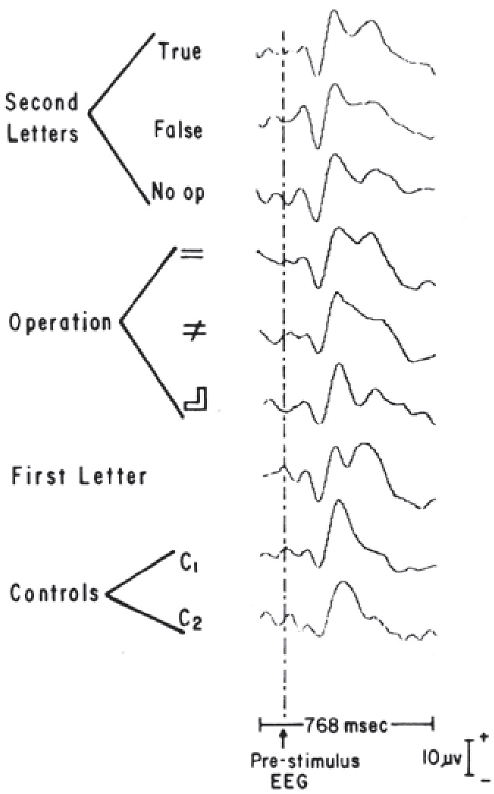

Fig. 5. Example of AEPs from 1 subject (T_5) elicited by the various stimuli in the logic task.

for by factor 3, thus most of the variance due to the various conditions of the experiment is accounted for by two factors. Since the two factors differentiate the response to random dots versus letters and operators, the occipital regions (0_1 and 0_2) are given the functional description of differentiating and formating information input. A somewhat different picture is seen in the parietal and posterior temporal derivations (P_3, P_4 and T_5, T_6). In these derivations the factor analysis differentiates between first letters (factor 2) and second letters (factor 3) as well as between the controls (factor 1) and first and second letters. Accordingly, the parietal and posterior temporal derivations are given the functional description of mediating, primarily, secondary operations since there is a differential loading on orthogonal factors between first letters and second letters and a somewhat different factor structure for operators versus second letters. This type of structure was not observed in the occipital derivations. Note that factor 1, which describes the control space, exhibits an early component, factor 2 a late component and factor 3 a complex early-late complex.

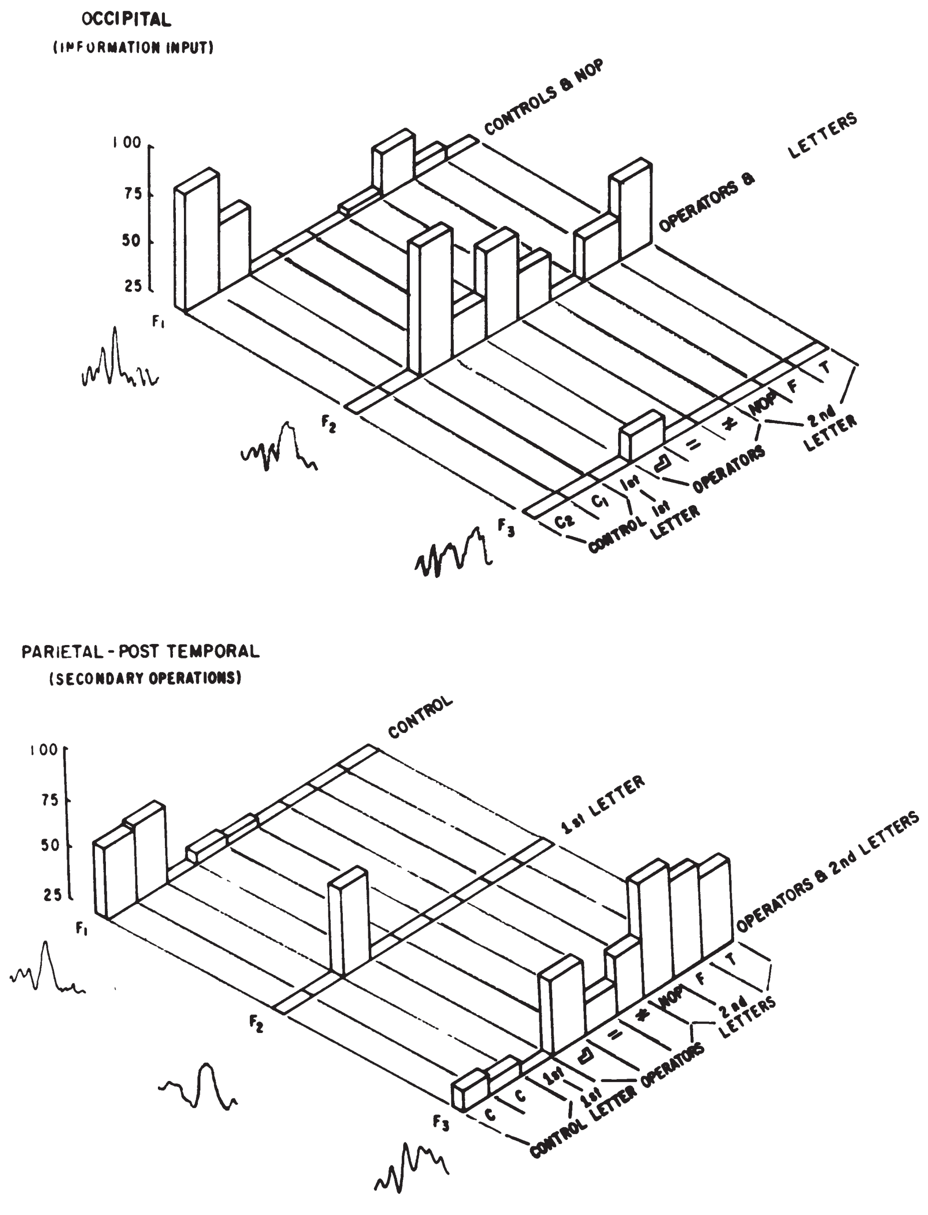

Fig. 6. 3-dimensional display of factor analysis of grand mean AEPs (7 subjects) from two different topographic regions. The conditions of the experiment are represented on the right, the factor waveshapes are on the left and the factor loadings are represented by the height of the bars (beginning at .25). Note that factor differentiation between first and second letters occurs only in the parietal-posterior temporal derivations. See text for functional descriptions.

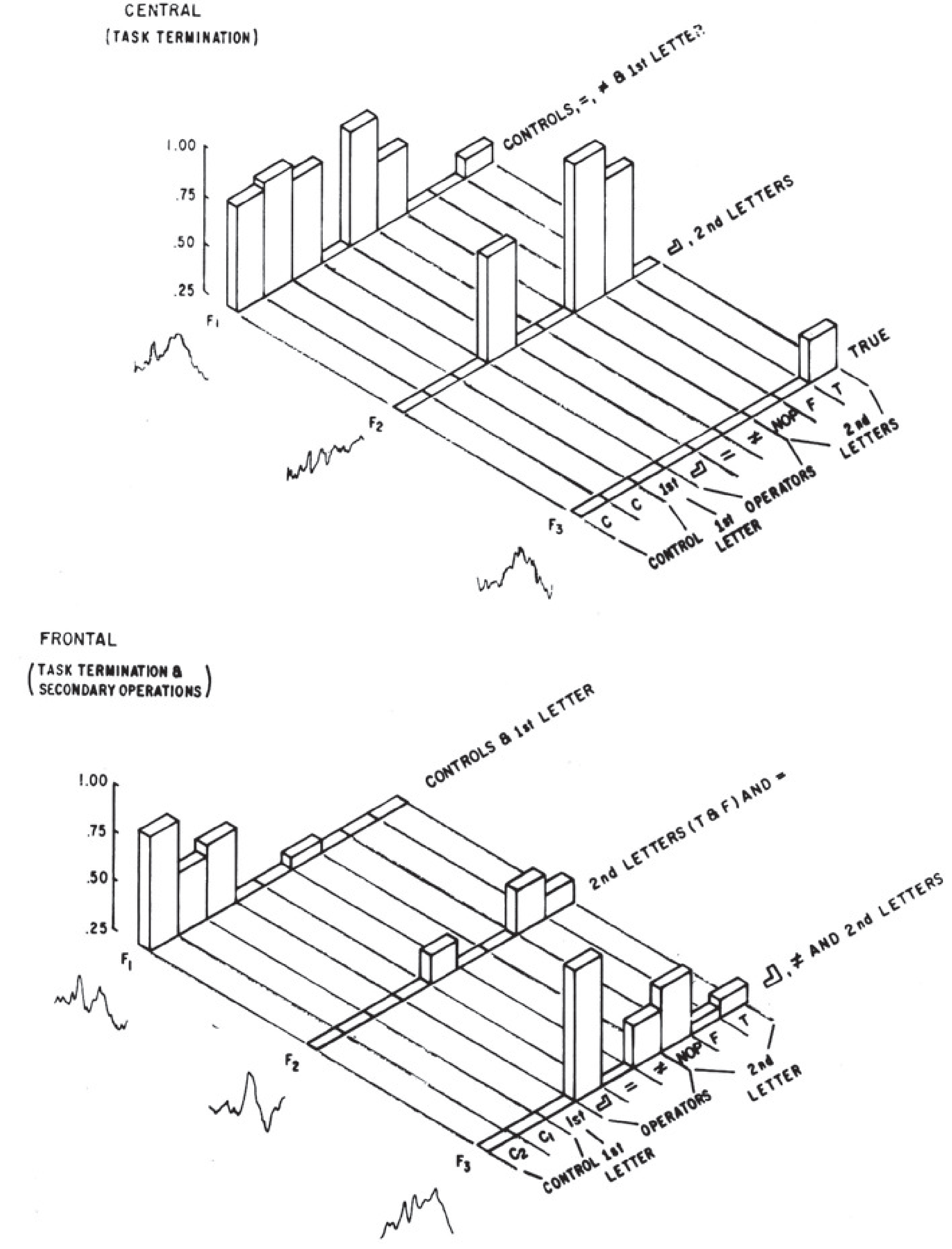

Fig. 7. 3-dimensional display of factor analysis of grand mean AEPs (7 subjects) from two different topographic regions. Explanation of the axes is same as in fig. 6. Note that, in contrast to the analyses in fig. 6, there is no factor differentiation between the random dot controls and first letters in these anterior derivations (i.e., central = T_3, T_4, C_3, C_4 and frontal = F_z). See text for functional descriptions.

A distinctly different factor structure is seen in anterior derivations (Figure 7). For example, in the central derivations (this same basic factor structure was present in T_3, T_4, C_3 and C_4) there is no differentiation (see factor 1) between controls and first letters and the "equals" and "not equals" operators. On the other hand, factor 2 shows heavy loadings for the no operation operator and second letters (NOP and false). In this task the no operation symbol which follows the first letter (◆) "closes" or terminates the task in the sense that the subjects know immediately what their response must be. Similarly, the presentation of the second letters "closes" the task and also determines the subject's response. Thus, the no operator symbol and the second letters have in common task closure or termination. Accordingly, the central derivations (including T_3 and T_4) are given the functional description of mediating task termination or closure.

The frontal (F_z, Figure 7) derivation exhibited a functional structure that was a combination of both the central and the parietal - posterior temporal regions. That is, there was no distinction between first letters and controls. Also, differential loadings occurred to the no operation symbol and the NOP second letter (and somewhat to the ≠). However, some differentiation occurred within the second letters (see factor 2) and between the second letters and the operators.

Thus, in summary, the factor analysis reveals differential AEP loadings according to the critical variables of the task which differ in the anterior-posterior plane. All of the AEPs within an analysis were amplitude normalized and no consistent evidence of interhemispheric asymmetries was observed. These results suggest the feasability of an "Electrotopographic Task Analysis" That is, different regions of the scalp exhibit AEP waveforms that change, differentially, as a function of task demands. The analysis suggests that the occipital regions are involved in information reception, the parietal and posterior temporal regions in secondary and abstract operations, the central regions in task termination and the frontal regions are complexly involved in both central and parietal functions. However, this is not to be interpreted as evidence for strict localization of function since shared functional structures are seen spanning the entire anterior-posterior plane. Also, the data are preliminary in that these particular phenomena were observed in this one experiment and need to be replicated in this and variations of this task. It should be noted, however, that orthogonal factor loadings between controls and words in the synonym-antonym task occur primarily in left side derivations (P_3 and T_5) and not in the right (see Table 4). Also, a complex anterior-posterior shift in shared factors from left side derivations has been noted in both the delayed letter matching experiment (see Table 2 and Thatcher, 1977a) and the synonym-antonym task (Thatcher, 1977b). This suggests that the exact topography is somewhat unique to each task. More work is needed before definitive statements about function can be made.

DELAYED SEMANTIC MATCHING

Another example of the application of BIP is in the delayed semantic task involving synonym, antonym and neutral word pairs. In this task delayed word pairs such as "large"- "little" (antonym), "small"-"little" (synonym), or "down"-"little" (neutral) are presented. There are 36 different first words and 12 different second words in a session of 36 trials. Thus, the same 12 second words are presented in three different semantic contexts with the three semantic conditions counterbalanced across trials (Thatcher, 1976; 1977b). This task requires remembering the first word and then comparing the meaning of the second word.

Figure 8 shows an example of AEPs elicited by first words, random dot controls and second words. In this experiment only synonyms and antonyms were presented. The AEP response to the first words (top row) was confined largely to occipital and parietal derivations. A similar anatomical distribution was elicited

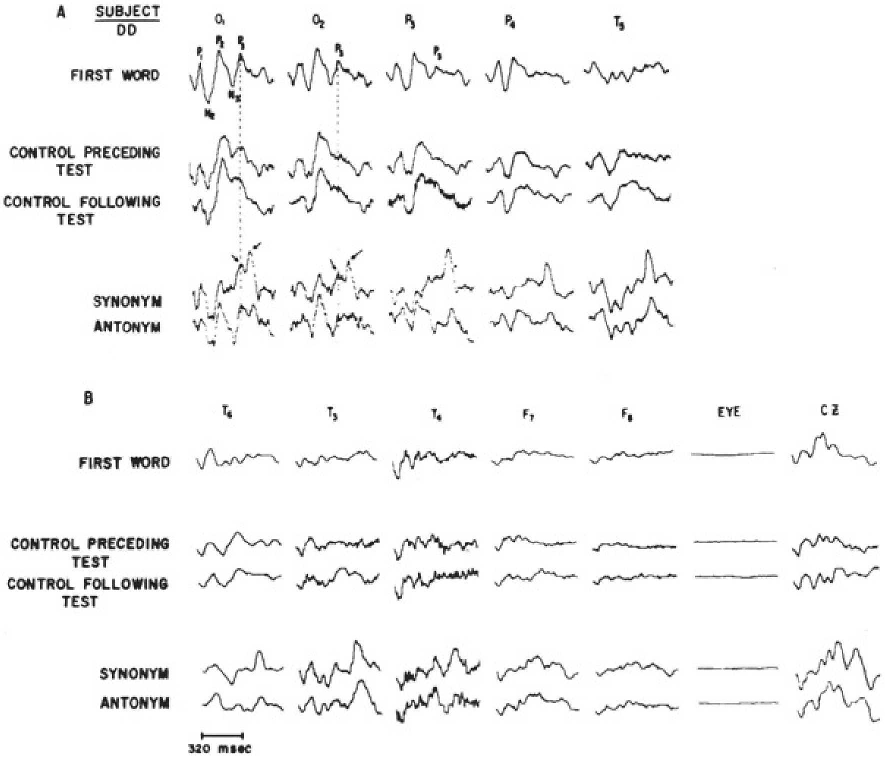

Fig. 8. AEPs from delayed semantic matching task (from Thatcher, 1976).

by control stimuli, although the latter elicited a significantly attenuated N_3-P_3 complex in comparison to first and second words. The bottom two rows show AEPs to the synonyms and antonyms. A very prominent late positive response (P-400) occurred in widespread regions (even F_7 and F_8) at 440 msec for the synonyms and 460 msec for the antonyms. Interhemispheric asymmetries were dynamic, occurring only to the second and not to the first words. The asymmetries were maximal in T_5 vs T_6 involving both the early and late components. An anterior-posterior gradient of asymmetry with maximal temporal involvement was noted in a second semantic experiment that required a Spanish to English and English to Spanish language translation (Thatcher, 1976, 1977c). Figure 9 shows an example of AEP waveform asymmetries in T_5 vs T_6 derivations elicited during the language translation task. Note that the component asymmetries occur primarily to second words and not to the controls or the first words. This indicates that interhemispheric waveform asymmetries are maximized when higher level language processes are challenged. Unlike other tasks (e.g., logic,

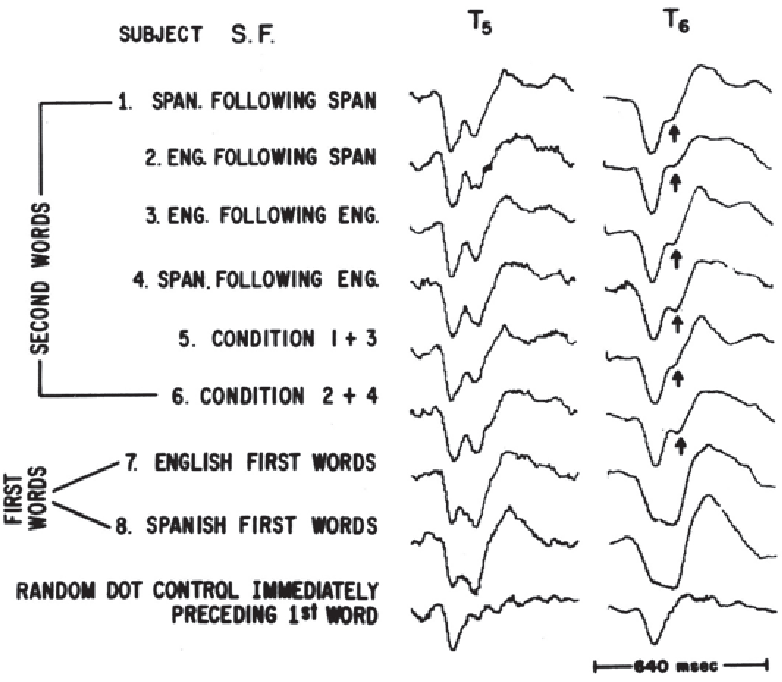

Fig. 9. AEPs from Spanish-to-English and English-to-Spanish translation task (from Thatcher, 1977c).

form matching, mathematics, etc.), the semantic tasks, such as those involving language translations or synonym-antonym comparisons, result in pronounced interhemispheric waveform asymmetries which occur independent of AEP amplitude (Thatcher, 1977b).

Another example of a functional topography revealed by the normalized factor analysis is seen in Table 4. The rows represent the various conditions of the synonym-antonym-neutral task while the columns represent the orthogonal factors that describe the AEPs elicited by the task conditions. This factor analysis was performed on the grand averages from all eight subjects performing in the task. It can be seen in Table 4 that in the P_3 and T_5 derivations AEPs elicited by the random dot controls and the AEPs elicited by words load on orthogonally different factors (factors 1 and 2) where as, in P_4 and T_6 or the right side derivations, very little factor differentiation between controls and words is observed. This data provides another example of a functional interhemispheric asymmetry in which the signal-to-noise ratio, represented by the brain's responses to randomness versus words, is greater from the left hemisphere than from the right.

DISCUSSION

A topographical perspective of brain function is desirable for both basic research purposes and clinical applications. Many attempts toward the development of EEG and EP topographic analyses have been made (see Regan, 1972; and John, 1977 for reviews of this literature). For example, Livanov (1962) and Gavrilova (1970) showed increased coherence of frontal-occipital EEG during mental activation (such as problem solving). Callaway (1975) and Callaway and Harris (1974) demonstrated left hemisphere increases in coherence (using the information theory coupling coefficient) during verbal tasks and right hemisphere increases during spatial tasks. Also, many workers have shown AEP and EEG interhemispheric asymmetries during verbal and spatial tasks (see Donchin et al, 1977 and Thatcher, 1977b for reviews). However, no global and comprehensive electrophysiological analysis has demonstrated reliable and regionally specific changes in brain physiology as a function of the qualitative aspects of a task. As discussed in the introduction, electrophysiology is lagging in that qualtitative physiological profiles have been provided by Ingvar and colleaques in their studies of regional blood flow changes.

Theoretically, electrophysiological analyses offer the advantage of very fine time resolution (on the order of milliseconds). This is important since the series transformations from patterns of energy falling on receptors, to spatial temporal electrophysiological activity (ionic flows), to intermediate molecular activity

TABLE 4. EVOKED POTENTIAL FACTOR LOADINGS FOR LEFT AND RIGHT HEMISPHERE DERIVATIONS FROM THE DELAYED SEMANTIC MATCHING TASK

	Left Parietal			Right Parietal		
	Factors			Factors		
	1	2	3	1	2	3
Control -	0.69	0.11	0.06	0.80	0.00	0.00
Control -	0.92	0.03	0.01	0.83	0.06	0.00
1st Word -	0.25	0.62	0.10	0.97	0.00	0.00
ITI-1 -	0.89	0.04	0.01	0.65	0.01	0.06
ITI-2 -	0.02	0.00	0.98	0.00	0.00	0.99
ITI-3 -	0.61	0.24	0.00	0.60	0.37	0.03
Neu. -	0.40	0.31	0.25	0.91	0.03	0.00
Ant. -	0.21	0.47	0.30	0.97	0.00	0.01
Syn. -	0.25	0.44	0.29	0.98	0.00	0.00

	Left Posterior Temporal			Right Posterior Temporal		
	Factors			Factors		
	1	2	3	1	2	3
Control -	0.80	0.08	0.00	0.50	0.32	0.18
Control -	0.89	0.06	0.00	0.42	0.41	0.07
1st Word -	0.23	0.73	0.03	0.86	0.03	0.02
ITI-1 -	0.80	0.11	0.01	0.66	0.24	0.04
ITI-2 -	0.04	0.00	0.95	0.00	0.98	0.01
ITI-3 -	0.81	0.11	0.00	0.27	0.61	0.08
Neu. -	0.31	0.54	0.12	0.96	0.01	0.01
Ant. -	0.21	0.69	0.10	0.95	0.01	0.03
Syn. -	0.25	0.65	0.08	0.95	0.02	0.03

Neu. = neutral second word; Ant. = antonym second word; Syn.= synonym second word. Underlines represent maximum factor loadings for a given condition on a single factor.

(biogenic amines, enkephalin, cyclic AMP, etc.), to macromolecular representations (proteins, aminoacids, etc.) can theoretically be monitored and quantified by a combination of topographic analyses. The brain's responses to drugs, recovery of function following trauma and the evaluation of remediation may someday rely on such measures.

The present chapter emphasizes the application of the varimax factor analysis in the development of an electrophysiological task analysis. The central idea of this approach is two-fold: One, in the between derivation analysis, the idea is to find AEP waveforms that are shared by a subset of topographic regions during a particular cognitive function but are not shared during other cognitive functions; and,two, in the within derivation analysis, the idea is to find AEP waveform differences within a given region that occur to different aspects of a task (also, between tasks or between groups). The varimax analysis maximally finds a subset of waves that reflect commonality or shared processes. An underlying supposition of this approach is that temporal patterns which occur nearly contiguously in different brain regions reflect a common function. Conversely, dissimilar temporal patterns represent a difference in function.

Given the goal of finding commonalities and differences in waveforms, it should be noted that factor analysis posseses a number of weaknesses that do not make this method ideal (see Cooley and Lohnes, 1971). Multidimensional scaling, cluster analysis, minimal spanning trees, and discriminate analysis offer greater promise, if used appropriately, to reveal replicable and invariant processes in time and space related to particular aspects of cognitive function.

In summary, the attempt at an electrophysiological task analysis presented here is still only preliminary. The data obtained to date, however, shows that the use of an active task with non-contingent probes and built in invariances reveals regionally specific electrophysiological profiles related to different aspects of cognitive function. Furthermore, these profiles reflect shared wave processes within subsets of anatomical derivations.

FOOTNOTES

[1] The factor analysis program was written by Dr. Paul Easton for the PDP-12 computer

[2] The amplitude normalization process involves first computing the epoch mean voltage $\bar{X} = 1/N \sum x_i$, where x_i equals the voltage values in each sample bin. Then a DC level is computed $(\bar{X} - x_i)$ and normalized $\bar{Y}^2 = \frac{(\bar{X} - xi)^2}{(\bar{X}^2 - \bar{x}_i^2)} Y2$. Unity variance is set for all the AEPs by scaling each voltage value so that $\bar{Y}^2 = 1$.

[3] The replicability of the factor analyses can be judged by a) 43 out of 43 subjects run in the various tasks to date show differential loadings on control AEPs versus information AEPs; b) 38 out of 43 subjects show a unique ITI factor; c) 7 out of 9 subjects run in the delayed letter matching task showed higher loadings between match and standard AEPs than between mismatch and standard AEPs; and, d) 39 out of 43 subjects showed an anterior-posterior factor structure with one factor loading heavily on anterior derivations (T_3 thru F_7) and another factor loading heavily on posterior derivations (O_1 thru $T_{5\&6}$).

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