

## chapter 4

In BEHAVIOR CONTROL AND MODIFICATION  
OF PHYSIOLOGICAL ACTIVITY.

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**Selective Attention:  
Distinctive Brain Electrical Patterns  
Produced by Differential Reinforcement  
in Monkey and Man<sup>1</sup>**

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When asked which body organ controls mental functions, the man-in-the-street would today answer unhesitatingly: the brain. Again, when asked which organ is most readily modified by experience, i.e., where might memories be stored, the ready answer would be: the brain. But this recognition of the brain's importance has not always been so. As recently as the year 1800, our feelings were credited to circulating humors and our thoughts were attributed to airy spirits. True enough, today we know that humors, biologically active chemicals, do in fact control basic feelings, moods, and states of mind, but these biologically active chemicals work locally upon receptive sensitivities of brain tissue. And true enough, early nineteenth-century man had entrapped the spirits of mind in the ventricles of the brain—the spirits (defined by Webster as “physical energy”) had only to be moved a few centimeters to brain substance and become identified as electrical. Yet the change in man's view of himself that has been wrought by these specifications is impressive, as attested to by the contents of this volume.

It is really only in the past half century that the spirits of the mind have materialized as the brain's electrical activities. In the late 1920s, electrical brain recordings were made possible; in the late 1930s, potential changes were evoked in brain systems by abrupt sensory stimulation and monitored by loudspeaker. The late 1940s saw the application of oscilloscopes to these studies and the general availability of recording devices such as the electroencephalograph. In the 1950s

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these applications became widespread and systematic electrophysiological brain research began to flower. The 1960s bore early buds of sophistication—microelectrode recordings and the computer analysis of brain wave activity reached a level of competence undreamed of even a decade earlier. To some considerable extent the spirits are harnessed. Today we study them at leisure and can, on occasion with appropriate feedback techniques, even put them to work.

The thrust of current interest in electrical brain activity, as represented in this volume, concerns the specification of electrical changes in the brain that reflect internal "mental" processes, rather than those changes produced by the immediate sensory events external to the organism. In the three independent, but parallel, studies presented here, we sought to determine whether we could identify characteristic electrical brain events when an organism selectively attends to one of several dimensions that comprise a multidimensional cue. As a common aspect of our experiments, selective attention is produced by a differential reinforcement history so that we are able to specify the environmental contingencies that produce the selective behavioral and brain responses in accord with the traditions of operant behaviorism. Yet we believe it appropriate to describe our experiments in terms of selective "attention" because there are no immediate sensory stimulus differences to account for the observed differences in brain activity.

An essential feature of our studies is the use of time-locked procedures in both the collection and analysis of electrocortical data. In general, *time-locked* refers to the occurrence of an event within some previously defined period of time (epoch), the beginning of which is clearly distinguished by another predetermined and consistently recurring event. For our purposes, each trial in a series of trials is considered to be one such epoch, of fixed duration, the beginning denoted by a stroboscopic flash for stimulus presentation. We regard each epoch as being composed of two separate parts, one related to the stimulus and one related to the behavioral response. Specifically, *stimulus-locked* events are those which immediately follow stimulus presentation, and continue to occur for a fixed period of time; *response-locked* events are those which occur in a fixed interval just preceding, and just following, the response so that the moment of response is located at the center of the interval.

By using a common framework to obtain time-locked electrical changes in the brain, while organisms are engaged in similar tasks requiring selective attention to common multidimensional cues, we are now able to distinguish certain specific differences in electrocortical activity between 1) the monkey, 2) the human adult, and 3) the human preadolescent. The studies to be described will be presented in this order.

#### The General Experimental Design

For each experiment the subjects and the type of electrodes used are specific; elements common to all experiments include computer control, stimulus presentation, data collection and processing. The experimental paradigm used involved

recording the transient electrocortical activity evoked by brief ( $10 \mu\text{sec.}$ ) self-initiated presentations of visual stimuli of flash intensity  $1.5 \times 10^6$  lumens that had to be discriminated by an appropriately rewarded differential panel or button press. Self-initiation, accomplished by pulling a lever or pressing a button, triggered stimulus presentation and simultaneously marked the beginning of each trial, or time-locked epoch. (See Figure 4-1.)

Generally the stimulus slides consisted of two color dimensions, red and green, and two pattern dimensions, circle and vertical stripes resembling a square. Each colored pattern could appear either on the right or left so that all color and pattern dimensions were always present in each display, but in different arrangements. Thus there were four possible color-pattern-placement combinations: and for each such series of combinations either one of the color dimensions or one of the pattern dimensions could be differentially reinforced. Subjects were trained to perform a color discrimination first, ignoring pattern differences, and after criterion was reached and brain electrical recordings completed, a color discrimination reversal procedure was instituted. Once criterion had again been achieved and the brain recordings made, the reinforcing contingencies were switched to train the subject to make a pattern discrimination and now ignore the color differences. Again, once criterion performance had been reached and brain recordings made, a pattern discrimination reversal was initiated and pursued until once more criterion brain recordings had been collected. Each criterion performance consisted of three

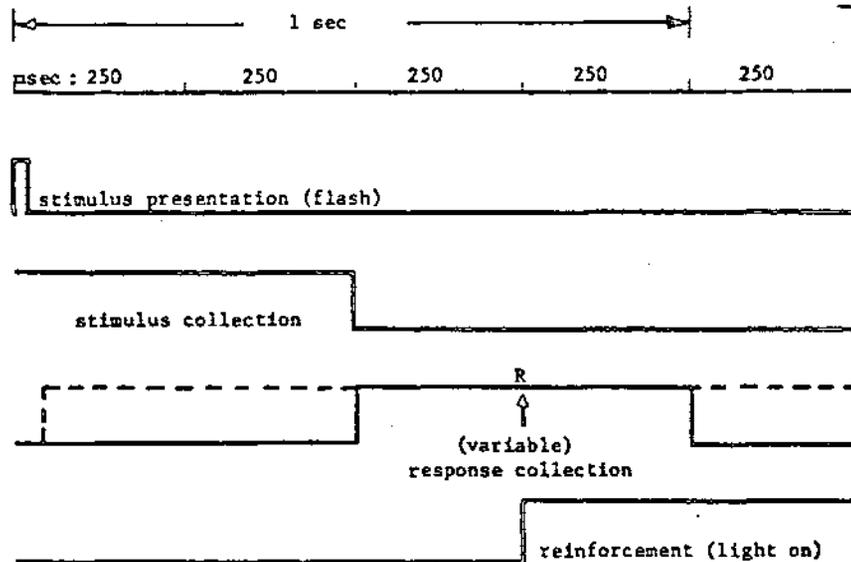


Figure 4-1. Schematic representation of experimental timing and control for one time-locked epoch. The moment of the behavioral response (R) is variable and occurs at the center of the response-locked interval. Maximum response latency is 1 sec.

consecutive days of performance of 100 trials per day at 90 percent correct. Thus 300 trial blocks furnished the data for analysis.

A general-purpose digital computer (PDP-8), programmed for real-time data acquisition, was used to control a modified Kodak Carousel projector for stimulus presentation. The modifications consisted of replacing the projector bulb with a flash bulb whose flash duration was approximately 10 microseconds. For shaping purposes flash trains of various durations could be obtained. During the actual experiment, however, single flashes sufficed, provided they were initiated by the subject. Training consisted of obtaining a computer scheduled reward when the appropriate of two panels or buttons was pressed no sooner than 250 msec. and no later than 1 sec. after the stimulus flash. Behavioral responses were recorded by the computer as was the electrical brain activity, sampled every two msec. and fed through an analog to digital converter, from the time of the stimulus flash to 250 msec. after the response was made.

Time-locked averaging methods were used for data reduction, the stimulus- and response-locked portions treated independently. The raw data were first sorted into appropriate groups, each group corresponding to one of the four stimulus categories (see Figure 4-2) and to one of the four reinforcing contingencies (red, green, circle, stripes). Thus 16 separate groups were established for each recorded

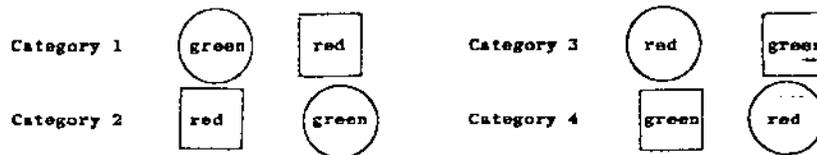


Figure 4-2. The four types of slides used for stimulus presentation.

electrode location (channel). Computer procedures were implemented for collating and reducing the raw data to averaged waveforms suitable for further analysis. To complete the data analysis, statistical comparisons by t-test were performed on the time-locked amplitude measures for each of the discriminations and discrimination reversals.

Note that in all of these color and pattern discriminations and reversals, each stimulus displayed in the series was always of one of the same four categories. Only the reinforcing contingencies varied. Therefore, the subjects' retinal images were invariant across tasks. The question is, therefore, can we identify the brain processes which determine the differentiation of the discrimination response mechanism?

#### *Study 1: Rhesus Monkeys*

Our initial focus (Rothblat and Pribram, 1972) was upon the visual system. We used monkeys and made recordings by means of electrodes (300  $\mu$ m nichrome steel bipolar-vertical separation 1.5-2.0 mm) implanted in the primary visual receiving

cortex, in the cortex immediately adjacent, and in the inferior temporal gyrus which had been shown by ablation experiments (see review by Pribram, 1969 and by Mishkin, 1966) to be critically involved in visual discrimination performance. As already noted, recordings were made continuously throughout each criterion trial. For analysis, however, the recordings were then classified into three sets according to the time of occurrence during a trial: the first set consisted of records made for 500 msec. following stimulus flash (stimulus-locked data); the second set contained 250 msec. of the record obtained after response was made, and the third set included 250 msec. of record obtained just *prior* to the time the response occurred (response-locked data). The data sets in each class were then processed and statistical results obtained according to the general procedures already described.

In an earlier experiment (Pribram, Spinelli and Kamback, 1967) different visual cues had been presented separately (successively) and the differences were shown to be reflected in the stimulus-locked activity recorded from the visual receiving cortex. The results of the current experiment confirmed the earlier ones ( $df = 5$ ,  $P < 0.05$ ) in demonstrating differences in stimulus-locked waveforms when the color trials were compared with those in which patterns were presented. These results were not dependent on correct discriminations being performed—they held for erroneous trials as well and were already present during control runs recorded while the subjects were still performing at chance (Figure 4-3).

Of greater interest here are the results of the analyses of the response-locked data set. For this set, analysis of control data yielded only straight lines when trials were summed. All brain electrical activity appeared random with respect to the presses of buttons and panels. Only when criterion data were analyzed did differences become evident. Now the records clearly separated according to the four stimulus pairs: the brain electrical activity just preceding and following response was similar when the discriminated cue was similarly placed ( $t$ 's = 5.54 to 4.71,  $df = 2$ ,  $P < 0.05$ ).

These differences appeared primarily in recordings made from the inferior temporal cortex, the part of the brain shown to be involved in visual discrimination by ablation experiments (Pribram, 1969). With overtraining at criterion in any particular discrimination, however, such differences also appear in primary visual receiving cortex, perhaps reflecting the now-automatic selection of the appropriate cue dimension.

Four preadolescent monkeys with a total of 32 electrodes were studied in these experiments. Of these, 20 electrodes, 12 of which were implanted in the visual receiving cortex and 4 in the inferior temporal gyrus, gave consistently reliable responses over the three years of recording that were necessary to obtain the data.

#### *Study 2: Human Adults*

We have now extended these results to man. In a first experiment 28 college student volunteers were tested in the same paradigm as that used in the monkey experiments, except that monopolar scalp recordings from the occipital pole and

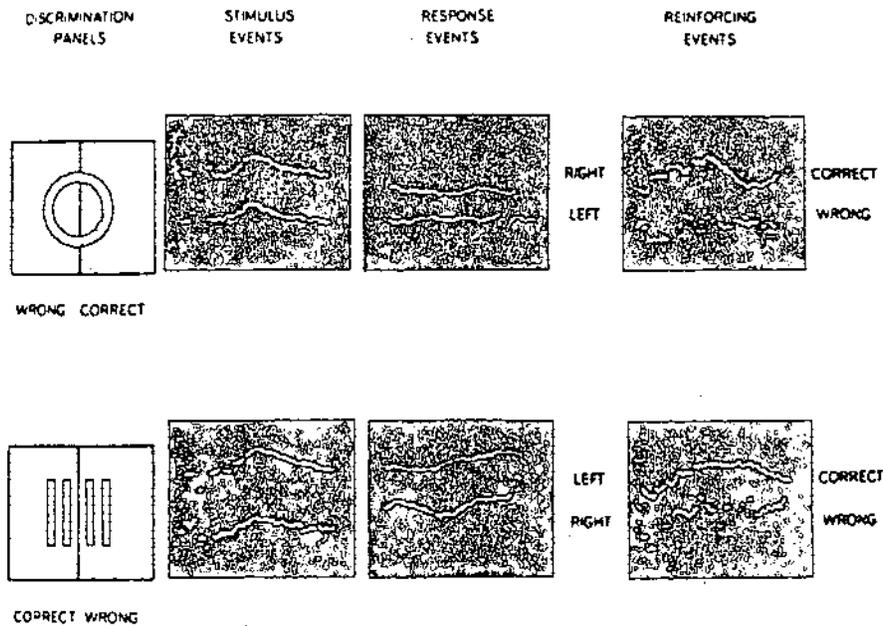


Figure 4-3. Results of visual discrimination experiment. The records under "Stimulus Events" are averages of three days' recordings of waveforms that appear immediately after circle or stripes have been flashed in visual cortex. The records under "Response Events" were those generated just prior to the moment when the monkey actually responded by pressing either the left or the right half of the panel. The records under "Reinforcing Events" were produced when the monkey was rewarded with a peanut if he was correct or not rewarded if he was wrong.

A difference in the second trough of the W-shaped part of the "stimulus" waveforms indicates whether the monkey has seen stripes or a circle. Only after he has learned his task do the "response" waveforms show differences in pattern and these appear just *prior* to the moment the monkey presses the right or the left half of the panel. These differences appear regardless of whether he has seen a circle or stripes. Thus the waveforms reflect his intention to press a particular half of the panel and do not indicate whether his response is going to be right or wrong. However, differences in the "reinforcing" waveform do indicate whether a reward has been obtained: a slow shift in baseline following the movement of response indicates anticipation of reward and a 25-50 Hertz waveform indicates disappointment.

from the temple just above the ear replaced the implanted electrodes. Analysis of the recordings in the time domain proceeded essentially as in the earlier experiments. Results were essentially identical to those obtained in the monkey, with the exception that the response-locked differences were obtained from the occiput as well as from the temple. The immediate appearance of response-locked effects in the visual cortex may be due to the fact that the task was excessively simple for the students (less than 10 percent error in the first session) or it may reflect the posterior migration of the human cortex homologous with the monkey's inferior temporal gyrus. (In man the visual receiving area has migrated to the extremity of

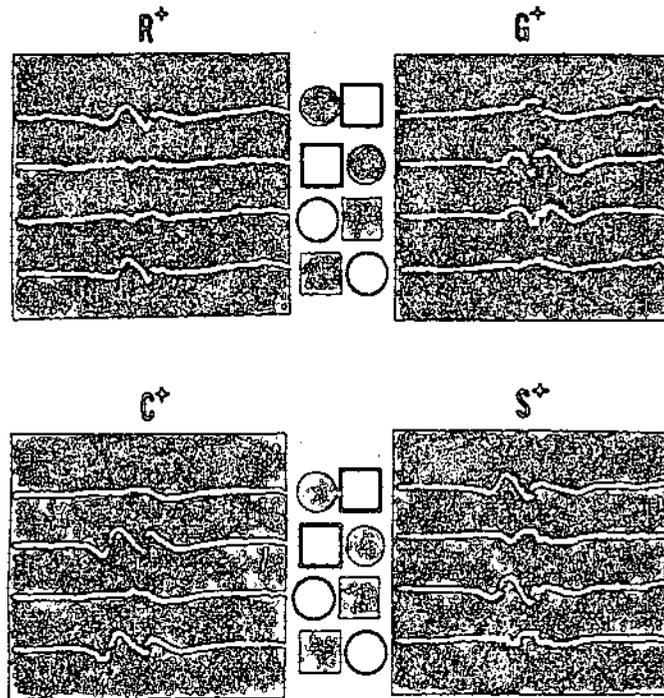


Figure 4-4. Results of an experiment demonstrating the functions of the infero-temporal cortex. Comparison of *response-locked* activity evoked in temporal cortex (IT) when monkeys are performing (90 percent correct) color (top panels) and pattern (bottom panels) discrimination. Each trace, summed over 300 consecutive trials, is the activity recorded when the stimulus configuration presented to the monkey appeared as in the diagrams between the panels. Each trace includes 500 msec. of electrical activity—250 prior to and 250 just after each response. Note that during the color discrimination the first and fourth (and the second and third) traces are similar, while during the pattern discriminations the first and third (and second and fourth) traces are alike. These similarities reflect the position of the color cues in the color task and the position of the patterns in the pattern task. Position per se, however, is not encoded in these traces. Note that this difference occurs despite the fact that the retinal image formed by the flashed stimulus is identical in the pattern and color problems.

the occipital pole and its major portion lies on the medial surface rather than over the majority of the lateral part of the occipital lobe as in the monkey.)

In order to understand the response-locked potential changes more fully, a series of experiments was undertaken in which verbal instructions, i.e., auditory instead of visual cues, were used. The subjects were simply told which button to press and the correct order was kept the same as in the visually cued experiments. The data were once again analyzed in the identical fashion and again the same results were obtained. This finding underlines the fact that the differences in waveforms were indeed *response-locked* and clearly independent of the stimulus which was presented. But what does it mean for a brain potential to be response determined?

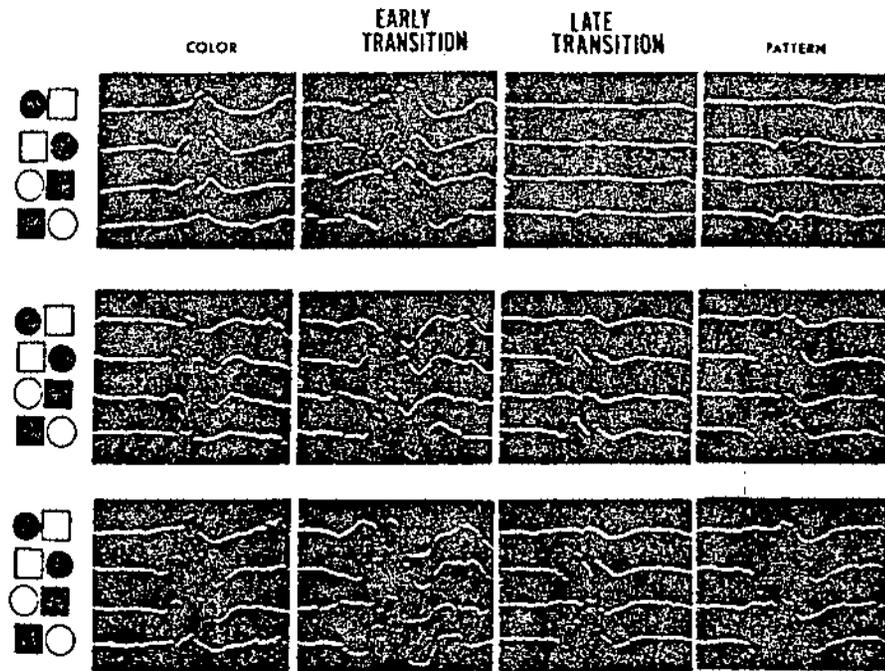


Figure 4-5. This figure demonstrates the electrical activity during the shift from color to pattern discrimination recorded from the striate cortex (top row), the pre-striate cortex (middle row), and the IT cortex (bottom row). The left bottom and right bottom panels replicate in a different subject the essential findings from Figure 4-4. Transitional records from the inferotemporal cortex are shown in the middle two panels of the bottom row. Note that clearcut changes (columns three and four) in the electrical activity of the striate cortex lag behind those obtained from the inferotemporal cortex. This is especially evident in column three which represents discrimination behavior at the 75-80 percent level of performance. With overtraining (column four), the records obtained from the striate cortex approach those obtained from the inferotemporal cortex in their distinctiveness.

Are the movements of particular muscle groups responsible, or for that matter are movements involved at all?

To investigate these problems a third experiment in this series was performed. No visual or auditory stimuli were presented. The subject rested both index fingers passively on the response buttons which were then automatically depressed in the same sequence used in the previous experiments. Thus no active movements were required of the subject and he had no knowledge of the required response until the response buttons actually moved. Analysis, as in previous experiments, again showed a difference in the response-locked brain activity preceding the onset of the response as it had in the earlier sessions.

The result of this experiment could be accounted for by differential stimulation of two fingers. Another study was therefore run in which the active responses were required to be carried out by a single finger. This procedure failed to abolish the

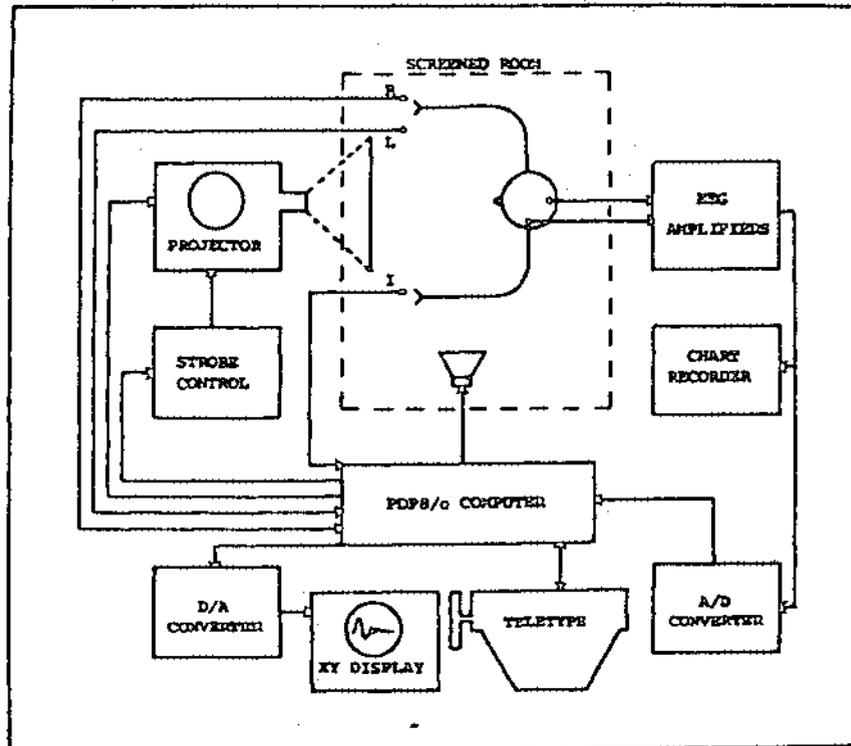
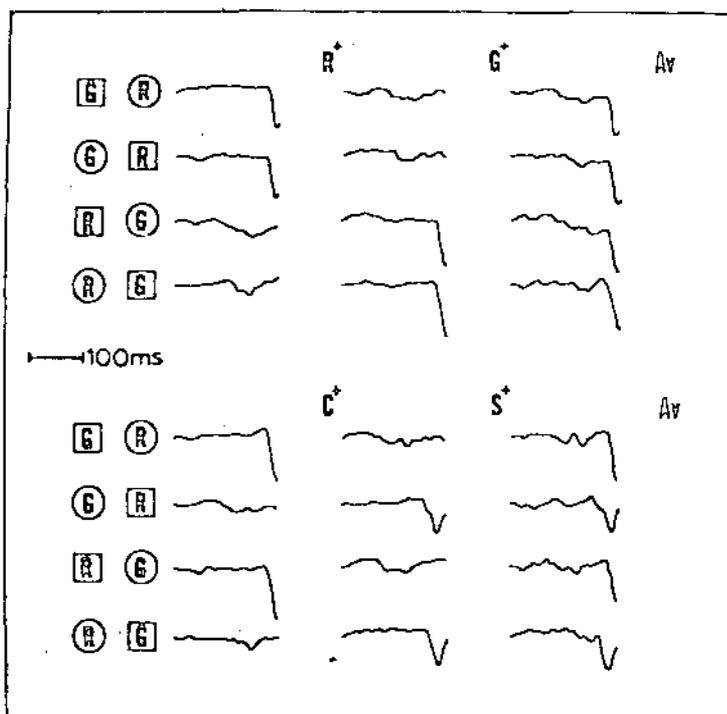


Figure 4-6. Experimental arrangement for the recording of response-locked potentials from human subjects. The subject initiates a stimulus presentation by depressing button "I" with his left hand. A multiple stimulus is back-projected onto a plexiglass screen and the subject responds by depressing either response button R or L with his right hand. A PDP8/e computer controls all experimental contingencies and stores the prerresponse waveforms (computed by averaging the record backward from the time of response) according to the task in operation, the stimulus presented, and the nature of the response.

differences in brain electrical response, perhaps due to the slight shift in hand, arm, and body attitude necessary to accomplish each button push.

The final experiment in the series was an attempt to abolish all differences in tactile input from the buttons by anesthetizing the fingers involved with multiple injections of procaine. The experimenters themselves and their assistants served as subjects. The active form of the experiment was repeated both with fingers unanesthetized and anesthetized. In the unanesthetized condition the usual results were obtained. However, when sensory input is reduced by the procaine, the differential aspect of the response-locked activity is practically abolished. This effect could be due simply to the blocking effect of the procaine on sensory input; it could also be due to interference with the normal patterning of input caused by such a block, and that it is this pattern upon which the differential brain activity depends; or it could be due to the development of a new response topography which becomes necessary in the absence of sensory feedback from the button



**Figure 4-7.** Response-locked potentials (averaged backward from time of response) recorded from the occipital pole of a student volunteer performing the four experimental tasks (R+, G+, C+, S+). The left-hand column shows the stimulus configuration which preceded each averaged wave form. A comparison of the averaged wave forms for the two color tasks (upper right) and the two shape tasks (lower right) reveals that similar preresponse wave forms reflect similar color configurations of the stimulus during color relevant tasks, and similar form configurations of the pattern stimulus during pattern relevant tasks.

press. Nonetheless, whether by deprivation, disruption, or new response development, the anesthetic did attenuate the differential brain response: the conclusion must be reached, therefore, that input from the fingers was critical in evoking the response-locked differences in brain activity in these experiments.

The issue is raised by these results as to the relationship between the response-locked activity in these experiments and such brain electrical events as the motor potential and the contingent negative variation. These negative preparatory (readiness) potentials are usually terminated by a sharp positive deflection in the electrical record. Further, these potential changes occur in the several regions of the cortex whenever the task demands the participation of a particular region (Donchin et al., 1971). Finally, in an earlier study (Pribram et al., 1967), we found that with training, response-locked differential brain activity related to panel press per se (as contrasted to differential activity related to visual stimulus) could be obtained from the visual receiving as well as from the motor areas of the brain. It seems likely, therefore, that the current series of experiments in man has

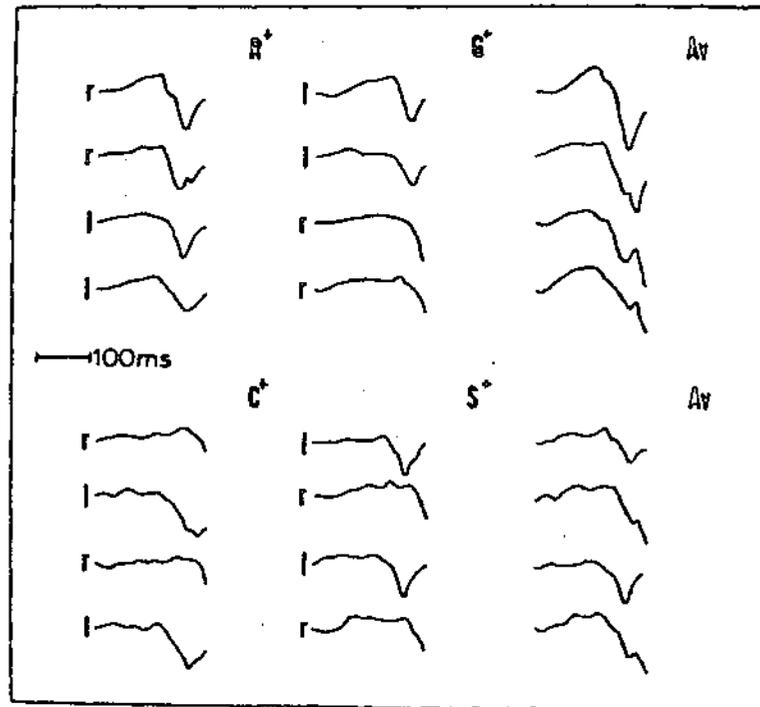


Figure 4-B. Response-locked potentials (averaged backward in time) recorded from the occipital pole of a student volunteer who has been verbally instructed to perform the identical response sequence corresponding to the visual sequence employed for the four experimental tasks. In this case, the prereponse waveforms reflect the direction of the response (r-right; l-left) instead of the stimulus dimensions.

produced sets of compressed and therefore indistinguishable brain waveforms over larger regions composed of the sequence: visual stimulus means move right index finger (which produces stimulation evoking a brain potential change) against button which produces more stimulation and more potential change.

### *Study 3: Human Preadolescents*

In order to disentangle the origins of this compressed evoked brain activity another series of experiments has been undertaken with children who, more like monkeys, find the selective attention task somewhat of a challenge. The records of four preadolescent children have so far been analyzed (Pribram, Day & Glick, 1973). Again, the experimental paradigm is the same as that used in the monkey experiments—in fact, most of the equipment used is identical. And again, as in the other human studies, recordings are made from scalp electrodes—this time bipolarly and not only from placements over the occiput ( $O_2$ ) and temple ( $T_6$ ), but over the somatosensory-motor cortex ( $C_4$ ) as well. Data analysis proceeded as before.

However, despite these similarities in procedure, the results of these studies

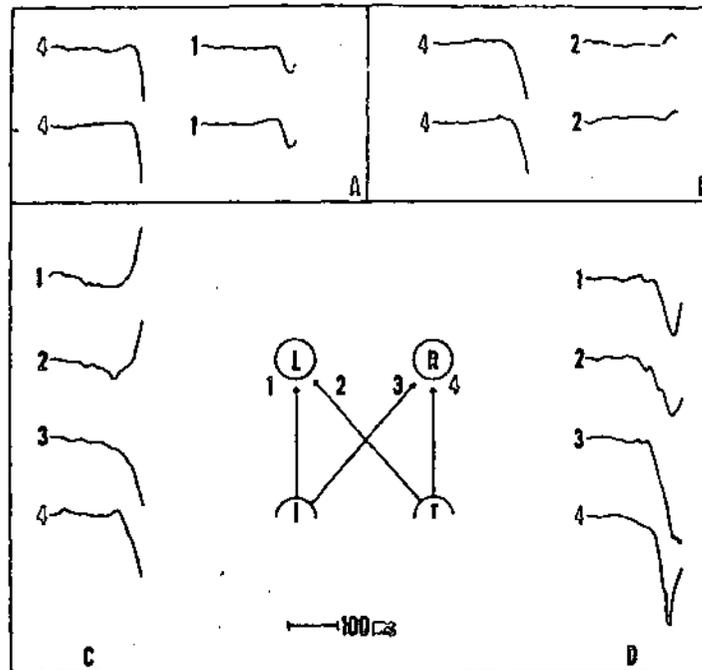


Figure 4-9. Response-locked potentials (averaged backward in time) recorded from the occipital pole of student volunteers. The numbers denote the different finger-button combinations as illustrated in the central key (L-left button; R-right button; l-left finger; r-right finger). A: the response sequence was generated by the movements of the response buttons and required no active participation by the subject. Each wave form is the average of 20 preresponse potentials. B: In this case the same finger was used to make both responses. C: Preresponse waveforms recorded from an experimenter with normal sensory input. D: Preresponse waveforms recorded from the same experimenter after the fingers have been anesthetized with procaine.

differ sharply from those of the earlier ones. The monkey studies had clearly shown distinct differences between the variables that influenced stimulus-locked and those that influenced response-locked activity. By contrast, the study with children provides a much richer set of interrelations. Five specific findings can be listed:

1. In the monkey, *stimulus-locked* activity recorded from the striate cortex could be directly related to the color and the pattern of the stimulus. In children, stimulus-locked activity recorded from the occiput varies not only as a function of color and pattern but also in relation to the position of the stimulus, and, what is perhaps more important, *stimulus-locked* activity was found to be especially sensitive to the conditions of reinforcement.

2. In children, stimulus-locked activity recorded from the temple also exhibits similar sensitivity to differences in reinforcement; such stimulus-locked differences were absent, it will be recalled, from inferotemporal cortex recordings obtained from monkeys. Furthermore, these differences recorded from the temporal lobe of

children precede those recorded from both the occiput and the sensory-motor cortex.

3. In the monkey, only *response-locked* activity recorded from the temporal cortex was correlated with the reinforcing contingencies. In children, response-locked activity recorded from the vertex (our "sensory-motor" lead) shows marked differences at about 50 msec. prior to response. Thus this sensory-motor cortex record from children is similar to the temporal cortex record of monkeys (for which no sensory-motor recordings were made).

4. However, we noted that the stimulus-locked, reinforcement sensitive differences in electrical activity recorded from the temporal lobe of children precede both the stimulus-locked differences in the record from the occiput and, even more, differences recorded from sensory-motor cortex. The response-locked differences exhibit a similar sequence (see Tables 4-1 and 4-2). Thus the order of occurrence is temporal—visual—sensory-motor. This precedence of temporal lobe electrical activity is present therefore in both monkeys and children.

5. Finally, differences in reinforcement were reflected in both the stimulus-locked and the response-locked recordings made from children when individual stimulus categories were compared (i.e., when only the reinforcing contingencies were changed for the identical visual display). Such stimulus-locked differences

Table 4-1. Stimulus-locked Activity: Color vs. Form  
Summary of Significant Differences Between Segments  
When Grouped by Stimulus Category

Reinforcement:	Color (green+, red+)					vs	Form (circle+, square+)				
Segment:	1	2	3	4	5	6	7	8	9	10	
All categories:											
Temporal	**	**	**				**	**	*		
Visual		*	*	*	**	**	**	**	*		
Motor								*	**	*	
Category 1:											
Temporal	*	**	**				**	*	*		
Visual			*		*	*	**			*	
Motor		*							*		
Category 2:											
Temporal	*	**	*	**	**		**	*			
Visual		*		**	**	**	**	**			
Motor		*	*					**	*	**	
Category 3:											
Temporal	*	**									
Visual		**	*		*	**				*	
Motor							*	**	**	*	
Category 4:											
Temporal	**	**	**				*				
Visual				**	**	**		**	**	**	
Motor									**	*	

\*P < .05

\*\*P < .01

mean response  
latencies

**Table 4-2. Response-locked Activity: Color vs. Form**  
**Summary of Significant Differences Between Segments**  
**When Grouped by Stimulus Category**

Reinforcement:	Color (green+, red+)					vs	Form (circle+, square+)				
Segment:	1	2	3	4	5	6	7	8	9	10	
All categories:											
Temporal	**	**	**	**	*				*	*	
Visual	*		**	**							
Motor							*	**			
Category 1:											
Temporal	*	**			*					**	
Visual	*							**			
Motor											
Category 2:											
Temporal	*	**	**	**	**						
Visual			*								
Motor							*	**			
Category 3:											
Temporal	*	*						**	**	**	
Visual	**		**	**	**	**	**	*			
Motor				*			*	**			
Category 4:											
Temporal	**	**	**	*							
Visual		*	**	**	*						
Motor							**	*			

\*P < .05

\*\*P < .01

were not looked for in the records made from monkeys. Generally, the stimulus-locked epoch also contained differences related to the stimulus itself (color-pattern-position), and these differences were found in the early components of the evoked waveforms; while others related to the response itself (button press) were found in the very late components.

These results for children, in contrast to monkeys, show that, once learning has occurred, stimulus selection is neither stimulus-locked nor response-locked, but an ongoing process related to both epochs. Unlike the results for the monkey, no particular portion of either the stimulus- or response-locked activity could be called a decision wave or even an intention wave. The selection of an appropriate response appeared to begin at stimulus onset, proceed through what previously has been thought of as stimulus registration (VER), and culminate in the actual correct motor response. As noted above, the process was not confined to a single channel, but involved an interaction among channels. Such a process suggests not just one decision, but a variety of parallel decisions among different parts of the brain. The selection process seems to involve a time-ordered sequence of matching amplitudes, each new comparison based on what was learned previously.

For example, the Green and the Red reinforcement conditions were compared for each electrode by matching the color cues for the four stimulus categories. Two

traces (green left and green right) were generated for each reinforcement condition. By overlaying plots of the four resulting traces, several points at which the amplitudes coincided were observed throughout the epoch. The sequence of matching amplitudes, or nodes, usually ended with a correct left press for one reinforcement condition matching a correct left press for the other, at the moment of response. The effect was observed in both the stimulus- and response-locked epochs in segments preceding the response, and as noted, especially at the moment of response. Furthermore, the effect of amplitude convergence at the moment of response was observed not only in a single electrode channel, but across channels as well. These effects were most noticeable in the response-locked epoch across all categories, conditions, and channels.

Since the effort to interpret these effects is hardly begun at this time, no attempts will be made to completely illustrate such complicated relationships. However, Figure 4-10 gives some idea of the complexity of these crossover relationships in the stimulus-locked activity. Each crossover point represents a node at which the amplitudes match exactly. Note that the portions to the right of segment 7 represent response activity recorded from stimulus onset forward in time, and the nodes are points where actual responses occurred (segments 7, 8, and 9). It is not clear at this time exactly how this array interacts, but the information obtained thus far strongly suggests that the entire recorded epoch represents a complex decision process.

The crossover relationships at the moment of the response, which appeared in different segments of the stimulus-locked epoch, are readily observable at the

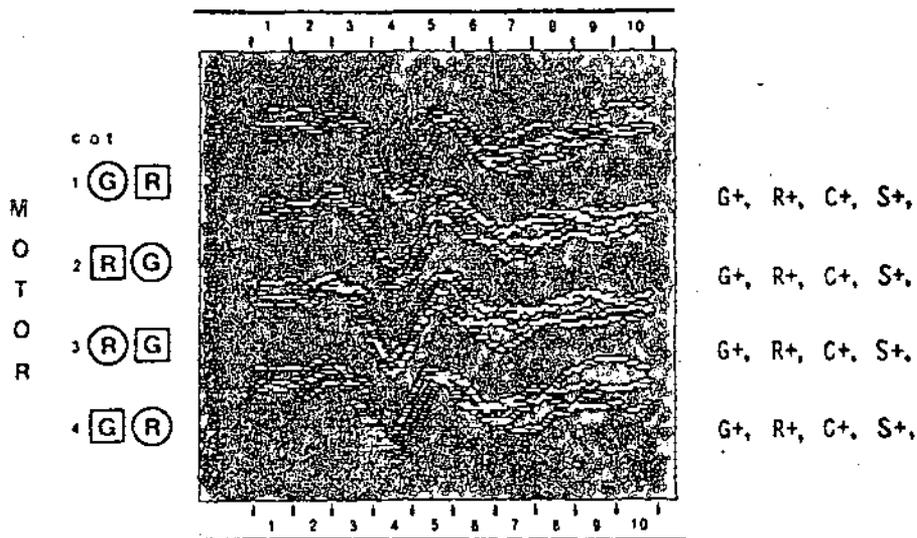


Figure 4-10. Stimulus-locked activity for the motor electrode ( $C_2$ ) recorded from a human subject. The differences in averaged electrical activity for the same visual display are shown for each different reinforcement condition: Green+, Red+, Circle+, and Square+. Each segment on the lower scale represents 50 msec.

center line of the response-locked epoch. The effect is best seen for the motor electrode in Figure 4-11. In spite of the pronounced activity preceding the button press, the wave trains appear to coincide (in amplitude) when the response occurs. In addition, what can be seen is not simple amplitude matching, but more important, frequency and phase shift relationships. These relationships are most evident in the 150 msec. interval preceding the response (segments 3, 4, and 5).

Note that the response-locked data presented in Table 4-2 show almost no significant differences for prereponse motor activity between the Color and the Form conditions. What has happened, in part, is that these important frequency and phase shift relationships shown in Figure 4-11 have been lost. By combining the Red and the Green conditions to produce Color information, the relevant information related to each specific condition has, in this case, been averaged away. We will refer to this effect again later.

#### Discussion

As noted in the introduction, we initially undertook this series of experiments simply to make electrocortical records that reflect mental activity—i.e., records not solely and directly tied in time to the occurrence of an abrupt physical change in

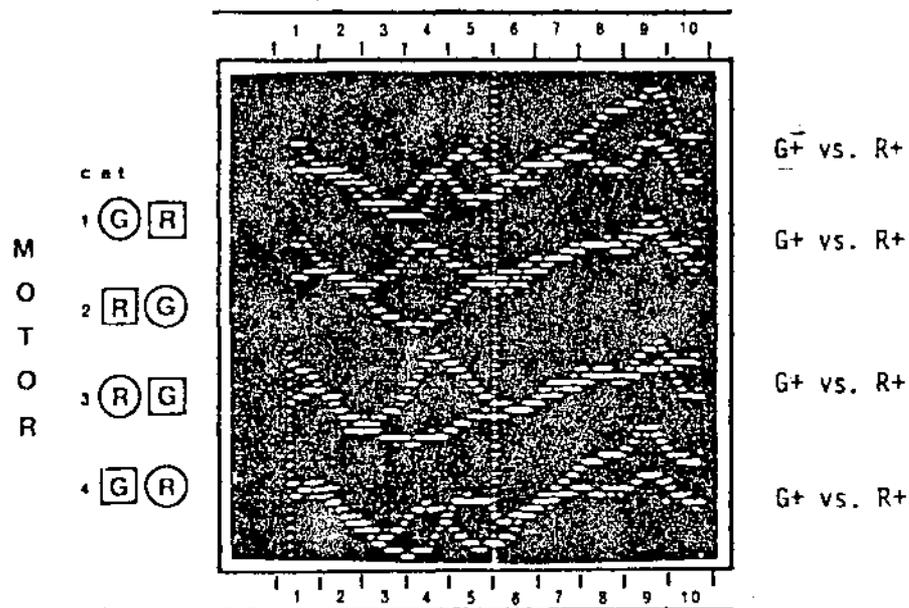


Figure 4-11. Response-locked activity for the motor electrode ( $C_m$ ) recorded from a human subject. Each pair of traces shows the averaged electrical activity recorded for the individual visual displays indicated. The differences between each pair of traces demonstrate the effects of frequency and phase shift relationships when only the reinforcement conditions have been changed from Green+ to Red+. The center line indicates the moment of the behavioral response (button press). Each segment on the lower scale represents 50 msec., i.e., 250 msec. just preceding, and 250 msec. just following the response.

the environment as in the classical evoked response. Others have modified the classical paradigm to similar purpose in their own fashion: notably e.g., John (John et al., 1973; Bartlett and John, 1973), Sutton (Sutton et al., 1967), Lindsley (Lindsley, 1969; Lindsley, Heider and Spring, 1964), and Hillyard (Hillyard et al., 1973; Picton et al., 1974). Our modification emphasized the presentation of a multidimensional stimulus and differential reinforcement of one or another dimension so that it would be selectively "attended" to for a particular recording session. We began our studies with monkeys because implantation of electrodes allows better localization of the electrical response; however, our ultimate interest is in the manner in which humans selectively attend and so studies on man were undertaken. We found that adult humans react so quickly, somewhat as we would expect intelligent monkeys who were super-overtrained, that we next tried children who might be expected to provide results intermediary between those obtained in monkeys and adult humans.

Our analyses were performed in the time domain, i.e., we looked for differences in the shapes of waveforms evoked by the stimulus or by the subjects' response. In the case of the response we analyzed the brain electrical record for some milliseconds prior to response in order to discover response-related brain activity that occurs before any overt behaviors can be observed. Our technique is as yet not sufficiently comprehensive to completely rule out covert peripheral responses coterminous with these early response-locked waveforms. However, the brevity of the stimulus flash serves to control for differential eye movements and the results of the various procedures undertaken with adult human subjects reported here indicate that covert peripheral muscular responses are unlikely to be the cause of the differential brain electrical responses.

What we have found in our time domain analyses of electrical brain records in monkeys, adult, and preadolescent humans is that during selective attention some change appears to occur in the temporal cortex prior to any changes that can be observed in primary visual or sensory-motor records. This precedence of the temporal lobe activity depends, however, on the amount of experience of the subject with the particular multidimensional display—in highly overtrained or sophisticated subjects the differential electrical brain potentials occur at all locations almost simultaneously. A more elaborate analysis (see below) must therefore be called upon to unravel the decisional mechanism which operates to select one stimulus dimension for attending in such subjects.

Nonetheless the analyses in the time domain allow some insights to be obtained with regard to the issues that have been discussed by experimental psychologists regarding the process of selective attention.

Thus the observation that stimulus selection is neither solely stimulus- nor solely response-locked is in agreement with observations made by Lawrence (1949, 1950) and developed by Neisser (1967). Lawrence suggested that discrimination learning must involve some kind of central coding process that, when it occurs, functions to speed up discrimination in a new situation. Neisser generalized a theory originally proposed by Liberman (Liberman, Cooper, Shankweiler and Studdert-Kennedy,

1969) in which selection is an active constructive process of analysis by synthesis. Central events select the components necessary to reconstruction.

Our data on overtrained subjects do not directly support the hypothesis of Deutsch and Deutsch (1963) who suggested that selection is not of the stimulus dimensions but only of responses to them. However, a modification of their view by Norman (1969) is compatible with our results: Norman suggests that central units similar to those assumed by Neisser are gradually constructed on the basis of both sensory input and some sort of weighting function that sets the criterion of activation of the unit.

Finally, our data on subjects just attaining criterion do not support a simple filter theory as originally proposed by Broadbent (1958). However, later modifications such as Treisman and Geffen's (1967) and Broadbent's (1971) filter-attenuation theories are supported, but only by the data obtained in *overtrained* monkeys and children and, of course, as well in adult college students when stimulus-locked changes in occipital recordings occur.

In short, we believe that the characteristic brain electrical patterns which emerge in our experiments which record selective attention after learning has occurred represent a learned strategy, a constituted constructive process that selects, and after overtraining even partially filters input. As we shall show shortly, we even have evidence that the constructive process proceeds in steps: the initial wave forms that are established as a result of learning the first correct set of responses within each stimulus category seem to serve as reference patterns for subsequent learning. We have, however, as yet not interchanged the order of categories to be learned (e.g., form before color), to determine whether all subsequent matching is done relative to the first condition learned, or to what extent the previously learned patterns facilitate or interfere with subsequent patterns.

In a sense, this succession of electrical events represents evidence for a preattentive reference pattern, a standard or attenuation filter, which becomes encoded as a result of overlearning. The preattentive mechanism must have certain properties usually discussed under the heading "memory." It must be capable of initiating not just one response, but a repertoire of responses. It must be able to group incoming signals in such a way that not only new categories can be established, but that existing categories can be implemented. The preattentive, precategorical mechanism thus cannot be confined to a single channel, but must somehow account for an interaction among various parts of the brain. Furthermore, it cannot be a two-dimensional mechanism, like a grid, since it must extend through a third dimension: time. But it is also hard to imagine a mechanism with all of these qualities that would exist *simply* in the time domain (serial processing).

#### New Directions: The Frequency Domain

Because of the observed phenomenon of matching amplitudes, which might be more reliably related to coherence and phase shifts at particular frequencies, a precategorical mechanism related to the frequency domain might be more relevant.

A frequency model would more easily handle interactions among channels (parallel processing). Such a frequency mechanism, or cascade of mechanisms, could describe the ongoing interactions among various parts of the brain. The activity resulting from populations of neurons and synapses exhibiting temporal and spatial summation would thus be correlated by the principle of superposition. Communication channels would become temporarily established by a cross-correlation process based on a match or mismatch between combinations of within- and across-channel parameters.

Such a model would provide a wider range of more accurate detail than time-locked averages and, as well, a legitimate basis, stochastically, for analyzing the electrical activity not only within, but between electrode channels. The information provided by a frequency model is a set of variables descriptive of the momentary state of the brain when the organism responds to a particular stimulus display, i.e., one of four categories, and allows those variables altered by a change in the state of the brain, i.e., changing the reinforcement conditions, to be distinguished and identified.

We tested the hypothesis that the frequency model might be a better fit to our data. Portions of the discrete (digitized) time series recorded for each trial were mathematically transformed, via computer, into a corresponding set of time invariant variables. The transformation operations are often referred to as *spectral analysis*. The new set of variables obtained by the transformation has the capability of describing the now time invariant *state* of the system that was sampled during the epoch (time interval) of interest. (Note: theoretically the lower limit for sampling is determined by the Nyquist rate, twice the highest frequency to be analyzed. Also, these techniques allow reconstruction of the original time series from the state variables, if desirable.)

The particular method of spectral analysis used to obtain the variables of power, phase shift, and coherence (as described below) may be thought of as a transformation from the time domain (a time-locked series of digitized voltage fluctuations) into the frequency domain (a set of descriptive variables related to each frequency, or frequency band, comprising the spectrum). Specifically, cross-spectral analysis, yielding variables descriptive of the state of the system as a function of electrode pairs, was used to obtain the phase shift and coherence parameters.

The analyzed data consisted of the first 250 msec. of stimulus-locked activity for the Green condition only. The frequencies examined were from 1 - 50 Hz. Values for intensity ( $\mu\text{v}^2/\text{Hz}$ .) were obtained for each frequency and then summed over the frequencies in each of six frequency bands. The six bands were theta (4-7 Hz.), alpha (8-12 Hz.), sigma (13-15 Hz.), beta (16-20 Hz.), high beta (21-30 Hz.), and high (31-49 Hz.). In addition, cross spectral values for phase shift and coherence were also obtained for each band, resulting in 72 variables for each raw data trial.

Note that intensity is defined in the same units as power, and is therefore a measure of the energy in the spectrum at each particular frequency, and subsequently, within each band. Power estimates are obtained independently for each electrode location. Bandwidth is defined in Hz., and is an estimator of the peakedness of each band. Phase shift (degrees) indicates the angle by which the first

channel of each electrode pair leads or lags behind the second in a given frequency band. The coherence function, being a dimensionless number between zero and one, provides a measure of the linear relationship between channel pairs. The coherence function acts like a coefficient of correlation between the records: a value near one indicates that, at a particular frequency, nearly all the activity in the one record can be explained as a linear transformation of activity in the other record; a value of zero means that there is no linear relationship between the records at that frequency.

The trials were arranged into four groups, by stimulus category, and subjected to a stepwise discriminant analysis program (Dixon, 1970). The results are shown in Figure 4-12 and Table 4-3 for stimulus-locked activity and in Figure 4-13 and

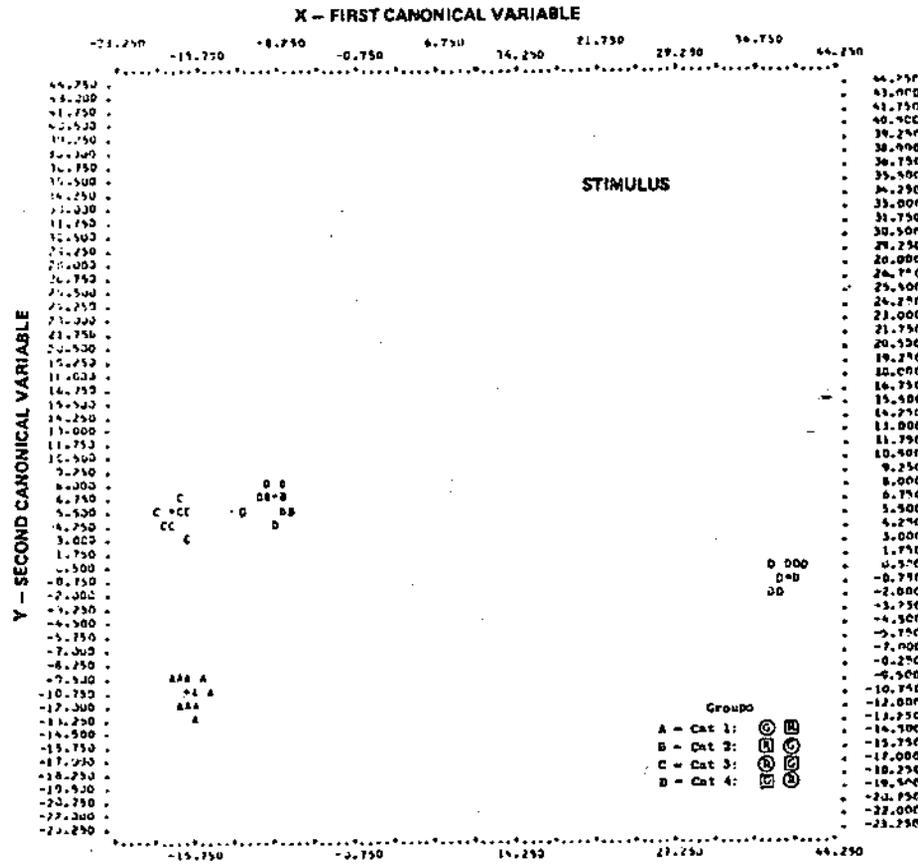


Figure 4-12. Canonical analysis of stimulus-locked data obtained from human subject (from stepwise discriminant analysis program). Each trial for Green correct has been classified into one of four stimulus groups on the basis of electrocortical activity. The scattergram illustrates the clustering of the trials about the group mean (\*) for each of the four visual displays.

Table 4-3 Summary of Stepwise Discriminant Analysis of Stimulus-locked Data for Green Correct. Each Step Indicates the Variable Selected Which Was Found To Be the Best Discriminator Among the Four Stimulus Categories

Step	Variable Selected	Percent Correct
1	52 Phase: Temp X Motor Beta (16-20)	41.509
2	5 Intensity: Temporal Hi Beta (21-30)	
3	46 Coherence: Temp X Striate Beta (16-20)	
4	48 Coherence: Temp X Striate High (31-49)	
5	70 Coherence: Striate X Motor Beta (16-20)	
6	64 Phase: Striate X Motor Beta (16-20)	
7	69 Coherence: Striate X Motor Sigma (13-15)	
8	41 Phase: Temp X Striate Hi Beta (21-30)	
9	6 Intensity: Temporal High (31-49)	
10	62 Phase: Striate X Motor Alpha ( 8-12)	79.245
11	61 Phase: Striate X Motor Theta ( 4- 7)	
12	53 Phase: Temp X Motor Hi Beta (21-30)	
13	72 Coherence: Striate X Motor High (31-49)	
14	23 Bandwidth: Striate Hi Beta (21-30)	
15	71 Coherence: Striate X Motor Hi Beta (21-30)	
16	40 Phase: Temp X Striate Beta (16-20)	
17	57 Coherence: Temp X Motor Sigma (13-15)	
18	34 Bandwidth: Motor Beta (16-20)	
19	18 Intensity: Striate High (31-49)	
20	63 Phase: Striate X Motor Sigma (13-15)	90.566
21	67 Coherence: Striate X Motor Theta ( 4- 7)	
22	49 Phase: Temp X Motor Theta ( 4- 7)	
23	42 Phase: Temp X Striate High (31-49)	
24	38 Phase: Temp X Striate Alpha ( 8-12)	
25	54 Phase: Temp X Motor High (31-49)	
26	15 Intensity: Striate Sigma (13-15)	
27	11 Bandwidth: Temporal Hi Beta (21-30)	
28	43 Coherence: Temp X Striate Theta ( 4- 7)	
29	44 Coherence: Temp X Striate Alpha ( 8-12)	
30	47 Coherence: Temp X Striate Hi Beta (21-30)	96.226
31	9 Bandwidth: Temporal Sigma (13-15)	
32	20 Bandwidth: Striate Alpha ( 8-12)	
33	13 Intensity: Striate Theta ( 4- 7)	
34	21 Bandwidth: Striate Sigma (13-15)	
35	37 Phase: Temp X Striate Theta ( 4- 7)	
36	68 Coherence: Striate X Motor Alpha ( 8-12)	
37	58 Coherence: Temp X Motor Beta (16-20)	
38	12 Bandwidth: Temporal High (31-49)	
39	3 Intensity: Temporal Sigma (13-15)	
40	45 Coherence: Temp X Striate Sigma (13-15)	98.113
41	28 Intensity: Motor Beta (16-20)	
42	14 Intensity: Striate Alpha ( 8-12)	
43	59 Coherence: Temp X Motor Hi Beta (21-30)	
44	56 Coherence: Temp X Motor Alpha ( 8-12)	
45	50 Phase: Temp X Motor Alpha ( 8-12)	
46	66 Phase: Striate X Motor High (31-49)	
47	33 Bandwidth: Motor Sigma (13-15)	
48	2 Intensity: Temporal Alpha ( 8-12)	
49	10 Bandwidth: Temporal Beta (16-20)	100.000

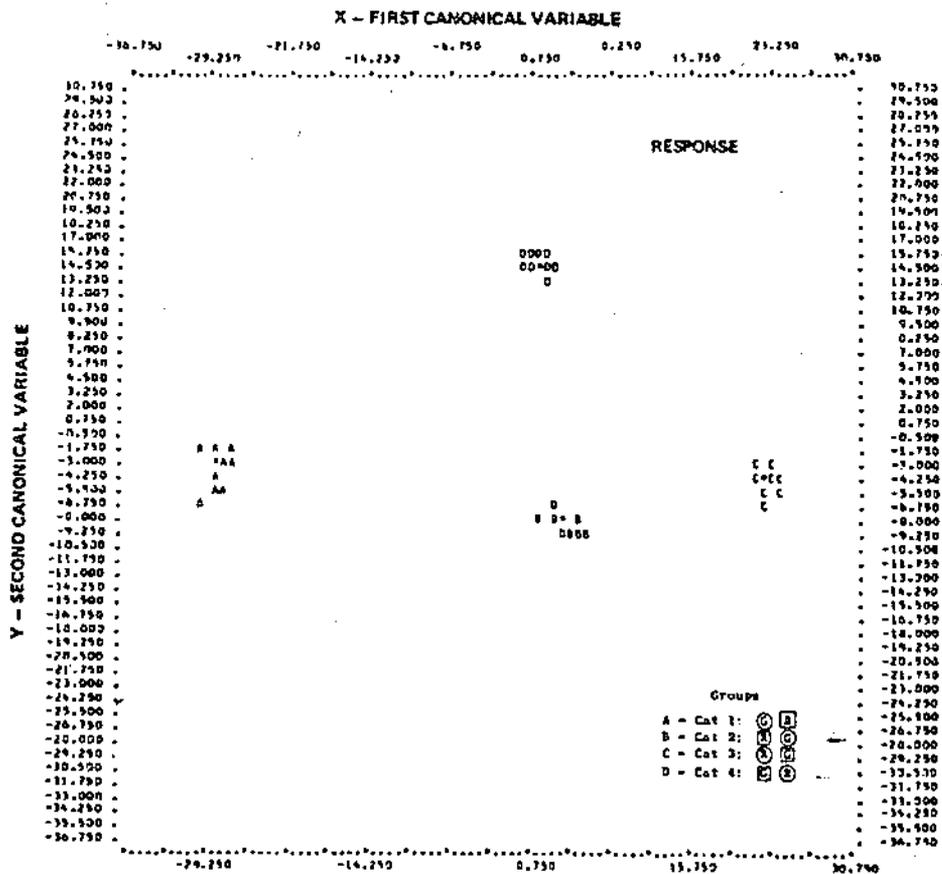


Figure 4-13. Canonical analysis of response-locked data obtained from human subjects (from stepwise discriminant analysis program). Each trial for Green correct has been classified into one of four stimulus groups on the basis of electrocortical activity. The scattergram illustrates the clustering of the trials about the group mean ( $\bar{x}$ ) for each of the four visual displays.

Table 4-3 for response-locked activity. Each trial was distinctly classified into one of four separate groups (categories) on the basis of the 72 auto- and cross-spectral parameters, with all trials correctly identified. Forty-nine steps were required to achieve 100 percent correct separation for the stimulus-locked activity, but only thirty steps were required for the response-locked activity.

For both stimulus and response-locked activity, the cross-spectral values for phase shift and coherence were the most important discriminators. Almost 42 percent of the stimulus-locked epochs for each trial were identified at step one on the basis of phase shift between the temporal and motor channels in the beta frequency range (16-20 Hz.). The order of importance of the variables selected by the program

Table 4-4 Summary of Stepwise Discriminant Analysis of Stimulus-locked Data for Green Correct. Each Step Indicates the Variable Selected Which Was Found To Be the Best Discriminator Among the Four Stimulus Categories

Step			Variable Selected		Percent Correct
1	67	Coherence:	Striate X Motor	Theta ( 4- 7)	43.396
2	53	Phase:	Temp X Motor	Hi Beta (21-30)	52.830
3	66	Phase:	Striate X Motor	High (31-49)	62.264
4	46	Coherence:	Temp X Striate	Beta (16-20)	60.377
5	39	Phase:	Temp X Striate	Sigma (13-15)	60.377
6	43	Coherence:	Temp X Striate	Theta ( 4- 7)	73.585
7	71	Coherence:	Striate X Motor	Hi Beta (21-30)	75.472
8	61	Phase:	Striate X Motor	Theta ( 4- 7)	79.245
9	42	Phase:	Temp X Striate	High (31-49)	73.585
10	32	Bandwidth:	Motor	Alpha ( 8-12)	81.132
11	8	Bandwidth:	Temporal	Alpha ( 8-12)	
12	6	Intensity:	Temporal	High (31-49)	
13	30	Intensity:	Motor	High (31-49)	
14	26	Intensity:	Motor	Alpha ( 8-12)	
15	25	Intensity:	Motor	Theta ( 4- 7)	84.906
16	63	Phase:	Striate X Motor	Sigma (13-15)	
17	34	Bandwidth:	Motor	Beta (16-20)	
18	18	Intensity:	Striate	High (31-49)	
19	35	Bandwidth:	Motor	Hi Beta (21-30)	
20	56	Coherence:	Temp X Motor	Alpha ( 8-12)	96.226
21	51	Phase:	Temp X Motor	Sigma (13-15)	
22	59	Coherence:	Temp X Motor	Hi Beta (21-30)	
23	23	Bandwidth:	Striate	Hi Beta (21-30)	
24	5	Intensity:	Temporal	Hi Beta (21-30)	
25	64	Phase:	Striate X Motor	Beta (16-20)	98.113
26	19	Bandwidth:	Striate	Theta ( 4- 7)	
27	17	Intensity:	Striate	Hi Beta (21-30)	
28	48	Coherence:	Temp X Striate	High (31-49)	
29	45	Coherence:	Temp X Striate	Sigma (13-15)	
30	11	Bandwidth:	Temporal	Hi Beta (21-30)	100.000
31	40	Phase:	Temp X Striate	Beta (16-20)	
32	52	Phase:	Temp X Motor	Beta (16-20)	
33	47	Coherence:	Temp X Striate	Hi Beta (21-30)	
34	3	Intensity:	Temporal	Sigma (13-15)	
35	7	Bandwidth:	Temporal	Theta ( 4- 7)	100.000
36	16	Intensity:	Striate	Beta (16-20)	
37	36	Bandwidth:	Motor	High (31-49)	
38	57	Coherence:	Temp X Motor	Sigma (13-15)	
39	21	Bandwidth:	Striate	Sigma (13-15)	
40	37	Phase:	Temp X Striate	Theta ( 4- 7)	84.906
41	60	Coherence:	Temp X Motor	High (31-49)	
42	55	Coherence:	Temp X Motor	Theta ( 4- 7)	
43	44	Coherence:	Temp X Striate	Alpha ( 8-12)	
44	9	Bandwidth:	Temporal	Sigma (13-15)	
45	1	Intensity:	Temporal	Theta ( 4- 7)	50.943
46	28	Intensity:	Motor	Beta (16-20)	
47	49	Phase:	Temp X Motor	Theta ( 4- 7)	
48	4	Intensity:	Temporal	Beta (16-20)	

are arranged according to step number and indicated in Table 4-4. For response-locked activity, 43 percent of the cases were identified at step one by coherence between the striate and motor cortex in the theta frequency range (4-7 Hz.). Note that this information is consistent with the photographs of the response-locked data in which low frequency activity is visible. Most of the activity is between one and two cycles in the .25 sec. period preceding the response. This would be the same as four to eight cycles in one second. The remaining steps are shown in Figure 4-13.

These results indicate that further investigation of the frequency domain should give valuable insight into the nature of the cross-channel variations as well as within channel activity. By combining the evoked potential technique (time domain) with cross-spectral analysis (frequency domain), a fuller understanding can be obtained of the complex relationships described here.

### Conclusion

One final observation seems worth comment. Some criticism has been made concerning the value of scalp electrode recordings in the attempt to explain brain function. The main criticism has been that scalp recordings reflect gross activity from whole populations of cells. This apparent limitation may in fact prove to be a strength. Improved scalp recording techniques have great value, especially in that they do reflect interactive relationships, hyper- and depolarizations at synaptic and dendritic locations, as well as neuronal firing patterns. Such recordings thus provide a supplement to research restricted to sampling of unit activity. In this manner the principles relating to individual neurons, groups of neurons, and communication channels amongst them can be specified.

A major difficulty in using scalp electrodes has been to determine exactly what parameters would be most suitable for describing the system. Failure to describe a system will result if inappropriate or insufficient parameters are used. As we saw, time domain averages are not inappropriate, but they are insufficient, and often mask the relevant details that are averaged out. Frequency information has been useful, but often restricted to single channels. Cross-spectral parameters, involving several channels, have yielded the extent of covariance over time, particularly in terms of phase shift, coherence, and intensity of the activity at various frequencies of interest. Each has produced its own kind of two-dimensional perspective. This has resulted in static descriptions thus delineating static systems, the explanations of the dynamics being left to inference. A three-dimensional system cannot be adequately described by two-dimensional parameters, any more than the trajectory of a missile or its behavior in flight can be described by its speed alone.

Quantitative three-dimensional analysis, essentially describing the directional flow of information across brain space, and the constraints operating among brain systems, has only begun to be examined. What is lacking are vector parameters,

involving both magnitude and direction. Despite the complexities involved, we believe that techniques are now sufficiently advanced to proceed with such three-dimensional analyses of the brain's electrical "spirits" that come to constitute "mind."

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