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Some Current Methods in Neuropsychological Research

KARL H. PRIBAM
ROBERTA DAY
JOHN GLICK

DADTA: An On-Line Computerized System for the Experimental Analysis of Behavior

The experimental analysis of behavior had been revolutionized by the study of conditional behavior. Perhaps the most important change that has occurred in behavioral studies as a consequence is that precise automated control of the contingencies which guide or produce behavior is now possible and commonplace, as well as the unequivocal recording of stimuli and their behavioral effects.

Most studies employing operant techniques use continuous performance recordings of one sort or another. These have been eminently successful in analyzing situations in which the temporal course of behavior is being investigated. Further, ingenious modifications have allowed such innovations as the measurement of sensory thresholds in animals. The ease with which apparatus can be modified has allowed a rich search, only some of which has been reported in the literature.

In our experience, however, one application of operant techniques was consistently found wanting. Continuous performance procedures proved relatively inefficient when simple discrimination behavior was in question. With these procedures many more responses accumulate before a criterion is reached than when discrete manual techniques are used. This inefficiency was usually more than counteracted by the facility provided by automation. But, again, data analysis proved cumbersome—less was recorded than was needed and some of the fine grain of the behavior was difficult to extract from the record.

These limitations led to the modification of a system for the experimental analysis of behavior in the direction of being able to record more fully *discrete* happenings while retaining the capacity to study S's continuous performance. When electrical brain events are to be analyzed the division of the course of

behavior into discrete events that can evoke recognizable brain potential changes becomes imperative. At first a special purpose device was constructed and used successfully for about 3 yr.; this was superseded by the present system which has now been operating for 7 yr. and is reported in detail here. The original device was christened DADTA (Discrimination Apparatus for Discrete Trial Analysis) and was described in an earlier report. (Pribram et al., 1962.) The current configurations are known as DADTA III and DADTA IV, since they are the third and fourth major versions of the technique.

There are now some 20 or so studies reported in the literature (see References denoted by asterisk) which were accomplished with the use of DADTA systems. Modifications have produced increased flexibility and reliability to a point where "down" time compares favorably with ordinary operant equipment and even manual testing. The result is that "E" deals with biological and behavioral rather than with electronic problems. Meanwhile costs have plummeted so as to make DADTA an attractive package even to the small laboratory. At least one manufacturer (Grason-Stadler) of behavior control equipment is making commercially available a complete DADTA-type system with capabilities similar to those described below.

DADTA III

The DADTA III system utilizes a small (12-bit, 4 K core storage) real time, on-line general purpose computer with a cycle time of 1.5 msec. This computer, a PDP-8 (Digital Equipment Corporation), is interfaced with a square matrix of 16 ID display panels each of which is covered with a clear plastic disc which, when depressed, closes a microswitch activating an IEE (Industrial Electronic Equipment) one-plane digital readout projection unit. Each unit is capable of displaying 12 patterns; 10 of these can be presented against the background of the other two, which are colors.

A particular computer program is commonly controlled through one of several input devices. Programs are usually initiated on a teletype which activates a magnetic tape read-in to place in the computer the desired program. As described in detail below, a unique subroutine system permits each E flexibility in selecting experimental parameters. The programs as a whole are initially composed and debugged on the teletype.

The entire constellation of events which determine the behavior of the organism and the consequences of this behavior are recorded on-line by the teletype and optionally on punched tape. As the organism performs, an instantaneous report is typed of the characteristic of the cue displayed on the panel pressed, the position of the cue on the display panel, the latency of response, the correctness or incorrectness of the response (according to the program in effect), and whether or not a reward was given. At the end of each testing session these parameter characteristics and their outcomes are automatically summarized in a simple numerical tally.

The construction of an appropriate interface makes all of this possible. The major tasks of interfacing the computer with its external devices are matching the informational and electrical characteristics of the two systems and signaling the timing of a data transfer (Fig. 1). Since DADTA III computer system interfacing components can be purchased from the computer manufacturer, the problem of such matching can be minimized.

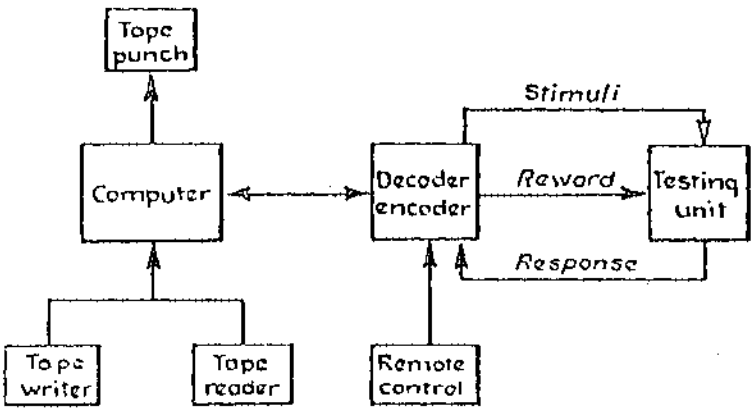

Fig. 1. Overall schematic of DADTA III.

Transfer of stimulus information is effected with a 64-bit flip-flop memory buffer. The codes for two symbols (8 bits) are loaded into the accumulator and transferred to the flip-flop buffer. An input-output command, with appropriate device-selector address, gates the data into the buffer. From the flip-flop, indicator-driver circuits decode and amplify the display signals. (See Fig. 2.)

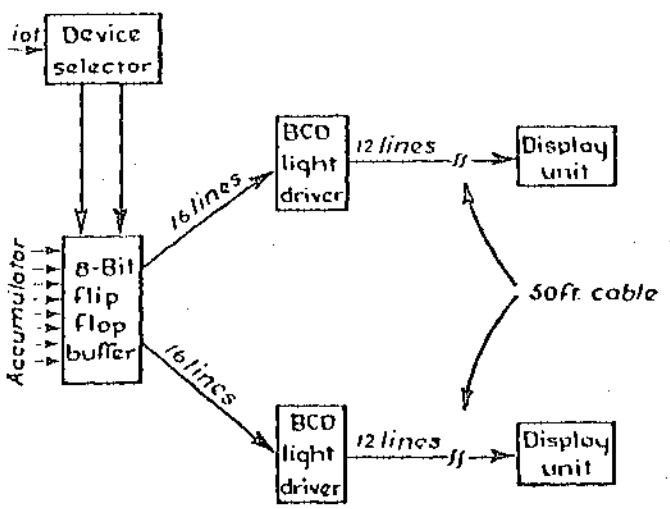

Fig. 2. Schematic of interface between computer and display panels.

DADTA IV: A Computerized Discrimination Apparatus Based on Scan Conversion

Thus, computer controlled behavioral testing devices are rapidly reaching the point of development where they can be put to general use (e.g., Pribram's DADTA III (1969); Grayson Stadler's SCAT system, Lehigh Valley's Interact System). Although the initial cost of such equipment is no longer prohibitive, it is still beyond the reach of many single investigators, especially those just beginning their research career. Further, the current computerized systems are of considerable size, demanding more or less permanent installation.

Two recent developments have suggested to us a way to break the price and size barriers. Digital Equipment Corporation among others has marketed a really low cost general purpose computer (the PDP-8)E) and Tektronix has produced a Scan Converter (4501) which readies the output from a computer for visual display on a TV monitor. Under computer control the Scan Converter can produce a virtually infinite variety of both static or dynamic patterns or symbols for visual stimulation. The Scan Converter can drive several conventional TV monitors or commercial quality TV sets. This makes feasible a multiplicity of visual testing stations and remote experiment monitors. The Scan Converter can also be used for text output, for graphic display of reduced data or for large screen viewing of raw data. (If a Tektronix 4601 Hard Copy unit is added to the system, hard copy output can be obtained for anything displayed on the Scan Converter.)

When the system is used in the DADTA (Discrimination Apparatus for Discrete Trial Analysis) configuration the TV monitor is located in a testing chamber in front of the subject. A mask, in which a 4 x 4 matrix of viewing ports are cut, covers the front of the monitor. A single symbol is displayed behind each of one or more of the ports and the subject makes appropriate responses by pressing switches located at each port. Masks with other configurations of the viewing ports can be used as need dictates; however, the 4 x 4 matrix has proved adequate for a majority of studies. The switches are connected to two 12-bit input registers which are used to record the subject's responses and for input from other peripheral equipment.

Computer control is achieved by means of a 6 bit output register which connects to two channel D/A converter (and stroke generator) with the Scan Converter which it controls. In addition, a 12 bit output register with dc and ac switches is used to control miscellaneous peripheral equipment such as feeders (for reinforcement), stimulators, lights, audiogenerators, etc. as demanded by the experiment. An interrupt clock running at 1 KH$_z$ is used by the software (programming) for sequence timing and interval measurement.

At present the Scan Conversion based DADTA IV can be put together for $10,000. All but response panels, 3 connecting cables, and 2 wire wrap panels of the equipment necessary to interface the computer and Scan Converter are commercially available shelf items. DADTA IV can be housed in two standard 5 ft. by 19 in. relay cabinets, one containing modules to be brought into proximity of the

subject to be tested, the other containing modules used to control the display and reinforcing contingencies and to record responses. The recording devices, including teletype, take up 2 ft. x 5 ft. Three easily demountable tied connector cables, 3/4 in. in diameter, completes the system configuration which can be wheeled about and set up where necessary, e.g., in hospitals at the bedside, in EEG rooms, in psychological testing chambers, and the like.

The Programs

The crux of the control provided by the DADTA III and DADTA IV systems lies in programming. With earlier versions of the DADTA system, as in most operant setups, we accomplished our programming through hardware; with the advent of inexpensive general purpose computers—machines such as the PDP-8—we were able to turn to the more flexible facility of software manipulations. This is achieved via a unique (and extensive) library of sub-routines each of which can be added or removed in moments by simple keyboard commands. At present we have accomplished a software package for our interface; should another interface be employed, a skilled programmer must be enlisted to meet the specific needs of the system and laboratory. A typical core program will include the following basic characteristics.

First, of course, is *stimulus* control. Each of the 16 ID panels is capable of 12 possible displays without any hardware change (with an exchange of masks the number of possible displays becomes unlimited). A subroutine stores the symbols representing the display in a buffer in a form available to a calling sequence. When called, the contents of this symbol buffer are moved into the display buffer and are transmitted to the ID panels via another DADTA buffer in which are represented the panels by location. Another subroutine operates on the symbol-display location table and presents the next symbol display. It also saves the time of the display for the latency calculation. This is done by clearing the symbol buffer and filling it with the next symbol in the table. The latency measure is stored in a latency buffer until printed out.

Second, the computer must control the scheduling of *reinforcement*. For accomplishing this a "reward" subroutine activates the pellet dispenser according to the investigator's parameters for that program. In addition to the activation of the dispenser, the routine must set a flag to signify that the reward was given and, when completed, bump the reward counter, i.e., increase it by one. Another subroutine determines whether or not to reward a press based on whether a particular symbol was displayed in the panel pressed. This subroutine works by checking a prestored reward table, provided by the investigator, for the presence of the appropriate symbol.

Third, a *print-out* subroutine provides a response-by-response record of which panel and symbol were pressed. The operation of this subroutine is typically as follows: As already noted, both a symbol and a panel buffer are available. In these a record can be readily made of each response (panel depression) as it occurs.

a subroutine then loads these records into the accumulator prior to on-line print-out. In addition, when it is desired, a latency subroutine computes and prints the latency between the time of display of the symbols and either the press or the release of a lighted panel. The operation resembles a skip-on-a-hardware flag instruction: when the software latency flag is set as a lighted panel is released, the program proceeds to print out the latency. Until this occurs the program stays in a tight loop continually checking the latency flag and clocks. Once the flag is down the display time is subtracted from the release time and the print-out is activated; minute, second, and millisecond differences are recorded.

These are, of course, only overviews of some of the critical subroutines needed to compose the desired program. They give a flavor of what is necessary; the specifics depend on the particular configuration needed to make the behavioral analysis sought.

An Experiment

In order to demonstrate the power and flexibility of DADTA-type installations, a specific experiment performed with this instrument will be detailed. The chief concern of our laboratory is the analysis of brain-behavior relationships. Many experiments accomplished over a 20-yr period have established the fact that bilateral resection of the inferior gyrus of the temporal lobes of monkeys markedly impairs the acquisition of visual (but no other) discriminations. Since this impairment comes about without any invasion of the primary visual mechanism of the brain, the question has repeatedly been asked whether the defect in discrimination is due to an inability to process cues or to shifts in the criterion for making a response.

An analytic technique has been devised to tease apart behavioral situations in which just this sort of question is raised. This is the technique of signal detection in which the response-operator characteristics are plotted as curves (ROC curves) from which sensitivity to differences among cues can be separated from other factors which bias responses. While this technique has been extensively applied in human studies, it has only recently been adapted, at considerable cost in labor and limitation, to studies with animals. DADTA III seemed to be the ideal instrument to automate ROC procedures for the extensive analysis of discrimination behavior necessary to our interests.

The complete results of an ROC analysis of the behavior of monkeys with bilateral resections of the inferior temporal cortex will be presented elsewhere. Here we want to present only the details of the procedure and some ROC curves obtained when normal monkeys are tested.

Shaping. The actual testing in the DADTA begins, of course, with a shaping procedure. This procedure has been standardized, and one of the dividends of using DADTA has been its ability to record a large segment of the changes produced by shaping. Several such reports have been prepared and published

(Blehart, 1966; Dewson, 1967; Pribram et al., 1969) both for unoperated and brain-operated monkeys.

We begin shaping by accustoming the monkey to the pellets used in the dispenser, then presenting him with the pellets in the DADTA feeder cup, then delivering the pellets to him by remote operation of the feeder (behavior is observed through a one-way window) until the monkey makes a response toward the cup upon hearing the click of the feeder relay. We then shape this contingent behavior upward until the monkey actually presses a panel (on rare occasions we might have to attach a pellet to a panel with transparent tape). Learning is remarkably swift: an average of only two or three daily sessions of a half hour accomplish the first panel press.

After this point the E does not intervene; the procedure is completely automated. Twelve of the 16 panels display the number "1"; the other four are dark, i.e., blank; lit and dark panels are randomized over trials. Whenever a display is pressed, a reward is given. Thus the monkey immediately works on a .75 fixed-ratio distributed-response schedule. After this becomes well established (2 or 3 days of 50 trials per day) the number of displays is cut to 10, 8, 6, 4, and finally, 2. The number of presses made to the displayed panels versus the number made to the blank panels determines the ratio of reinforcement obtained. A complete record of each response (panel pressed and whether rewarded) is printed out instantaneously by the teletype, as is a trial-by-trial summary at the end of the run.

The Discrimination Task. On completion of shaping, the monkey was presented the discrimination problem. The middle two ID panels of the fourth row displayed a red disc. The monkey was required to press either of these in order to initiate the stimulus display, thus self-pacing the task and providing precise reaction time latencies. Once he pressed, a green disc and a blank panel simultaneously appeared in the middle two panels of the second row. The light intensity of the green disc was varied. This was accomplished by flickering the displayed figure at varying rates, all above the fusion threshold of monkeys (Mishkin and Weiskrantz, 1959). Reward was given only if the panel on which the green disc appeared was pressed, but report of reinforcement or of nonreinforcement due to press of the blank panel extinguished the display, and 5 seconds later the lower panels again lighted up in red, preparatory to the initiation of another stimulus display.

A record of each response was printed out by the teletype. Each trial record detailed which panel was pressed, the latency between the press of the red trial-initiating panels and the press of the discrimination panels, the intensity of the green disc on that particular trial, and whether reward was or was not obtained. At the end of a run (100 trials) a summary was collated and printed. The summary showed how many responses were made at each "stimulus" location, how many responses were made at all other panels, and how many rewards were obtained.

The ROC Experiment. The study was performed with monkeys who had been

shaped and had learned consistently to accomplish discrimination at the highest intensity of the green disc which was expressed as points in an ROC space and evaluated according to Norman's techniques (Norman, 1964). Reaction time latencies were used in accordance with Bloug's procedure (Blough, 1967) to construct ROC curves. An example is shown in figure 3.

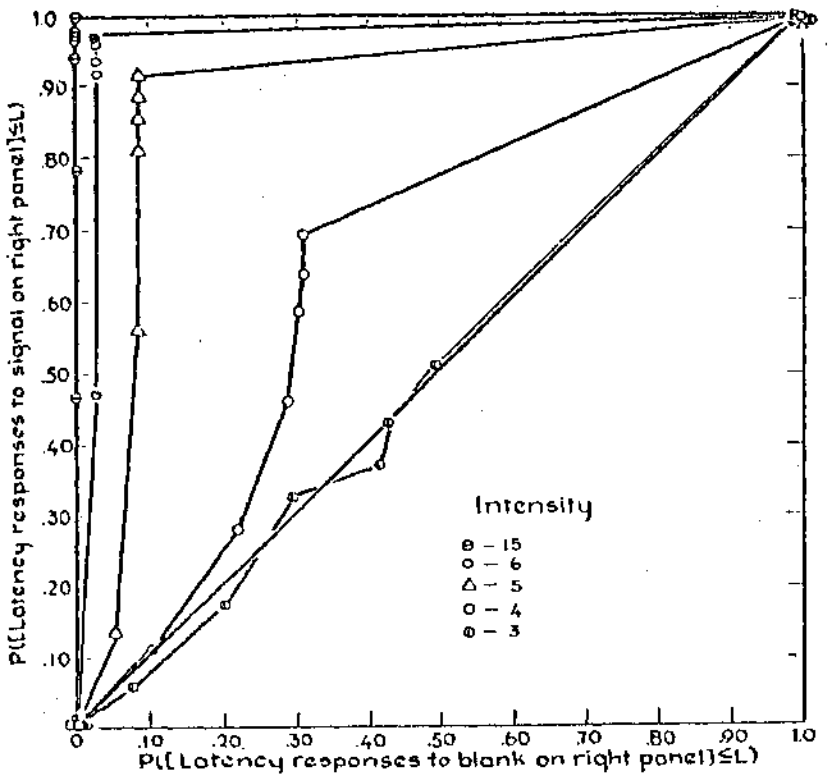

Fig. 3 Receiver-operator characteristic curve based on latency of responses made to various intensities of panel illumination as indicated.

This experiment represents only an initial examination of the uses of signal-detection techniques to separate performance into its input and output dynamics. Current research now in progress attempts to extend these analytic procedures to the successive discrimination condition paradigm which will allow the use of choice as well as latencies to constant ROC curves. Successful completion of this work should sharply enhance the usefulness of signal-detection procedures in the evaluation of brain-behavior relationships.

FATLIP: Filter Analysis of Time Locked Inflection Points

One additional advantage of analyzing behavior in terms of divisions into discrete trials is that this procedure allows a ready analysis of the electrical brain activity concomitant with that behavior. Discrete stimulus presentations and discrete responses ordinarily evoke abrupt potential inflections in the electrical activity recorded from the appropriate regions of the brain. Thus the record of brain activity preceding and following these "markers" can be studied with a view toward understanding how stimuli are processed by the brain, how responses are generated, and how the effects of the consequences (reinforcements) of a response influence brain activity (see for instance, Pribram et al., 1967).

FATLIP is one such procedure for analyzing the brain record accompanying discrete behavior and was chosen for detailed description because it shows promise of wide applicability at reasonable cost.

Electrode placement is determined experimentally by examining the quality of the electrophysiological recordings obtained from several preliminary S's performing one task. In general, three areas of the brain are monitored on three separate channels: temporal, visual, and motor cortex. Bipolar recording techniques are used. An additional channel is used to monitor eye movement. The right ear lobe is used for reference. By placing one pole of each electrode at a common, indifferent location (the ear lobe), the potential differences recorded represent the ongoing activity at the other pole. In this way the activity at one particular scalp location can be examined, rather than the resultant activity between two scalp locations.

At the beginning of the first session with the S, careful measurements are made of the head and the exact electrode locations determined. A small patch of hair the size of the electrode is clipped from the S's scalp at each electrode location. This is done to ensure that the same locations would be used during subsequent sessions.

Before the S entered the booth to begin a session, the scalp is prepared and electrodes applied. Scalp resistance is kept under 10 Kohms. Each channel is checked for 60 H_z and for general quality of the amplified signal before proceeding with the collection of data.

Data Collection

Fluctuations in voltage (± 250 uV) due to localized cortical activity, monitored by bipolar electrodes implanted in brain cortex or on the scalp, are differentially amplified (gain 20K) and fed into separate channels of an analog to digital converter. Cutoff frequencies are set at 0.8 H_z and 50 H_z. Sampling rate for digitization is 0.002 sec, so that continuous data (voltages) are converted to a set of numerical (digitized) data points representative of a fixed interval of time. Each data point is a sample of the ongoing, continuous, real time electrical activity occurring at the electrode which, when recorded, becomes part of an ordered set of

numbers which numerically describe the continuous electrical activity over a period of time. Since continuous information represents an infinite number of data points, the digitization process reduces the total information to a meaningful number of discrete points, ordered according to time, with fixed intervals of separation.

Digitized information is collected on magnetic tape according to the time locked sequence diagrammed in Figure 4. The trial duration time, or latency from

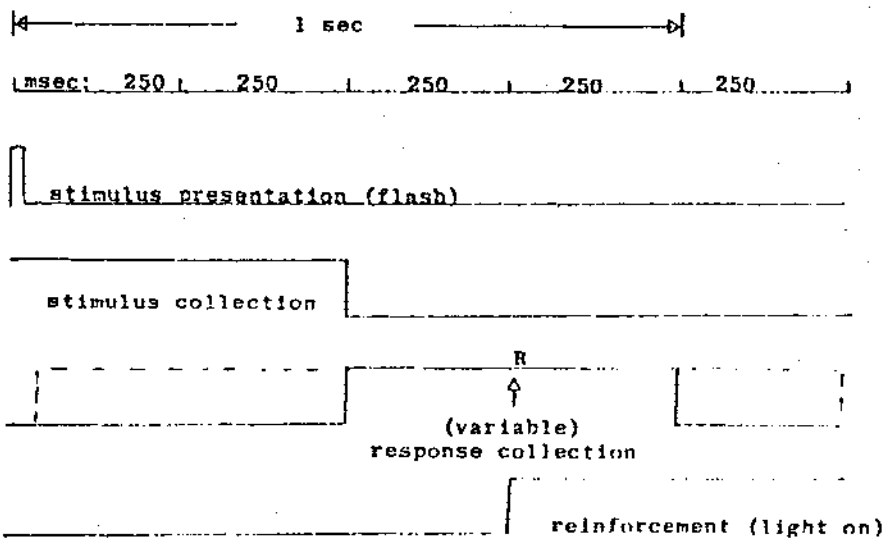

Fig. 4. Example of experimental timing for one trial.

stimulus onset to behavioral response, is set to a maximum of 1 sec., followed by an additional 250 msec post response (reinforcement) period. The maximum length of any single trial is 1.25 sec. The minimal length of the intertrial time is determined by the delay due to the mechanical action of the apparatus.

With a sampling rate of 0.002 sec, 250 raw data points are collected for each 500 msec of continuous information. Since two such period are established, the result is 500 time locked data points for every trial: 250 points of stimulus locked activity and 250 points of response locked activity. For any one day (N = 60 trials), 30,000 raw data points are recorded for each electrode.

It is important to distinguish one main difference between the stimulus locked and response locked collection procedure. The stimulus locked data points are recorded as they occurred in time, i.e., *forward* in time from t_0 (at the flash) to t_{500}. The first data point recorded would be s_1 at t_2, 2 msec after the flash, and the last data point would be s_{250} at t_{500}. However, since the response is variable, it could occur before 500 msec, which would place it within the stimulus locked period. At the time of collection, the point at which the response occurred is shifted so that all

such points are placed at the center of the response segment. All data points around the response retain their relative positions. The resulting effect of shifting the data in this manner is that the response locked data points just preceding the response are no longer relative to the flash, but rather proceed *backward* in time for 250 msec before the response. The 250 msec following the response again proceeds forward in time from the response. If the response is said to occur at t_0, then the data points in the response locked period would begin at r_1 at t_{-250}, would be centered at r_{125} at t_0, and would end at r_{250} at t_{250}. The purpose of this is to align all data with respect to time preceding the response before further data reduction is performed.

Data Reduction

Time locked averaging methods are used for data reduction. Single averages over one day are performed on the raw electrophysiological data according to the general format shown in Figure 5a. The single averages for each of six days are then averaged to obtain the final double average for each task. A total of 36 single averages are reduced to six double averages (one double average per task). Double averages are performed according to the same format as the single averages (Fig. 5b).

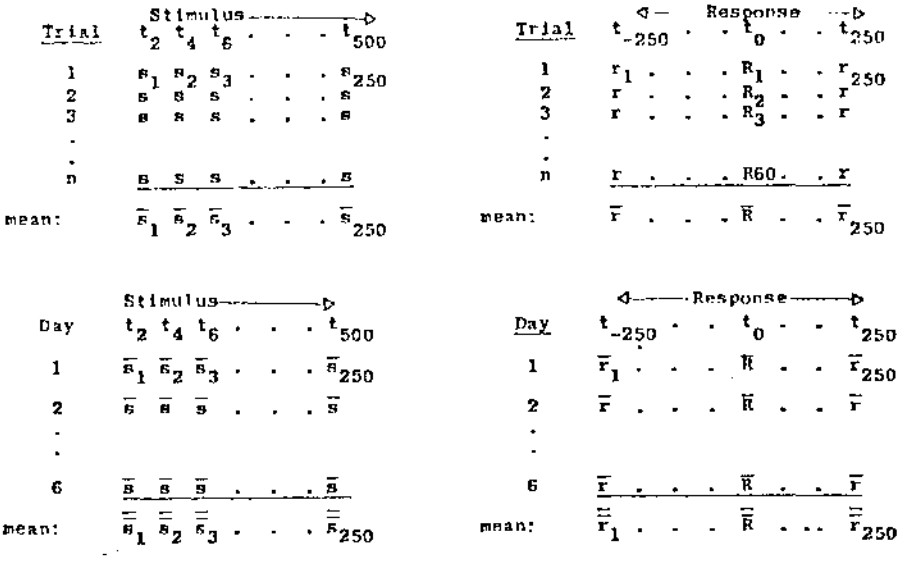

Fig. 5(a). General format representing point by point averaging technique used for time locked data. The means obtained are single averages for one day. (b) General technique for obtaining double averages. Means represent all trials for one task. Note that stimulus and response locked averages are performed separately.

This method has been used successfully in previous work and can be recognized as a digital method of filtering a pure signal of relatively low amplitude from random background noise inherent in the system being measured. The number of trials averaged, however, must be sufficient to establish columnwise Gaussian distribution, i.e., within each column of time. If this condition obtains then point by point t-tests can be made between two such averages, since each average is simply a set of mean values.

For example, if the activity occurring in column 1, at t_2 (Fig. 3), is purely random from trial to trial, then the values of s_1 would be expected to be normally distributed over the 60 trials. The mean of such a normal distribution would be the baseline, s_1, with an equal number of values occurring above and below the baseline. If the activity in each time column from t_2 to t_{500} is also random, then the corresponding means from s_1 to s_{250} will constitute a straight line, the baseline. If the activity is not random, however, then each mean will represent an average deviation from the baseline, or relative amplitude of the brain voltage at that point in time. In this case, the set of means will constitute a waveform. Note that the waveform emerges because the noise *is* random, and is therefore "averaged out" (the mean approaches zero amplitude).

Using the general principles explained thus far, all data are processed by means of several specialized computer programs designed for these purposes. An oscilloscope display routine is used to screen each trial for muscle and eye movement artifact. All bad trials are eliminated by the E before averaging. The data are then collated on the basis of behavioral information and averaged according to appropriate groups (Fig. 6). Thirty groups were distinguished on the basis of five

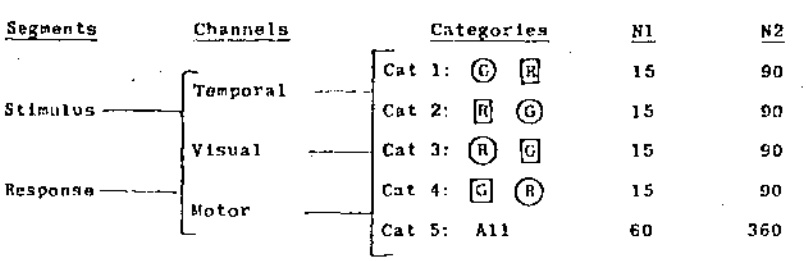

Fig. 6. The classification used for separating data into 30 groups. N1 is the maximum number of correct trials per group averaged for one day, N2 one task.

categories per channel, three channels, and two time locked segments. Separate single and double averages are obtained for each group. Since data are collected at criterion, requiring 55 to 60 correct trials, only the correct trials are used. If all trials are correct, there would be 15 trials per stimulus category per day, and 90 trials over 6 days. The actual number of trials averaged for each task are listed in Appendix I.

Data Analysis

Significant differences between waveforms are established by further averaging techniques which do not rely entirely on point by point t-tests. When comparing *patterns* of activity, it is sometimes more meaningful to examine inflection points: the number, direction, and mean amplitude between them. Inflection points of each wave pattern serve as break points for data analysis, so that the amplitude values of the segment of the wave between two break points can be averaged. In this way the mean amplitudes of comparable segments of different waves can be compared. Similar waveforms would be expected to have similar inflection points and mean amplitudes; when different, such differences can be established statistically in terms of p-values derived from standard t-tests (Fig. 7).

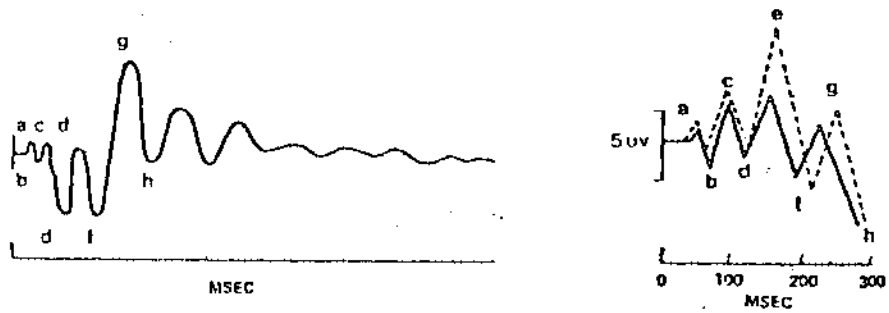

Fig. 7. Amplitude and latency differences between similar waveforms (Rhodes et al., 1969).

Amplitude changes represent one degree of freedom, directed along the ordinate (voltage fluctuations). Latency changes represent a second degree of freedom, directed along the abscissa (time fluctuations). Fluctuating latencies are more difficult to deal with, since the results of averaging may create an erroneous illusion that no information is present. Note that a shift in the latency is the same as a shift in the inflection points (phase shift). This effect can best be seen at the inflection points e, f, and g in Figure 7. The illusion created by fluctuating latencies is due to the physical principles of superposition and interference. If the waves have the same frequency and wavelength, there are two limiting cases: a) if the crests of the waves coincide, the amplitudes are additive, and the waves reinforce each other; b) if the crests of one wave coincide with the troughs of the other, the waves cancel each other (resultant amplitude is zero), and the effect is total interference. Another way of stating this principle is to say that the waves are either in phase or out of phase.

No attempts are made to detect shifts in latency for individual trials, since this would require careful plotting of each trial in order to determine the exact time at which inflections occurred. Considering that there are 2,160 trials, this seems

impractical. Instead, latency shifts are handled by aligning the data in the response locked segment as described.

It is assumed at the outset that the phenomenon to be observed will appear in the averaged data as a characteristic pattern of activity (wave form) similar to the visual evoked response (VER) which is known to occur in the human early in the stimulus locked segment. In general, there are three types of activity patterns to be considered (a priori): (a) registration, a charactersistic VER associated with each of the four visual stimuli; (b) decision, a characteristic pattern associated with a correct decision to press right or left and based on the information contained in the stimulus; and (c) anticipation, a characteristic pattern associated with a motor response to press right or left.

Using the present methods of analysis, it was most likely that a) would appear in the stimulus segment and probable that c) would appear in the response segment. It was not known whether b) existed independently, was the same as or a part of c), or part of a). It was also possible that any type of response locked activity might be masked by the stimulus locked activity (by superposition) and woud therefore remain undetectable after averaging. It is important to realize that if the response occurred before 300 msec. for example, a large amount of the stimulus locked activity (VER) would be shifted, out of phase, into the response locked segment. This introduced the possibility of contaminating the response locked data, and would require a different approach either to the method of collection or to the data analysis. For example, the S could be presented from responding before 500 msec, which would ensure that no stimulus activity would appear in the response segment. The other method would be to remove the stimulus activity from the response segment before averaging by means of different data processing techniques.

However, the method of data processing as described is followed through in order to observe the results, with the above examples remaining as possible alternatives. The analysis is based on four logical possibilities: a response pattern could appear in a) the stimulus segment only, b) the response segment only, c) both segments, or d) neither segment. If the response wave appeared in the stimulus locked segment, this would indicate that the phenomenon occurred at a fixed interval of time following the flash (function of the stimulus onset), and was independent of the response latency. If it appeared in the response locked segment, then the phenomenon occurred at a fixed interval of time following the flash (function of the stimulus onset), and was independent of the response latency. If it appeared in the response locked segment, then the phenomenon occurred at a fixed interval of time just preceding the response, and was therefore a function of the response latency. If it appeared in neither segment, then either it did not exist (not conclusive), or could not be detected by the methods used (as described above).

Aside from the shifting procedure used in the response locked segment, no other attempts are made to adjust the data for latency. The analysis is confined to amplitude changes only (one degree of freedom). The stimulus and response

segments are each subdivided into ten 50 msec intervals. Each interval contains 25 data points (Fig. 8). The 25 points are averaged across the interval to obtain a mean value (Fig. 8). The result is 20 mean amplitudes for each pair of averaged waveforms, 10 stimulus locked amplitudes and 10 response locked amplitudes. The number of intervals is determined by examining the number of inflection points in the averaged waveforms. By choosing intervals of standard length (50 msec) it is possible to compare the mean amplitudes of different waves (Fig. 8). Statistical comparisons are made using a t-test for related measures.

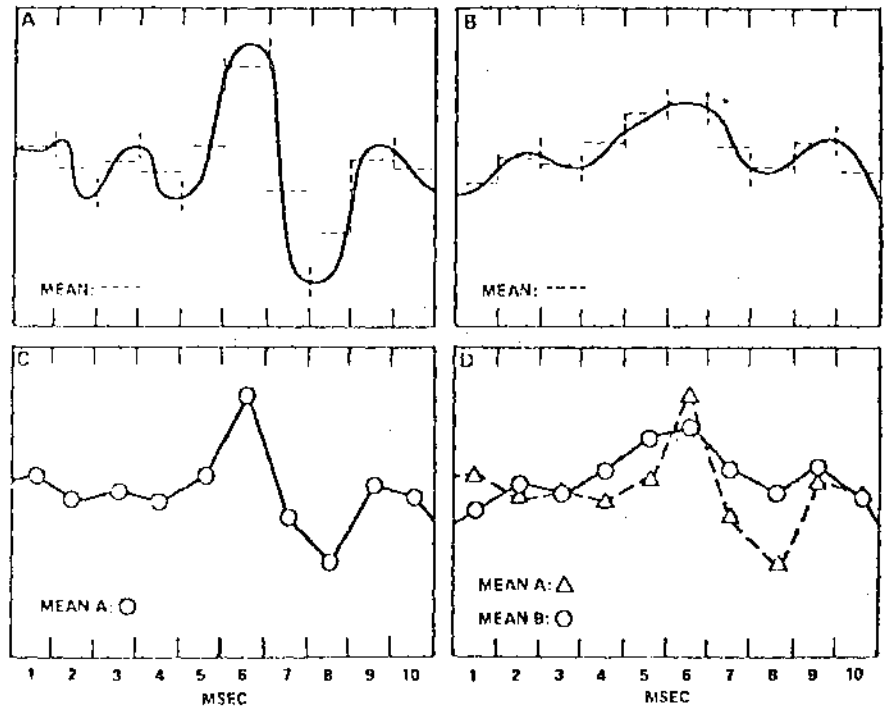

Fig. 8. Method of segmenting the time locked data. Each 50 msec interval contains 25 data points. Two same waveforms are shown in A and B. The same waveforms are represented by their mean values (per segment) in C and D. Differences between the mean amplitudes are indicated in D.

An Experiment

In an application of this procedure to man, the experiment on selective attention presented in an earlier section demonstrates its actual value. In this initial experiment a modified carousel projector rather than a DADTA type display was used to present the stimuli.

Colored patterns are used to provide the visual display and consisted of two colors, red and green, and two forms, circle and square. The square was composed

of vertical stripes of color on a black background, similar to a grating. The various colors and shapes were assembled so that four different colored patterns were produced (Fig. 9).

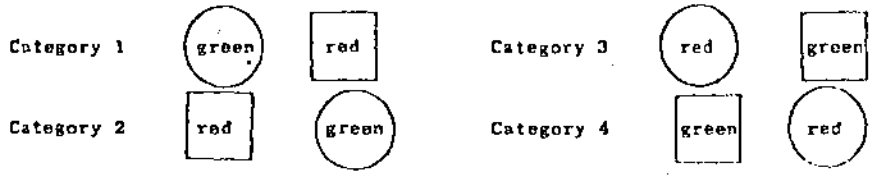

Fig. 9. Four types of slides used for stimulus presentation.

Fifteen slides of each type were arranged pseudorandomly in a projector tray, creating a repeatable random sequence of 60 presentations of the four different stimulus categories (see Rothblatt and Pribram, 1972). Pseudorandom arrangement was used to increase the probability that the response would occur on the basis of relevant cues (color or form) rather than on the basis of cyclic repetition of stimulus presentation. If the S memorized a sequence of responses, then the primary cue might be that sequence rather than the color or form dimension contained within the stimulus. Within 60 trials arranged pseudorandomly, it is unlikely that the S would be able to memorize the order of presentation, so that any subsequent inferences made would then apply to the intended, rather than irrelevant, cue dimensions.

The S was initially trained to respond differentially to one of two colors, followed by a reversal of the color cue and retraining, and then a second reversal to the original color cue and retraining. This procedure was necessary in order to establish a stable baseline for data analysis. The S was then shifted to one of two forms, followed by two similar reversals on the form cue. In this way six tasks, composed of the following correct cue dimensions, were established: red, green, red, circle, square, circle.

The S was seated in a chair inside an open booth in a dimly lit room. An initiate lever and two response buttons (1.5 in. separation) were centrally mounted on a horizontal surface directly in front of him and just below the vertical screen. Stimulus presentation was self-paced. By pulling the initiate lever when he was ready to observe the next slide, the S triggered the strobe light (1.0 msec flash) which marked the beginning of that trial and commenced the trail sequence.

The S, after observing the slide, would then respond to the information he saw. If the cue dimension was circle, for example, a correct response would be to press the left button if the circle appeared on the left side of the screen, the right button if it appeared on the right side. If a correct response was made within 1 second following the flash, a colored reinforcement light would go on. The light illuminated the screen from the back and on the same side of the screen as the button just pressed. The light remained on during the intertrial time and went off at the

beginning of the next trial. If the response was incorrect, the screen remained dark.

Since criterion on any one task was usually reached on the first day, training continued for the equivalent of six days at criterion (90% correct or better). This procedure was followed for each of the six tasks. Note that the retinal image remained invariant across all tasks, i.e., the visual stimuli were always presented in the same pseudorandom sequence (60 trials per day) while only the reinforcing contingencies varied. The contingencies of reinforcement were controlled by the computer in each training situation. Behavioral information was recorded at the end of each trial indicating the stimulus category, the moment of response (latency), its position, and whether it was correct, incorrect or absent. Such items were used to later collate the behavioral and the electrophysiological data.

In order to analyze the electrical activity the four slide categories were separated first on the basis of color: categories 1 and 4 versus categories 3 and 2. The two groups were comprised of 12 pairs of averages, matched by day and on the form dimension (df = 11). The two groups were distinguished on the basis of color, i.e., green to the left versus green to the right (Fig. 10). The second set of comparisons was made by separating the categories according to form: categories 1 and 3 versus categories 4 and 2. Again the two groups were comprised of 12 pairs of averages, also matched by day, but this time on the color dimension (df = 11). The distinguishing characteristic was form, i.e., circle to the left versus circle to the right (Fig. 10). These procedures were repeated, and performed independently, for each task. The results are given in Chapters IV, V and VI.

Three additional sets of comparisons were made, each between tasks (Fig. 11). The two groups were comprised of six pairs of averages (df = 5), matched by day and by category. The first set was distinguished by color (green correct vs. red correct), the second by form (circle correct vs. square correct), and the third by color and form (red and green, combined vs. circle and square, combined). Note that in all cases, the comparisons involved separate t-tests between each pair of 29 mean amplitudes.

Results in the Time Domain

The results show that once learning had occurred, stimulus selection was neither stimulus locked nor response locked, but an ongoing process related to both epochs in the time domain. 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 throught of as stimulus registration (VER), and culminate in the actual correct motor response. As might be expected, 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.

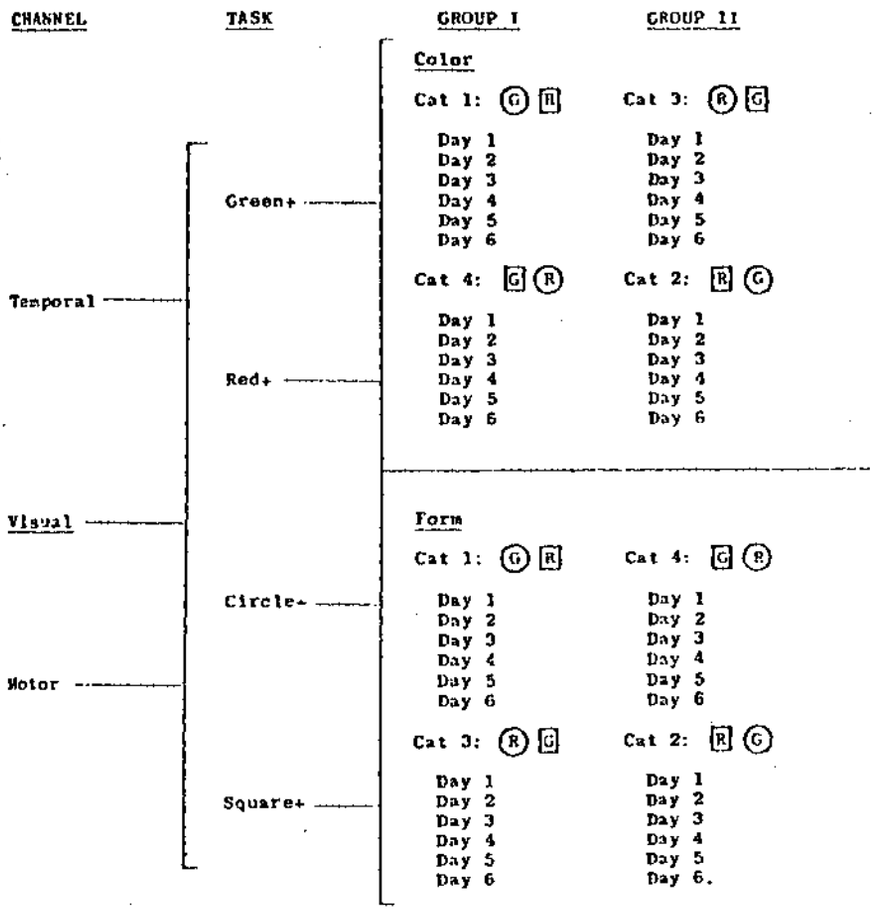

Fig. 10. Basic groupings used for statistical comparisons.

As previously stated, a thorough examination of the electrical activity did not necessarily justify comparisons on a dichotomous basis of color and form. Even though certain portions of various waveforms were found to be similar when compared in this manner, in general, each waveform was separate and distinct for each category, condition, and channel. An example of this is shown in Figure 12 for the motor electrode. Overlays have been constructed for each category demonstrating the differences in electrical activity across all four conditions. Since the amplitude ranges were much lower for the temporal and visual activity, the photographs do not illustrate this effect as clearly as those for the motor electrode. However ,plotted data (not shown) indicated that the same basic trends were present.

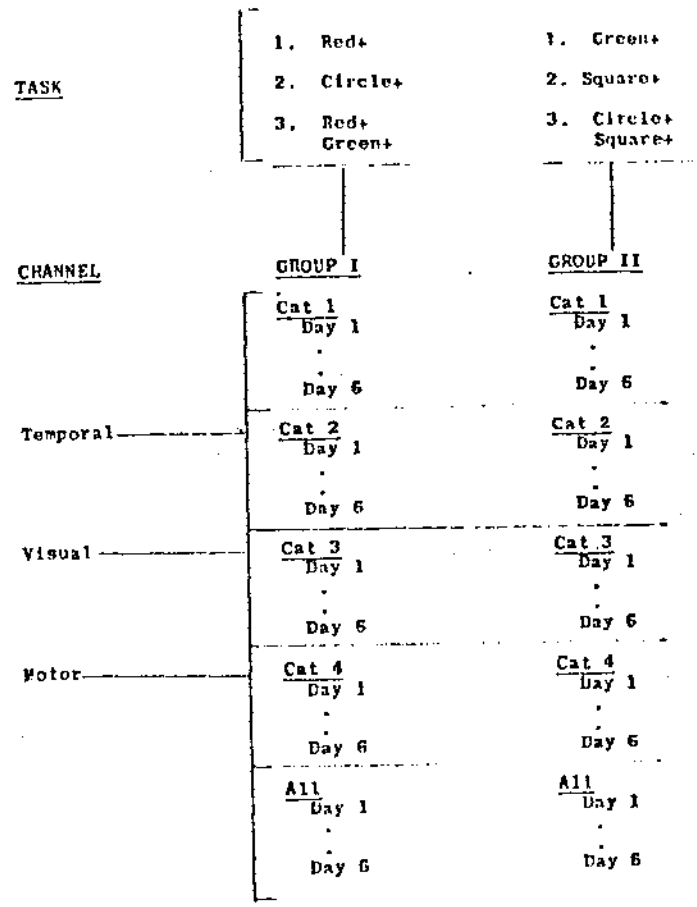

Fig. 11. Additional groupings for statistical comparisons.

Furthermore, this figure illustrates how focusing on significant differences between waveforms can be misleading, except to establish that they are different. What may be overlooked are the points at which the amplitudes match exactly. The effect can best be observed as crossover in the plotted data already presented. If it were possible to overlay all 48 waveforms, what would be seen would be a complex array of matching amplitudes across categories, conditions, and even channels.

At first inspection, the selection process seemed 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 conditions were compared for each electrode (Figs. 19 through 24 in Appendix II) on the basis of color. For

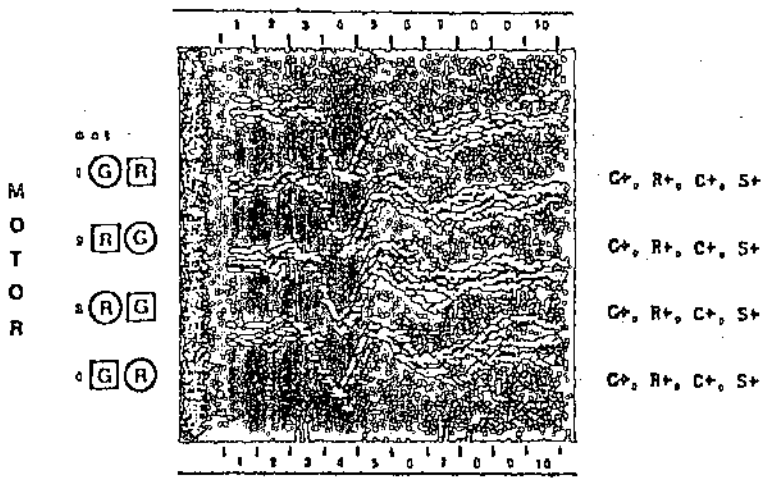

Fig. 12. Stimulus locked activity for the motor electrode. The differences in stimulus category are shown for each different reinforcement condition: Green+, red+, circle+, and square+.

the green condition, X represents a correct left press, while for the red condition Y represents a correct left press. By overlaying each pair of plots for each electrode, respectively, several points were observed at which the amplitudes coincided, usually an X of one matching a Y of the other (response left or response right). The effect was observed in both the stimulus and response locked epochs in segments preceding the response and, especially, at the moment of response. Furthermore, similar effects were observed across channels by overlaying the plots of the three channels for the red and green conditions, respectively. These effects were observed across all categories, conditions and channels.

Since any attempts to interpret these effects would be merely conjecture at this time, no attempts have been made to illustrate such complicated relationships. Figure 12 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 the center line represent response activity recorded from stimulus onset forward in time, and the nodes are points where the 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.

To further demonstrate the ongoing characteristics of the activity, Figure 13 was constructed. After completing the main part of the study, the S was asked to respond to an additional 120 trials during which the stimulus presented was a simple flash of light from the strobe. The experimental procedure was exactly the

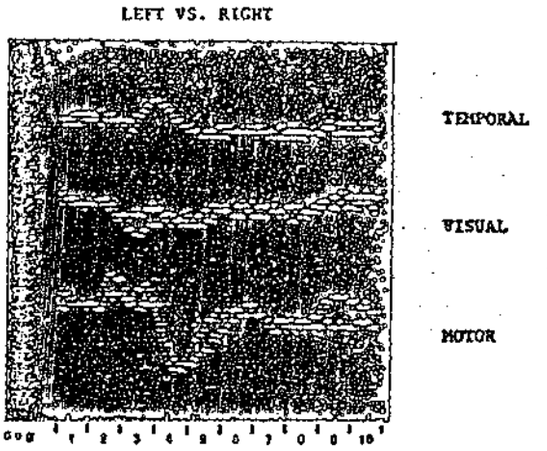

Fig. 13. Stimulus locked activity recorded from each electrode following a simple strobe flash. The overlays show differences between a left and a right press. The response occurred in segment 8.

same, except that the S was instructed to respond to the first 60 trials by pressing the right button every time, and to the remaining 60 trials by pressing the left button. The upper overlay (Fig. 15) represents the averaged electrical activity (60 trials per trace) recorded from the temporal lobe electrode. The overlay shows the differences in electrical activity between a left and a right press during the stimulus locked epoch. Similar activity recorded from the visual electrode appears in the middle overlay, from the motor electrode in the lower overlay.

Even though the stimulus was identical for all trials, differences which represented the selection of an appropriate response were observable throughout the stimulus locked epoch. Regardless of whether the term decision, intention, or selection is used, the process by which the S arrived at the appropriate response was clearly ongoing. When the stimulus was identical, little difference appeared at stimulus onset (segment one) for temporal love and visual activity. For motor activity, the intention to press right or left was shown by immediate differences in activity. Differences continued to be seen for the next 250 msec, especially for the motor and visual activity, through the period that could be thought of as stimulus registration. The stimulus to be registered, however, was identical.

The crossover relationships at the moment of the response, which appeared in the stimulus locked epoch simultaneously (segment 8, Fig. 15) across all channels, is clearly even in the response locked epoch. The effect is best seen for the motor electrode. Each panel in Figure 14 consists of four overlays, representing the activity for each visual display recorded from the motor electrode. One of the traces in each overlay shows the activity recorded when the reinforced cue was green. The other trace shows the activity recorded when the reinforced cue was red

(upper panel), circle (middle panel), and square (lower panel). The crossover effects are readily observable. In addition, what can be seen is not simple amplitude matching, but more important, frequency and phase shift relationships. To investigate these observations further, a portion of the data was subjected to spectral analysis.

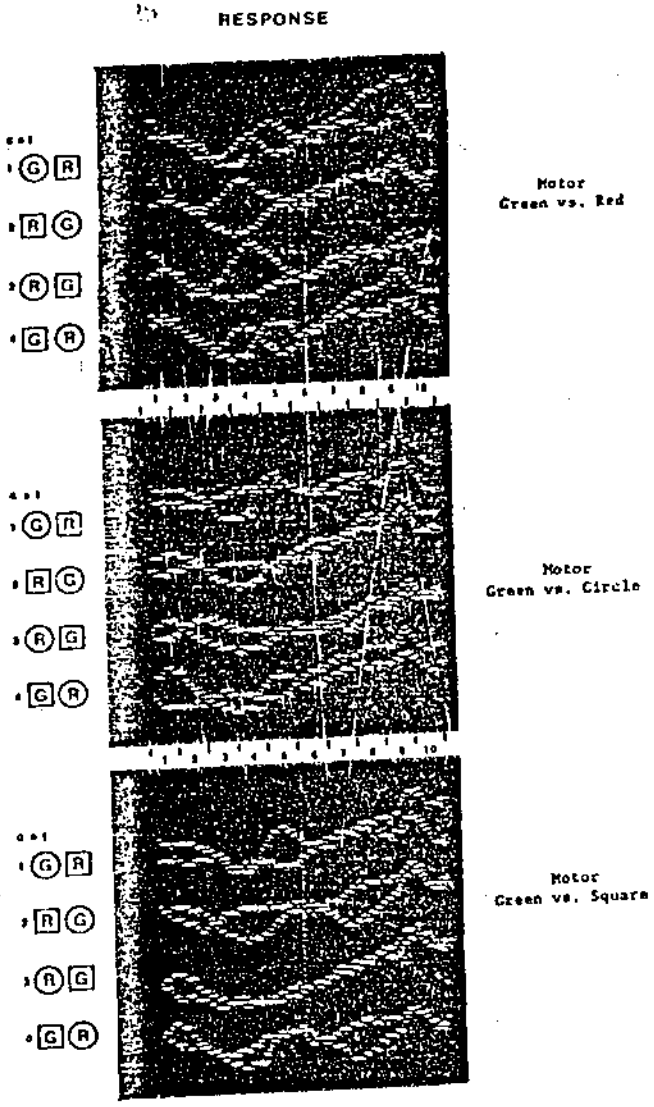

Fig. 14. Comparisons of response locked motor cortex activity.

J2151: TASK2=GREEN TAPE1 STIMULUS LOCKED 4 CATEGORIES(GROUPS)

STEP		VARIABLE SELECTED			PER CENT 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

Fig. 15. 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.

Results in the Frequency Domain

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

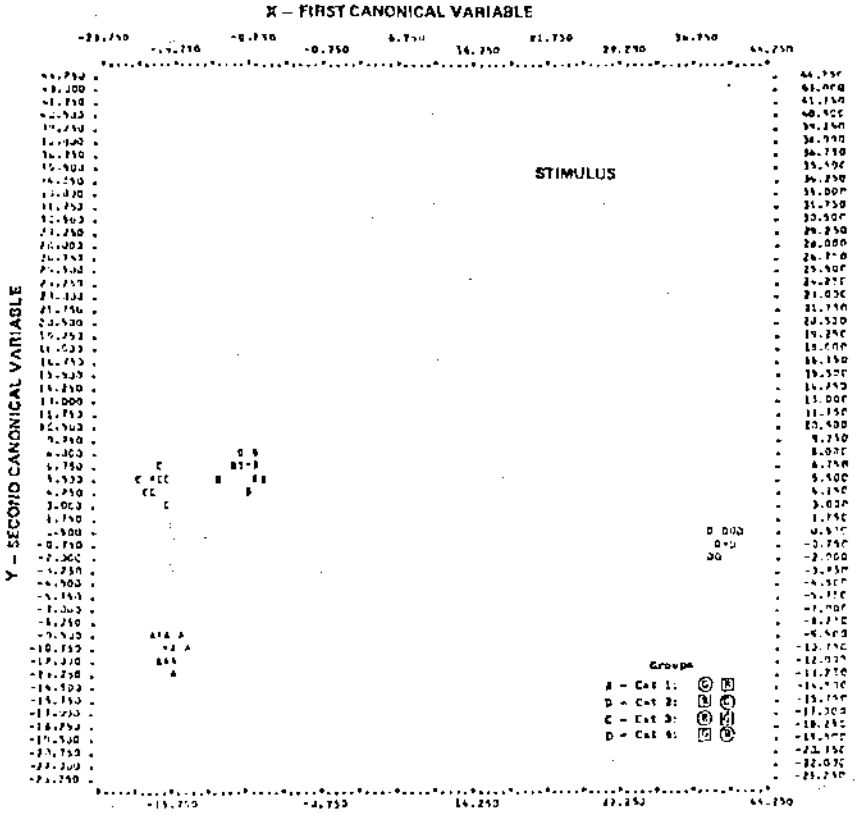

Fig. 16. Canonical analysis of stimulus locked data (from stepwise discriminant analysis program). Each trial for green correct has been classified into one of four groups. The scattergram illustrates the clustering about the groups mean (*) for each visual display.

Note that intensity was 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. Bandwidth was defined in hertz, and is an estimator of the peakedness of each band. Phase shift (degrees) indicated the angle by which the first channel of each electrode pair led or lagged the second in a given frequency band. The coherence function, being a dimensional number between zero and one, provided a measure of the linear relationship between channel pairs. The coherence function acts like a coefficient of correlation between the records: a value near 1 indicates that, at a particular frequency, nearly all the activity in one record could be explained as a linear transformation of activity in the other record; a value of 0 means that there was no linear relationship between the records at that frequency.

J2153: TASK2=GREEN TAPE1 RESPONSE-LOCKED 4 CATEGORIES(GROUPS)

STEP		VARIABLE SELECTED			PER CENT 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	19 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	14 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)	90.943
46	28 INTENSITY:	MOTOR	BETA	(16-20)	
47	49 PHASE:	TEMP X MOTOR	THETA	(4- 7)	
48	4 INTENSITY:	TEMPORAL	BETA	(16-20)	

Fig. 17. Summary of stepwise discriminant analysis of response locked data for green correct. Each step indicates the variable selected which was found to be the best discriminator among the four stimulus categories.

The trials were arranged into four groups, by stimulus category and subjected to a stepwise discriminant analysis program. The results are shown in Figures 15 and 16 for stimulus locked activity and in Figures 17 and 18 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% correct separation for the stimulus locked activity, but only 30 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% of the stimulus locked epochs for each trial were identified at step one on the basis of

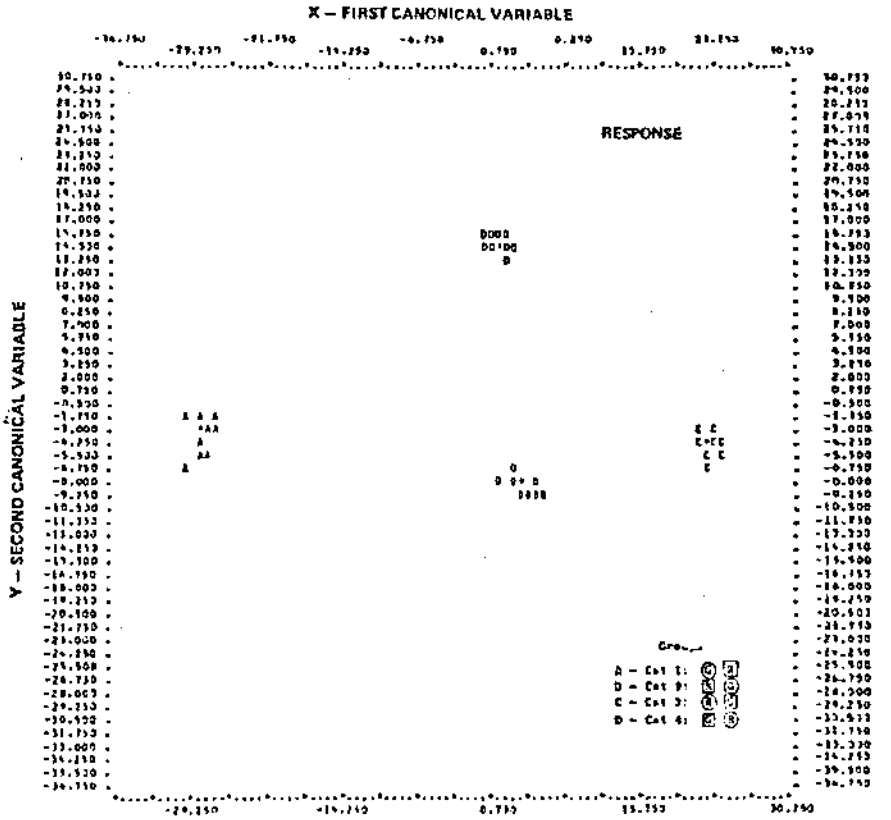

Fig. 18. Canonical analysis of response locked data (from stepwise discriminant analysis program). Each trial for green correct has been classified into one of four groups. The scattergram illustrates the clustering about the groups mean (*) for each visual display.

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 are arranged according to step number and indicated in Figure 16. For response locked activity, 43% 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 0.24 sec period preceding the response. This would be the same as four to eight cycles in 1 sec. The remaining steps are shown in Figure 18.

These results seem to indicate that further investigation of the frequency domain might give valuable insight into the nature of the cross-channel variations as well

as within channel activity. By combining time locked averaging methods (time domain) with methods of auto- and cross-spectral analysis (frequency domain), a fuller understanding might be obtained of the complex relationships described here.

Conclusion

We have detailed these procedures as examples of powerful and flexible tools for the analysis of brain-behavior relationships. As was shown, applications can begin to enhance our understanding of such processes as decision making and selective attention. Because the cost of these procedures can be kept within reasonable bounds once the new technology is fully exploited, its application in the clinic promises to afford diagnostic tools where they are so desperately needed. So many retarded children are diagnosed with the vague label "diffuse brain syndrome"; so difficult is it on occasion to differentiate autism from childhood schizophrenia; or for that matter a drug-induced from an endogenous psychosis at any age. So often the diagnosis of the origins of episodic violence hangs in the balance because our analytical tools have not been sufficiently sharpened. We are convinced that the analytical armamentarium described here can be produced for little more than the current cost of ordinary EEG equipment—and that the diagnostic power could even at present be increased tenfold were the initial applications embodied in DADTA and FATLIP properly and extensively employed. With this faith we continue our research; however the problems rest not only with us but with those who set priorities on the expenditure of funds. The question before us is—do we proceed *now* to make use of the accumulated knowledge and wisdom of the third quarter of the twentieth century or do we let another generation suffer the consequences of our earlier ignorance?